A Stochastic Approach for Analysis of Shadowing Effects in Urban Area

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DOI: 10.15598/aeee.v20i1.4338

Article history: Received Aug 19, 2021; Revised Dec 08, 2021; Accepted Jan 16, 2022; Published Mar 31, 2022.
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Abstract. *5G networks are started to be deployed in urban areas in the dynamic spectrum sharing mode. Therefore, the analysis of Non-Line-of-Sight (NLOS) shadowing effects behind buildings of different heights becomes particularly important. The shadowing of GSM (900 MHz), UMTS (2100 MHz) and LTE (1800 MHz) technologies was investigated in the urban area. The results are examined by using the log-normal path loss model and four different stochastic equations, specifically: normal, log-normal, Rayleigh, and Nakagami. The results showed that the fluctuations of path losses in the urban area correspond to the model of log-normal path losses. However, path losses for individual buildings do not fit this model. Therefore, stochastic methods were used to analyse shadowing effects. A path loss model based on a differential stochastic equation was proposed. This model includes the following values: free space losses, path losses disturbance due to the shadowing effect, standard deviation σ, and a freely chosen parameter b. This model allows a very accurate estimate of the path losses of the three technologies. A clear correlation was observed between parameter b and standard deviation σ.*

Keywords

Mobile networks, path loss, radio wave propagation, shadowing effects, statistical spatial channel model.

1. Introduction

Deployment of 5G technology is currently gaining acceleration because the data rates of the previous generation technologies do not meet consumers' expectations, especially when we are talking about Internet 3.0, IoT, Industry 4.0, or video transmission services that require even higher data transfer rates. For this purpose, the need will arise to use not only the new frequencies of a higher range with a sufficiently wide frequency band (up to 500 MHz) [1] and [2], but also the existing frequencies which are currently being used by the GSM, UMTS and LTE technologies. 5G requires the compaction and restructuring of the base stations. Therefore, it is fundamentally important to assess accurately the path losses, especially by virtue of solving the planning tasks in densely populated areas.

Such models are widely used today, albeit only for the GSM, UMTS and LTE technologies, and they are created for the frequencies lower than 6 GHz (many of them are valid for the frequencies up to 3 GHz). Therefore, new models are already being developed. An overview of such models in the highest frequency bands is provided in [3]. However, according to the experiments, the existing path losses evaluation models yield significant errors both for the lower and the higher frequencies. They can reach 10 percent or more [4], [5], [6], and [7]. Together with the modelling, analysis of the factors (usually called shadowing) influencing path losses both for the LOS and NLOS conditions is crucially important as well. It is especially important to evaluate these factors while taking into account the actual situation of 5G in the urban regions when the base stations will be built fairly close to one another.

Of course, as noted in [4], [8], [9], and [10], the new technologies, associated with highly directional and steerable beam combining techniques, can reduce path losses. Yet, it is still important to know the influence of shadowing because it is inevitable in the light of the current situation.

This research analyses the influence of shadowing on the path losses for the GSM, UMTS and LTE technologies. The authors presume that this approach shall lead to a better understanding and more precise assessment of the shadowing issue in the 5G technology.

The proposed models are verified by the experimental results of previous work [11].

2. Related Works

Shadowing is understood as the situation where two receivers that are separated spatially are influenced by different radio signal losses, even though the distances between the transmitters and receivers are the same. Therefore, the measured signal strength varies according to the average forecast values. In other words, the average received signal level, when the distances from the transmitters are the same, will be different due to various effects (diffraction, reflection, scattering, etc.) mitigating the radio wave propagation.

Currently, there is a high number of works investigating the shadowing effect in a wide frequency range. The shadowing effect is usually analysed in two ways:

- by the stochastic methods, i.e., by using Probability Density Functions (PDF) or the Cumulative Distribution Function (CDF),
- by the log-normal shadowing (path losses) model.

These two methods are often used together.

2.1. Log-Normal Shadowing Model

In order to determine the distance dependence of the path loss and the influence of the shadowing, the well-known model is used [4] and [12]:

$$PL(d) = PL\left(d_0\right) + 10 \cdot n \cdot \log\left(\frac{d}{d_0}\right) + c + X_\sigma, \quad (1)$$

where $PL(d)$ is the path loss average value, $PL(d_0)$ is the path loss in the reference point from the transmitter, n is the exponent describing the propagation environment, c is the offset factor considering the difference between the reference pattern and the measurements, X_σ is the factor evaluating the shadowing, and it is often called the shadowing depth. This factor X_σ is generally defined by standard deviation σ.

Some models, e.g., the one used in [4], include more correction factors employed in Eq. (1).

If the radio wave propagates under NLOS conditions (this is a more common situation in urban regions), then, exponent n in Eq. (1) is higher than 2. The precise value of exponent n depends on the environment. It also increases with the increasing frequency. As shown in [13], $n \approx 2.25$ at $f = 60$ GHz, and $n \approx 2.86$ at $f = 72$ GHz even for the LOS conditions.

The offset factor c is determined experimentally and may vary over a wide range. For the specific example of the Tampere (Finland) District, the c ratio ranged from 6.8 dB to 31.5 dB [14]. The shadowing factor X_σ, determined by the probability density function, is ranging from 1.6 dB to 8.2 dB depending on these areas. It has also been observed that the experimental results are best matched by the log-normal probability distribution function. It has also been noted that exponent n is increasing with the increase of the frequency from 900 MHz to 5 GHz.

The path losses and shadowing effects in different environments (Street Canyon, Open Square, indoor conditions) were analysed in [3]. It was shown that exponent n varies from 1.85 (Open Square LOS conditions) to 3.19 (Street Canyon NLOS conditions); meanwhile, the standard deviation ranged from 3.1 dB to 8.2 dB, respectively.

The results of investigation [4] which was executed after some previous research [15] show that exponent n strongly depends on both factors: the propagation conditions (LOS and NLOS) and the antenna height. Exponent n under LOS conditions varies slightly, and it is in the range from 1.8 to 2.0. Meanwhile, such a variation under NLOS conditions is significant and depends on the height of the transmitter antenna and the receiver antenna gain. Thereby, exponent n changed from 1.3 (the transmitting antenna height was 36 m) to 3.8 (the transmitter antenna height was 8 m) at the frequency of 38 GHz.

The shadowing effect at sufficiently high frequencies (28 and 38 GHz) in the cities of New York and Austin (USA) was also researched [15]. The obtained results show that standard deviation σ, describing the shadowing, depends not only on the transmitter and receiver antenna heights and frequencies, but on the selected model as well. The standard deviation value σ was ranging from 9.02 to 6.14 when using the Close-in

Reference Model ($d_0 = 5$ m); σ ranged from 5.78 dB to 8.52 dB when the Floating Intercept Model was used. It was revealed that log-normal PDF most closely matched the experimental results.

Marine wireless sensor networks at 5.8 GHz have been analysed as well [16]. It was observed that exponent n is not constant and varies depending on the route. Large objects (e.g., passing vessels) increase n from 6.46 to 21.98, while the shadowing effect caused signal variation of up to 21 dB.

2.2. Stochastic Methods

There are a lot of different proposals where PDF is used in order to research the shadowing effect. It was proposed as Nakagami probability density distribution with the objective to predict the influence of shadowing [17]. The different propagation conditions can be better evaluated and a better explanation of the experimental data can be offered than in the scenarios employing many other distributions in comparison to using this particular distribution. Meanwhile, the best results were obtained when using G-distribution [18]. Experimental results are consistent with the Rayleigh function when the transceivers are moving at a constant speed [19]. The best match to experimental results was achieved with the normal distribution [20]. Thus, it can be assumed that the experimental results can match different PDFs, and they depend on various factors determining the shadowing. So, it is difficult to offer the particular PDF in all the cases. By the way, it can be assumed that experiments [15] and [20] were carried out under the conditions of slow fading. Therefore, as it is already known, the normal and log-normal PDFs describe the experimental data with more accuracy.

3. Experimental Setup

The experimental setup is fully described in [11]. A simplified scheme of the measurements is shown in Fig. 1.

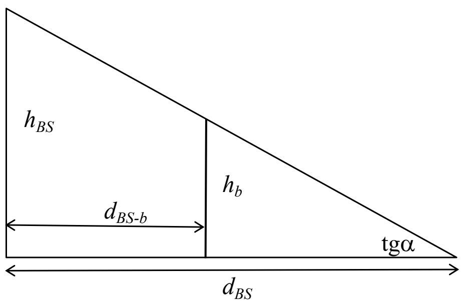


Fig. 1: Simplified measurement chart.

Here, h_b is the building height (m), h_{BS} is the height of the antenna of the base station (m), $\tan g\,\alpha$ is the angle corresponding to the direct sight behind the particular building (rad), d_{BS-b} is the distance between the base station and the back wall of the building (m), d_{BS} is the distance from the transmitter $T\chi$ to the measurement point, d_{BSR} is the distance from the backwall of the building to the measurement point.

Electromagnetic wave propagation in space is evaluated as the non-linear random process. Such processes are described by the stochastic models with the predetermined probability density distribution. In most cases, random processes can be expressed by the well-known differential Eq (2):

$$\frac{d\bar{x}(t)}{dt} = f(\bar{x},t) + v(\bar{x},t)\bar{\xi}(t), \tag{2}$$

where $f\{\cdot\}$ and $v\{\cdot\}$ are vector and matrix functions of the vector argument, $\bar{\xi}(t)$ is the noise. Changing $f\{\cdot\}$ and $v\{\cdot\}$ functions we can get random processes with different probability density distributions. For example, if $f\{\cdot\}$ is the linear function and $v\{\cdot\}$ does not depend on $\bar{x}(t)$, we have random process described by the normal (Gaussian) distribution.

It is known that each probability density distribution can be expressed as a stochastic differential equation.

The normal distribution is expressed by the following Eq. (3):

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right), \tag{3}$$

where σ is the variance, μ is the mean value of the measured variables x. The differential Equation corresponding to the normal distribution is:

$$\frac{dx}{dt} = -\frac{b}{2\sigma^2} x \,\mathrm{sign}(x) + \sqrt{\frac{2b}{N_\xi}}\xi(t), \tag{4}$$

where N_ξ is some diagonal matrix defining the noise influence, b is the factor which depends on the measurement environment. All other variables are the same as described above.

If all the members in Eq. (4) are variables, then, the equation does not have any final solution [21]. One of the variables should be selected, and this equation should be solved with respect to this variable.

Equation (4) can be simplified.

It is known that $\sigma^2 = \frac{2b}{N_\xi}$, therefore:

$$\frac{dx}{dt} = -\frac{b}{\sigma^2} x \,\mathrm{sign}(x) + \frac{1}{\sigma}\xi(t). \tag{5}$$

Other distributions have a different form of stochastic differential equations. For example, the differential equation corresponding to the log-normal distribution is:

$$\frac{dx}{dt} = -bx\left(\ln\frac{x}{\mu} - \sigma^2\right) + bx\xi(t). \quad (6)$$

4. Results

As mentioned above, the log-normality path loss equation (including its various modifications) and the stochastic equations (i.e., distributions) are usually used to investigate shadowing.

4.1. Investigation of Shadowing by Using Log-Normal Path Losses

Signal strength measurements were made in Dainava District of Kaunas City (Lithuania) (Fig. 2) to investigate how the path losses depend on the shadowing behind the buildings, that are of different heights.

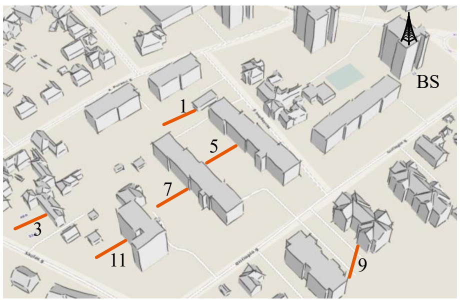


Fig. 2: Numbered GSM, UMTS and LTE signal measurement locations.

The experimental results of the log-normal path losses dependence on the mobile technology are presented in the Fig. 3.

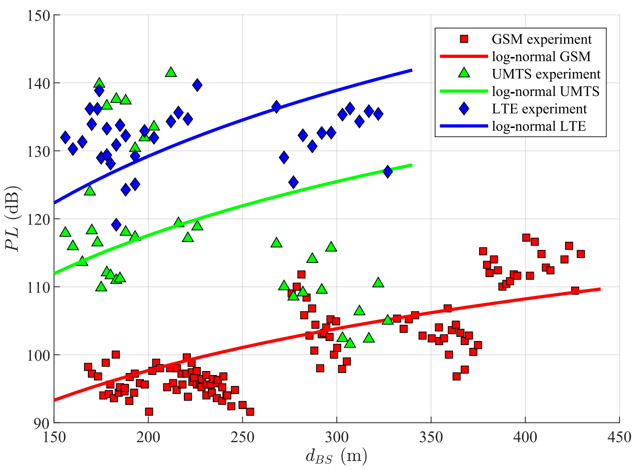


Fig. 3: Data comparison of path losses with the log-normal path losses model for the different mobile technologies.

One can see that the results basically meet the log-normal path loss model when not analysing each building's influence separately. The average shadowing depth X_σ is 3.36 dB for the LTE technology, 4.04 dB for the UMTS technology, and 2.00 dB for the GSM technology. It is obvious that the shadowing depth strongly depends on the frequency, i.e., the higher frequency corresponds to the greater depth. Such dependence can be explained by the fact that such shadowing mechanisms as diffraction, scattering, and reflection directly depend on the frequency. The results coincide well for the 2 GHz frequency band [12] and [14]. However, the shadowing depth is less than the values determined in [14] for the lower frequency band (900 MHz). This can be explained by the fact that the results of [14] were obtained under the fast-fading conditions, while the current research is carried out under the slow fading conditions.

The values of exponent n, see Eq. (1), best fitting the experimental results are about 5.5 for the LTE, 4.5 for the UMTS, and 3.5 for the GSM technologies. It is necessary to consider the fact that the UMTS frequency range is greater than the LTE one. Therefore, the clear influence of technology can be seen here. The comparison of these experimental results with the other investigations [12], [14] and [23] shows that the set of n values is very similar. It is plausible that exponent n [14] in some city districts is somewhat higher. Yet, these results can be explained by the specificity of the district as well as by the performance of the experimental conditions (as mentioned above, it was carried out under the fast fading conditions [14]).

Further analysis of the results showed that there is clear separation to the certain group (in red) where the losses decrease with the increasing distance from the base station (Fig. 2). This means that these results are contrary to the model, see Eq. (1). Therefore, the path losses variation should be described by another model. One of such models was introduced in [11].

However, it does not analyse the impact of shadowing, and the experiments were carried out by sampling relatively short distances behind houses ($d_{BS-b} < 68$ m).

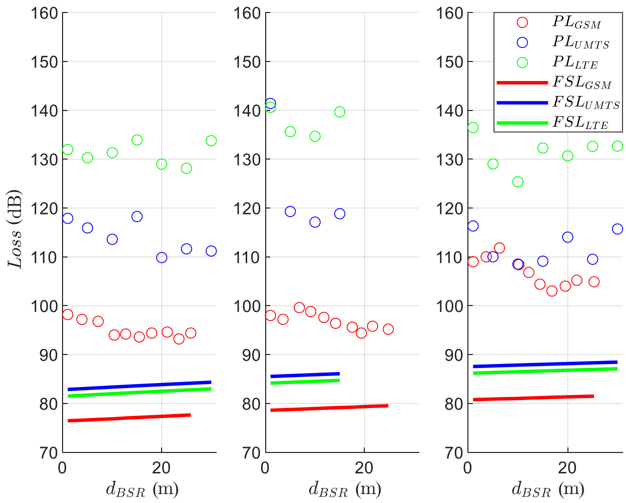
Due to this fact (of path losses decreasing with the distance from the base station), the shadowing effect shall be further analysed by using the stochastic methods.

4.2. Investigation of Shadowing by Using Stochastic Models

Analysis of the research made by other authors as presented above showed that shadowing can be analysed by using various distributions.

As the mathematical model is based on a probability density function, we needed to determine which probability distribution function best fits our experimental PL estimation results.

LTE has a lower frequency than UMTS, so the theoretical Free Space Loss (FSL) for LTE is lower than for UMTS. However, practical measurements of the received signal level show that in all cases LTE due technological peculiarities has a lower signal level compared to UMTS. For this reason, the calculated PL values for LTE are also higher than for UMTS (Fig. 4).



(a) Location 5. (b) Location 7. (c) Location 11.

Fig. 4: Experimental path and theoretical free space losses as a function of the distance d_{BSR}.

First, the attempt was made to find the Probability Distribution Function (PDF) best describing these experiments.

For this purpose, PDF was calculated according to the empirical data using four stochastic equations: the normal, log-normal, gamma, and Nakagami (Fig. 5).

Such results were compared with the corresponding theoretical PDF by selecting the appropriate settings (mean, variance, and others). The summary of the results for 18 m height buildings for the different technologies is shown in Tab. 1.

Subsequently, similar results were obtained for other heights of the buildings. The log likelihood parameter is given in Tab. 1 to compare how different distributions fits to the experimental data. The higher the log likelihood - the better fitting. These results, as it can be seen, depend on the technology. Analysis employing the full pool of the data, and the technology, shows that the best results correspond to the normal distribution. The gamma and log-normal distribution gives acceptable results as well.

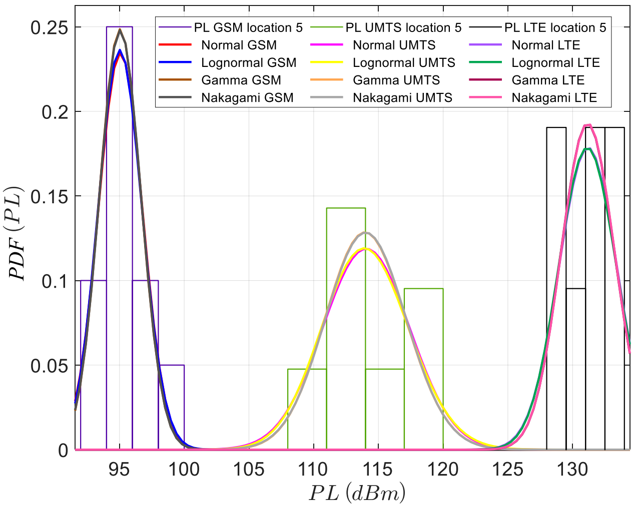


Fig. 5: Comparison of the experimental path losses PDF fitting.

Tab. 1: Analysis of path loss experimental results.

Distribution	Network technology		
	GSM	UMTS	LTE
Normal:			
- Log likelihood:	-18.9945	-17.9116	-15.0579
- Mean:	95.07	114.052	131.191
- Variance:	2.88933	11.2748	4.98905
Lognormal:			
- Log likelihood:	-18.9264	-17.8998	-15.0607
- Mean:	95.0714	114.059	131.194
- Variance:	2.85156	11.2515	4.99511
Gamma:			
- Log likelihood:	-18.922	-17.8638	-15.0201
- Mean:	95.07	114.052	131.191
- Variance:	2.57724	9.64607	4.27906
- Parameter α:	3506.97	1348.5	4022.19
- Parameter β:	0.0271089	0.0845764	0.0326169
Nakagami:			
- Log likelihood:	-18.9447	-17.8675	-15.0191
- Mean:	95.0701	114.052	131.191
- Variance:	2.58857	9.6527	4.27734
- Parameter μ:	873.03	337.02	1006.08
- Parameter ω:	9040.91	13017.4	17215.5

These experiments were carried out in the conditions when the movement of cars and people was virtually non-existent. Therefore, as it was mentioned above, the experiments comply with the slow fading conditions.

It can be assumed that the experimental results in the PDF form indicate the type of fading: it is called the slow or fast fading. Similar results were obtained for the heights of the buildings located at different distances from the base station. Figure 3 shows the results behind houses of a relatively similar height but at different distances from the base station processed by the normal distribution.

As already mentioned, the normal distribution complies with the stochastic differential Eq. (4). When overwriting the following equation in the adopted form and differentiating it with the distance x, the following form was obtained:

$$\frac{dP}{dx} = -\frac{b}{2\sigma^2} \cdot P' \cdot \operatorname{sign}(P') + \sqrt{\frac{2b}{N_x}}\xi(x) \quad \text{or}$$
$$dP = \left(-\frac{b}{2\sigma^2} \cdot P' \cdot \operatorname{sign}(P') + \sqrt{\frac{2b}{N_x}}\xi(x)\right) dx. \tag{7}$$

In this case, $\xi(x)$ is the disturbance caused by shadowing. This one has increased path losses compared to the losses in the free space. The values of $\xi(x)$ and b are independent variables in this equation. As already mentioned, if all the elements in the equation are variables, no similar differential equation can have the final solution. Thus, one of the variables must be selected freely. Usually, variable b is selected as the independent one. Let us assume that P' is the free space losses, and x is the distance from the base station.

As $P' = 92.45 + 20\log f + 20\log x$, then, P can be found by integrating, see Eq. (7). It must be considered that:

$$\sigma^2 = \frac{2 \cdot b}{N_\xi} \Rightarrow N_\xi = \frac{2 \cdot b}{\sigma^2}. \tag{8}$$

The value of $\xi(x)$ defining the shadowing influence is determined experimentally based on the obtained results, as shown in [11]. It depends on the technology, the building height, the distance from the base station, and the distance behind the building. Straight lines (Fig. 6) can approximate the results. Figure 6 shows the results for the UMTS technology, but similar results are obtained for the LTE and GSM technologies as well. It was determined that $\xi(x)$ depends on the above mentioned factors as well as on the mobile technologies.

$\xi(x)$ for the LTE, UMTS, and GSM technologies can be expressed as follows:

$$\xi_{LTE} = \{(-0.0047h_b - 0.0796) \cdot d_{BS} + \\ + [0.2028 \cdot (d_{BS} - d_{BS-b}) + 44]\} + \\ + \begin{cases} 8, \text{ if } \alpha \geq 0.05; \\ -757.46 \cdot \operatorname{tg}\alpha + 34.173, \text{ if } \alpha < 0.05. \end{cases} \tag{9}$$

$$\xi_{UMTS} = \{(-0.0047h_b - 0.0796) \cdot d_{BS} + \\ + [0.2028 \cdot (d_{BS} - d_{BS-b}) + 32]\} + \\ + \begin{cases} 0, \text{ if } \alpha \geq 0.05; \\ -757.46 \cdot \operatorname{tg}\alpha + 34.173, \text{ if } \alpha < 0.05. \end{cases} \tag{10}$$

$$\xi_{2G} = \{(-0.0047h_b - 0.0796) \cdot d_{BS} + \\ + [0.2028 \cdot (d_{BS} - d_{BS-b}) + 20]\} + \\ + \begin{cases} -8, \text{ if } \alpha \geq 0.05; \\ -757.46 \cdot \operatorname{tg}\alpha + 34.173, \text{ if } \alpha < 0.05. \end{cases} \tag{11}$$

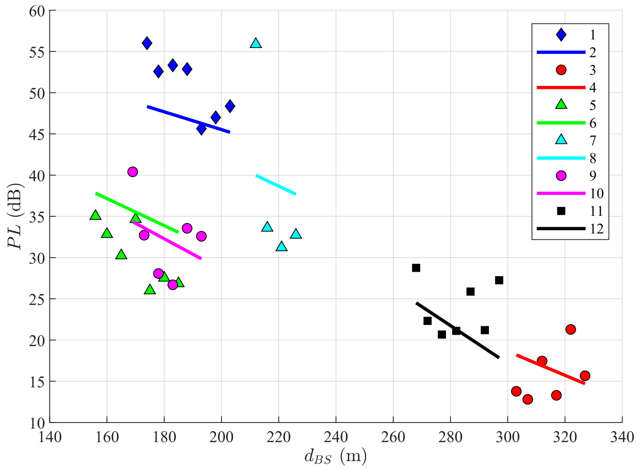


Fig. 6: $\xi(x)$ variation behind the buildings and comparisons with the straight-line approximation results for the UMTS technology: 6 m experiment - 1, 14 m experiment - 3, 18/1 m experiment - 5, 18/2 m experiment - 7, 23 m experiment - 9, 32 m experiment - 11, 6 m model - 2, 14 m model - 4, 18/1 m model - 6, 18/2 m model - 8, 23 m model - 10, 32 m model - 12.

After inserting Eq. (9), Eq. (10) and Eq. (11), into Eq. (7), and integrating it, the following Eq. (12), was obtained:

$$PL = -92.45 \cdot \frac{b}{2\sigma^2} \cdot d_{BS} - 20 \cdot \frac{b}{2\sigma^2} \cdot d_{BS} \cdot \log f + \\ -10 \cdot \frac{b}{\sigma^2} \cdot \frac{d_{BS}}{1000} \cdot \log \frac{d_{BS}}{1000} + \\ + \frac{1}{\sigma} \cdot (0.047h_b - 0.0796) \cdot \frac{d_{BS}^2}{2} + \\ +0.2028 \cdot (d_{BS} - d_{BS-b}) \cdot d_{BS} + \\ + C_f + \begin{cases} 8, LTE; \\ 0, UMTS; \\ -8, 2G. \end{cases} \tag{12}$$

where d_{BS} is the distance from the base station to the measured point (m), f is the frequency in GHz, σ^2 is the variance, h_b is the height of the building (m), d_{BS-b} is the distance from the building to the measurement point (m), C_f is a coefficient that is described by the following equation:

$$C_f = \begin{cases} (-757.46 \operatorname{tg}\alpha + 34.173)d_{BS}, \text{ if } \alpha < 0.05; \\ 0, \text{ if } \alpha \geq 0.05. \end{cases} \tag{13}$$

The calculations show that there is a very strong correlation $CORR$ between coefficient b and variance σ: $CORR \approx 0.956$ for LTE, $CORR \approx 0.986$ for UMTS, and $CORR \approx 0.868$ for GSM, respectively.

The comparisons of Model, see Eq. (13), with the experimental results are presented in Fig. 6, Fig. 7, Fig. 8 and Fig. 9. It is possible to determine accurately

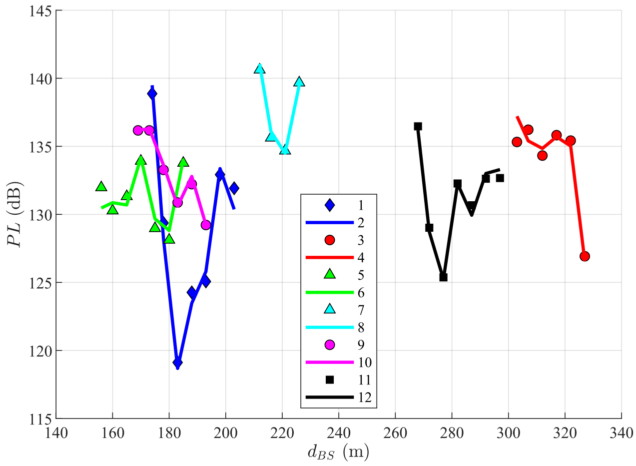


Fig. 7: Comparison of Model, see Eq. (13), and the experimental results for the LTE technology: 6 m experiment - 1, 14 m experiment - 3, 18/1 m experiment - 5, 18/2 m experiment - 7, 23 m experiment - 9, 32 m experiment - 11, 6 m model - 2, 14 m model - 4, 18/1 m model - 6, 18/2 m model - 8, 23 m model - 10, 32 m model - 12.

the variation of the path losses behind buildings by choosing coefficient b.

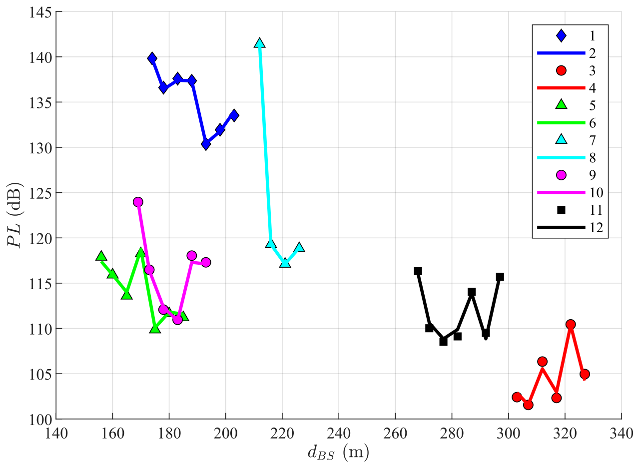


Fig. 8: Comparison of Model, see Eq. (13), and the experimental results for the UMTS technology: 6 m experiment - 1, 14 m experiment - 3, 18/1 m experiment - 5, 18/2 m experiment - 7, 23 m experiment - 9, 32 m experiment - 11, 6 m model - 2, 14 m model - 4, 18/1 m model - 6, 18/2 m model - 8, 23 m model - 10, 32 m model - 12.

4.3. Limitations of the Proposed Model

Model, see Eq. (13), suffers from some limitations and disadvantages. The first limitation stems from the fact that the model is valid for the slow fading conditions only. The next limitation is related with the distance behind the building. The experiments were carried out at the distances $d_{BS-b} < 70$ m only.

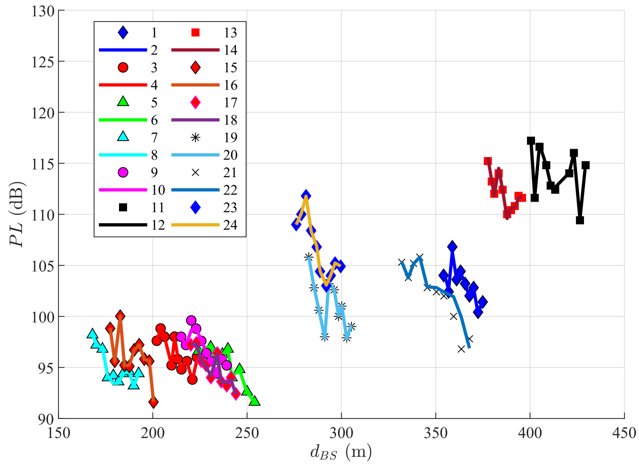


Fig. 9: Comparison of Model, see Eq. (13), and the experimental results for the GSM technology: 12/1 m experiment - 1, 12/2 m experiment - 3, 15/1 m experiment - 5, 15/2 m experiment - 7, 15/3 m experiment - 9, 18/3 m experiment - 11, 18/4 m experiment - 13, 18/5 m experiment - 15, 22 m experiment - 17, 35/1 m experiment - 19, 35/2 m experiment - 21, 41 m experiment - 23, 12/1 m model - 2, 12/2 m model - 4, 15/1 m model - 6, 15/2 m model - 8, 15/3 m model - 10, 18/3 m model - 12, 18/4 m model - 14, 18/5 m model - 16, 22 m model - 18, 35/1 m model - 20, 35/2 m model - 22, 41 m model - 24.

Certain limitations may depend on the base station antenna height h_{BS}. Although the proposed model evaluates the antenna height through $\mathrm{tg}\,\alpha$, some limitations could be somewhat decreased by specifying the influence of h_{BS}.

The main disadvantages are related to coefficient b which should be selected within the range of values 5 to 65. It reduces the versatility of the model.

5. Conclusion

It was determined that the total signal path losses variation in the city area corresponds to the log-normal path losses model. The shadowing depth varies depending on the signal frequency and the exponent, which is strongly influenced by the mobile technology.

It was determined that the use of the log-normal path losses model for the shadowing effect behind the individual buildings is not appropriate since the nature of the signal path loss variation differs from the one described by this model. The proposed model revealed the increase in the signal path losses with the distance, while the experimental data shows reverse dependability.

The comparison of the empirical data expressed by PDF was made with four distributions: normal, log-normal, gamma, and Nakagami. It was revealed that the normal distribution is the best one to describe the propagation path losses. Hence, this model was chosen to estimate the propagation path losses for three mobile technologies: GSM, UMTS and LTE.

This model is denoted by some limitations, mainly regarding coefficient b that must be selected individually from the range of values of 5 to 65. This limits the versatility of the proposed model. Another limitation is related with the strong correlation between coefficient b and variance σ^2, and it suggests the need to modify this model when seeking to increase its versatility.

The authors presume that the results of this research could contribute to the models for the evaluation of signal path losses in urban environments.

The path loss due to shadowing should be even greater for higher frequencies mmWave and THz. Therefore, the authors also are planning to continue the research for higher frequencies. This is especially relevant for the deployment of the 5G technology.

Author Contributions

S.J. and V.G. performed the measurements, developed the theoretical formalism, performed the analytic calculations, and performed the numerical simulations. R.J. and P.T. contributed to the analysis of the results and to the proofreading of this manuscript. All the authors provided critical feedback, helped to shape the research and conduct the analysis and thus contributed to the final version of the manuscript.

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