Development of a Simple Near-Ground Path Loss Model Verified by Measurements

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***Abstract*—The purpose of this paper is to get a better understanding of the path loss (PL) in near-ground scenarios and then to develop a simple PL model. This is done by conducting measurements of the PL, at two different locations; a school gym and an empty parking lot. Two types of antennas, a rectangular patch- and a monopole antenna, were used both at 858 Mhz. The measurements were performed at both horizontal and vertical polarization, at different heights and distances. Four different PL models have been investigated, to get a better understanding of the different conditions given for the PL models: Ground wave (GWPL), Friss free space (FSPL), approximated two-ray ground reflection (ATRPL) and the Norton surface wave (NSPL). The PL results obtained from the measurements are used to estimate the accuracy of the different PL models, and to explore the applicability of the PL models. The measurements also indicate that the polarization, antenna type and environment, are less influential compared to the distance and heights. The results validate the conditions of the PL models coverage areas. A PL model is developed based on the ATRPL and the NSPL, still subject to the condition of the ATRPL model. The prediction accuracy of the proposed model exceeds the individual PL models and the applicability is equal to the ATRPL. The prediction accuracy of the proposed model exceeds the individual PL models and the applicability is equal to the ATRPL.**

I. Introduction

In the future it is likely that more and more wireless sensor networks (WSN) will appear. Such WSNs could be used to monitor traffic flow or home power consumption. Examples could also include industrial or military uses. Many of the WSN nodes may be placed close to or directly on the ground. An example is to monitor the traffic flow, where sensors could be placed at ground level. In terms of military use, the nodes could also be placed at ground level at different locations to detect incoming enemies. In such networks both power efficiency as well as reliability is key to maximise the performance. A characteristic for these scenarios is that the antennas are placed near-ground, meaning that the ground has a significance for the path loss (PL). To estimate those, a reliable PL model is needed. Multiple models for estimating the PL for near-ground scenarios exists. Two articles found to have significant content on the subject are: Bullington's [1], which has a theoretical approach to the problem and suggests a thorough, but complicated solution to the problem and Chong and Kim's [2], who tries to simplify the model proposed by Bullington, but here the focus is mainly on irregular terrain and only one height has been used for the measurements.

This article focuses on exploring existing PL models and their strengths and weaknesses compared to each other. This is done based on a measurement campaign that focuses on near-ground PL but covers several other parameters, which could influence the PL. This concludes in an extended PL model, which removes some of the weak points in existing models.

II. Methods and materials

This section contains the theoretical link budget along with the theory of existing PL models and the description of the measurement campaign.

A. Link budget

A link budget can be calculated as (1) to find the power received for a specific link.

$$P_r = \frac{P_t G_t G_r}{L_p L_{sys}} \tag{1}$$

where P_r and P_t are the power received and transmitted in Watts respectively, G_t and G_r are the unitless gains in the Tx and Rx antenna respectively, L_{sys} is the system loss[1] and L_p is the PL, both unitless. As the aim is to develop a simple near-ground path loss model, it is necessary to identify the L_p from (1).

B. Existing Path Loss Models

In terms of finding the PL different propagation models can be used given different conditions. The PL models considerd are the: ground wave (GWPL), Friss free space (FSPL), approximated two-ray-ground-reflection (ATRPL) and the Norton surface wave (NSPL). One of the more extensive models is the GWPL model presented in (2). The GWPL model takes the three most dominant factors into account when calculating the PL: the direct wave, the reflected wave and the

[1]The system loss consists of all loses from the Rx reference plane to the Tx reference plane, except the PL and antenna gains, examples could include cable losses, polarisation loss, impedance mismatch etc.

surface wave [1], [2]. Furthermore, this PL model assumes that the antenna gain is isotropic [1].

$$L_p = \left(\frac{4\pi d}{\lambda}\right)^2 \cdot \Big| \underbrace{1}_{\substack{Direct\\wave}} + \underbrace{Re^{j\Delta}}_{\substack{Reflected\\wave}} + \underbrace{(1-R)Ae^{j\Delta}}_{\substack{Surface\\wave}} \Big|^{-2} \quad (2)$$

where λ is the wavelength of the transmitted signal in metre, d is the distance between Tx and Rx in metre, Δ is the phase difference between the direct and reflected wave in radians, R is the unitless complex reflection coefficient and A is the unitless surface wave attenuation factor [1], [2].

The complex reflection coefficient, R, given in (3) depends on the incidence angle and the surface materiel [1].

$$R = \frac{\sin(\theta) - z}{\sin(\theta) + z} \quad (3)$$

where θ is the incidence angle of the signal and the surface in rad and z which is unitless, differs from surface to surface and also differs for vertical and horizontal polarization, is respectively given in (4) and (5) [1].

$$z = \frac{\sqrt{\epsilon_0 - \cos^2\theta}}{\epsilon_0} \qquad \text{for vertical polarization} \quad (4)$$

$$z = \sqrt{\epsilon_0 - \cos^2\theta} \qquad \text{for horizontal polarization} \quad (5)$$

where ϵ_0 is the unitless complex relative permittivity of the surface and can be found using the methods described in [3]. The surface wave attenuation factor, A, can be approximated as given in (6) [1], [2].

$$A \approx \frac{-1}{1 + j\frac{2\pi d}{\lambda}(\sin(\theta) + z)^2} \quad (6)$$

As the GWPL model is quite complicated, due to the depenedcy of surface constants, which for accurate predictions require enviromental measurements. Different approximations of it has been made that in most cases makes it possible to calculate the PL without making measurements of the environment. The most simple model is FSPL model given in (7), which calculates the PL given only free space conditions [2]. This means that the reflected wave and surface wave can be set to 0 in (2).

$$L_p = \left(\frac{4\pi d}{\lambda}\right)^2 \quad (7)$$

This model is often used as a first estimate of the PL due to its simplicity, the assumptions of no multipath however does render its applicability inadequate in the case of near ground scenarios, as the free space conditions are not fulfilled [4].

A model that accounts for the single point reflected wave is the ATRPL model given in (8) [2], [4].

$$L_p = \left(\frac{d^2}{h_t h_r}\right)^2 \quad (8)$$

where h_t, h_r are the heights in m of Tx and Rx respectively. The ATRPL is a simplified and approximated version of (2). The approximations made to derive ATRPL include $\frac{\Delta}{2} < \pi/10 \Rightarrow \sin\frac{\Delta}{2} \approx \frac{\Delta}{2}$ as well as $R \approx$ -1 for near gracing angles [2]. This approximation is valid when (9) is true and thus the ATRPL (8) can be applied. If (9) is false FSPL (7) can be applied.

$$d > \frac{4\pi \cdot h_t h_r}{\lambda} \quad (9)$$

This fraction is often referred to as the critical distance, d_c, of the ATRPL. However, when placing an antenna at ground level the ATRLP predicts that zero power is received, which as the GWPL suggest is not the case partly because of the surface wave. NSPL as given in (10) assumes a minimum effective height of the antennas.

$$L_p = \left(\frac{d}{h_0}\right)^4 \quad (10)$$

where h_0 is the minimum effective height in m of the antennas given as.

$$h_0 = \left|\frac{\lambda}{2\pi z}\right| \quad (11)$$

NSPL assumes that $\Delta \approx 0$ and $R \approx -1$ in the GWPL model, for the same reason as ARTPL [2]. The condition in terms of when to use the NSPL (12) is further dependent on the height of the antennas and the wavelength og the signal [2].

$$h_{r,t} < \lambda \quad (12)$$

When (12) is true the FSPL and ATRPL respectively under and overestimate the PL.

C. Measurement Campaign

A measurement campaign is designed to explore the strength and weaknesses of the different PL models. For this the received power is measured from a reference signal to estimate the PL. The first step in the measurement campaign is to design the link. The link of the measurement campaign can be seen in Tab. 1, and the setup hereof can be seen in Fig. 1.

Tab. 1: *Equipment used for the Tx and Rx links in the measurement campaign.*

Tx link	**Rx link**
Marconi instruments low noise signal generator 2042 (AAUNR. 33376)	Rx antenna
1.5 m SUCOFLEX_104	2.5 m SUCOFLEX_104
SMA male/male	Rhode & Schwarz FSL spectrum analyser (AAUNR. 56915)
1 m RG223/U	
Tx antenna	

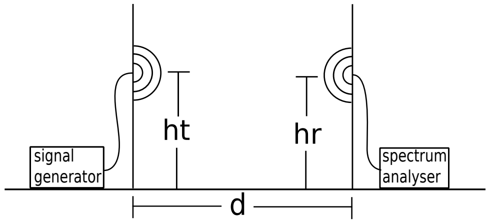

Fig. 1: *Equipment used for the Tx and Rx links in the measurement campaign.*

The measurement campaign accounts for six different parameters:

1) Two different locations, outside a big empty parking lot with no obstacles and inside a school gym (45 by 25 meters).
2) Both horizontal and vertical polarization are tested.
3) Two sets of different antenna structures have been tested, monopole antennas (858 MHz) and rectangular patch antennas (858 MHz).
4) The height of the Tx antenna is varied between 0.04 m, 0.14 m, 0.36 m and 2.02 m. This is achieved by mounting the antenna on 2.5 m wooden pole using a clamp.
5) The height of the Rx antenna is varied the same way as the Tx antenna[2].
6) The distance between Rx and Tx poles is varied across 1 m, 2 m, 4 m, 8 m, 15 m and 30 m.

This gives 480 measurement points at each point 10 measurements are performed. To minimize uncertainties at the individual test points the sample mean of the 10 measurements is found. The PL is then found from the received power by using the link budget calculation (1).

III. Results

The results from the measurement campaign are analysed to determine influence of the different test parameters. The influence of the parameters is found from the sample mean across the other parameters along with their 95% confidence interval. According to Tab. 2 when changing the distance from one measurement point to the next, there is an increase in PL of around 6 dB across all distances point.

Tab. 2: *Sample mean PL across all measurements for different distances*

Distance	1 m	2 m	4 m
PL	(34.7±1.6) dB	(41.4±1.4) dB	(49.0±1.7) dB

Distance	8 m	15 m	30 m
PL	(57.3±2.1) dB	(66.1±2.5) dB	(72.3±2.3) dB

[2]It is assumed that the PL for mirrored heights for example Rx = 0.04 m, Tx = 2.02 m and Rx at 2.02 m, Tx at 0.04 m is identical.

In Tab. 3, the sample mean PL for all height setups is shown. It should be noted that it is expected that the confidence interval is larger as fewer samples is used to estimate the mean PL across the heights compared to the other parameters. It is further seen from Tab. 3 that, by lowering the heights, the PL increases between 3 dB and 5 dB.

Tab. 3: *Sample mean PL across all measurements for different height combinations*

Tx \Rx	0.04 m	0.14 m	0.36 m	2.02 m
0.04 m	(63.7±5.2) dB	(60.7±5.1) dB	(55.4±4.7) dB	(52.4±3.8) dB
0.14 m	(60.7±5.1) dB	(58.1±5.2) dB	(53.4±4.5) dB	(50.2±3.2) dB
0.36 m	(55.4±4.7) dB	(53.4±4.5) dB	(49.0±2.9) dB	(47.6±4.8) dB
2.02 m	(52.4±3.8) dB	(50.2±3.2) dB	(47.6±4.8) dB	(44.4±3.1) dB

The rest of the test parameters (Environment, Antenna type and Polarization) sample mean PL is seen in Tab. 4. It can be seen on Tab. 4 that by changing the parameters, the mean PL varies between 2 dB and 4 dB.

Tab. 4: *Difference bewteen setups of different parameters.*

Environment		Antenna type		Polarization	
Gym	(52.4±1.8) dB	Monopole	(55.6±2.0) dB	Vertical	(51.8±1.9) dB
Parking lot	(54.6±2.2) dB	Patch	(51.4±2.0) dB	Horizontal	(55.1±2.1) dB

It should be noted that even though there only are a minimum of two setups tested for each parameter, these setups are quite different, so if the parameters have any influence on the PL, it should be apparent.

IV. Discussion

This section contains the discussion about the results compared to the parameters and the exiting PL models, ending by proposing a new PL model.

A. Less influential parameters

So from the analysis of the test parameters, it is seen that only the distance between the antennas and the heights of antennas has a influence that exceeds 5 dB. By that account the other parameters are deemed to be less influential parameters (LIP). Because of this the sample mean can be taken across these parameters. This is in accordance with PL models where only the GWPL and to some extent the NSPL take the environment and polarization into account. It should however be noted that at 30 m in the school gym the Rx pole started to get close to the back wall which can be seen in the measurements as a extra reflection giving a lower PL than expected.

B. Comparison and coverage of exiting PL models

The measured PL is now compared to the models described earlier, to see if the models predict the PL accurately according to their coverage area[3]. This is done at all height combinations and selected combinations can be seen on Fig. 2, Fig. 3, Fig. 4 and Fig. 5.

[3]The coverage area is here defined as the part of the measurement campaign which fulfils the condition for the individual models.

IV. DISCUSSION

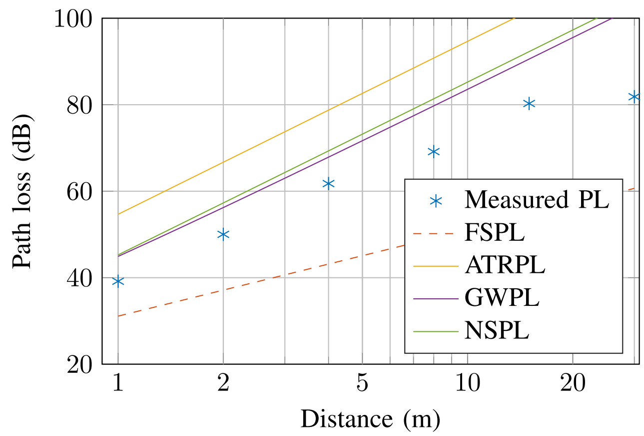

Fig. 2: *Comparison between measured PL and predicted PL from models at a height of 0.04 m for both Tx and Rx.*

On Fig. 2 it can be seen that GWPL and NSPL predicts the PL best, as expected due to the measured points being inside the coverage area of these PL models. However both PL models overestimate the PL by around 10 dB, which could suggest that the measurements of ϵ_0 might not be completely accurate, as it occurs in both PL models. The procedure to determine ϵ_0 is described in [3], a few inconsistencies occurred when calculating ϵ_0 which further supports that it might be inaccurate. The effect of changing ϵ_0 will be an offset of the slope. A problem occurring at low heights is that ATRPL greatly overestimates the PL, even though the measured points are inside its coverage area. The FSPL underestimates the PL as expected as none of the points are inside its coverage area.

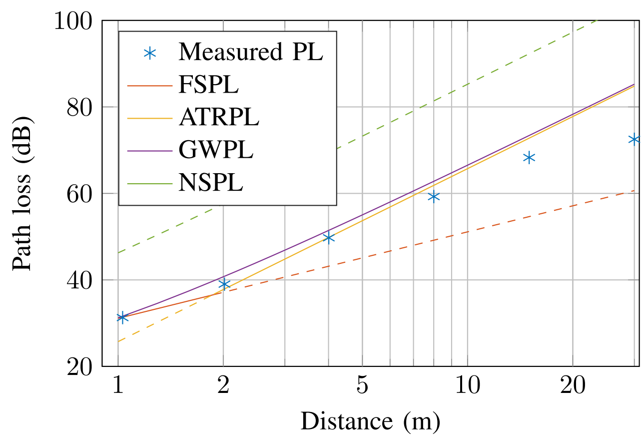

Fig. 3: *Comparison between measured PL and predicted PL from models at a height of 0.14 m and 0.36 m for the Tx and Rx respectively.*

On Fig. 3 and Fig. 4 it can be seen that GWPL predicts the PL across all distances, where the predictions from FSPL and ATRPL crosses at a distance, which matches the condition mentioned in (9). The NSPL greatly overestimates the PL, which is expected since the measured points are outside its coverage area.

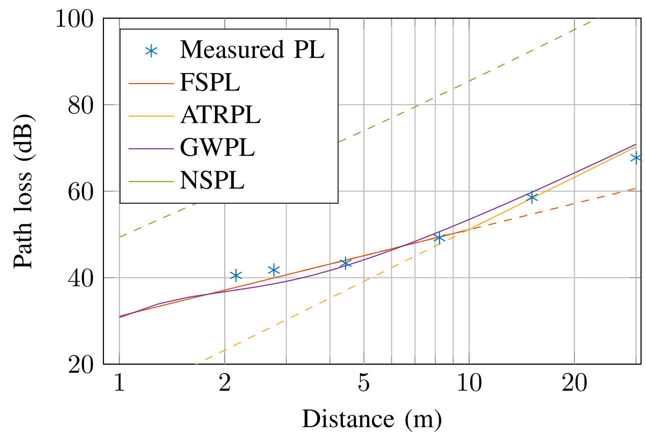

Fig. 4: *Comparison between measured PL and predicted PL from models at a height of 0.14 m and 2.02 m for the Tx and Rx respectively.*

On Fig. 5 it can be seen that GWPL together with the FSPL predicts the PL across all distances. As can also be seen, the GWPL model response indicates ripples, the explanation for this is the interference between the direct and reflected wave components. The predictions from ATRPL and NSPL are underestimating and overestimating the PL respectively as expected from their coverage areas.

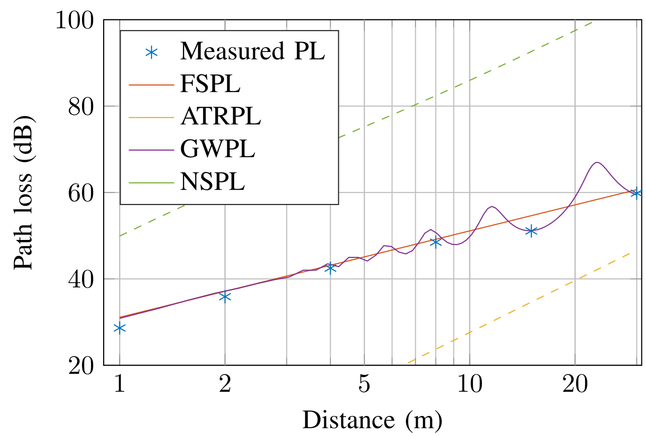

Fig. 5: *Comparison between measured PL and predicted PL from models at a height of 2.02 m for both Tx and Rx.*

To compare the different PL model's accuracy the mean square error (MSE) is calculated based on the measured PL. To make this estimate valid it is of course necessary to work only inside the coverage area of the different PL models.

The most optimal PL model is the GWPL model (2) as it can be seen from the Tab. 5, the GWPL model gets the best coverage of 100%, as it takes all waves into account and has a MSE of 35.49. However, it is also the most complicated, as it requires to make measurements at the desired locations.

IV. DISCUSSION

Tab. 5: The MSE of the different models, inside their coverage area. The applicability, is the percent of the measurement points, that is inside the coverage area.

Models	MSE	Applicability
FSPL	15.95	35 %
ATRPL	141.58	65 %
GWPL	35.49	100 %
NSPL	230.05	30 %

Furthermore, by looking at Tab. 5 it can be seen that by making the simplification of the GWPL it is now necessary to look at the conditions for the simplified PL models, as their applicability is now restricted. It can be further seen from Tab. 5, that the accuracy of the predictions generally degrade for the simplified PL models. The general reason of the degradation of prediction accuracy is due to some weak points of the simplifications made. It can be seen from Tab. 5, that the MSE for the NSPL is quite large, this is believed to primarily be due to the measurement uncertainty of ϵ_0, as mentioned earlier.Where ATRPL has the highest valid region of the simplified models, but has a rather high MSE, this is due to its lack of ability to account for the surface wave, as seen from (8), when the heights goes to zero, so does the power received. It can be seen that FSPL actually predicts quite well inside its valid region, but it is also the model that has second fewest valid points in the measurement campaign, due to the assumption of no multipath.

This leaves all PL models with crucial weak points, some being complicated to calculate others having a very limited coverage area and some lacking accuracy. Therefore this paper propose a model that accounts for some of these weak points.

C. Proposed model

In terms proposing a PL model all six parameters from the measurement campaign have been considered. From Tab. 2 and Tab. 3 it is shown that the distance and heights are very influential and should therefore form the base of the proposed model. The proposed model is designed around the existing models, as the theory for those are still firm. The aim is therefore to make a model that is simple, compared to the GWPL model, but has high applicability and high accuracy compared to the other PL models.

The base of the model is chosen to be the ATRPL as it already has the highest applicability of the models except for the GWPL and a simple structure compared to the GWPL. The weak point in the ATRPL is its inaccuracy at very low heights which is a problem as the focus are near-ground scenarios. This could be compensated by the NSPL, the reasoning behind this is that NSPL accounts for the surface wave part that has been set to zero in the approximation of the ATRPL. Together these model will account for the all three waves in the GWPL. These can however not be simply added together as it is the power of the waves that can be added and not the respective PL. To find the predicted P_r from the models, (8) and (10) are inserted into (1) and added finally the PL is isolated again. A more simple way to express this is seen in (13).

$$Proposed\ PL\ model = \left(ATRPL^{-1} + NSPL^{-1}\right)^{-1} \quad (13)$$

$$L_p = \frac{d^4}{h_t^2 h_r^2 + h_0^4} \quad (14)$$

This model still suffers from the weak point of NSPL's dependency upon z which is expressed in (11). However, as only the magnitude of z is needed this can be guestimated in most cases and in more critical cases it can be measured using the method described in [3]. From the measurements the average magnitude of z across environment and polarization is 0.8122. To find out the performance of the model it is compared to the other models using this average of z. First to analyse the applicability of the model it has the same applicability as the ATRPL model which means it can be used if (9) is true else FSPL should still be used. This can be seen from Fig. 6 and Fig. 7 as the intersection between the two aforementioned models.

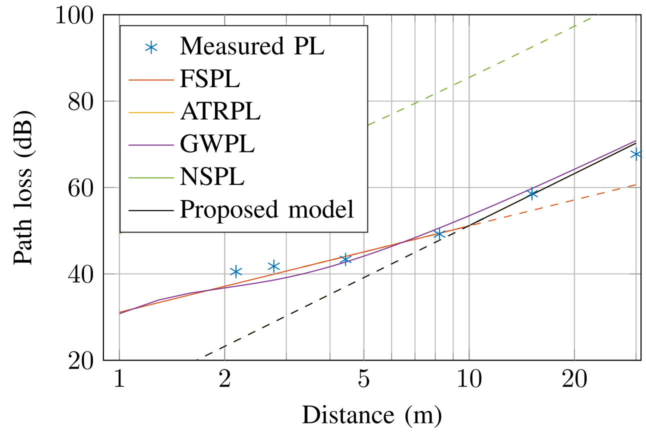

Fig. 6: Comparison between proposed model, measured path loss existing PL models at a height of 0.14 m and 2.02 m for Rx and TX respectively.

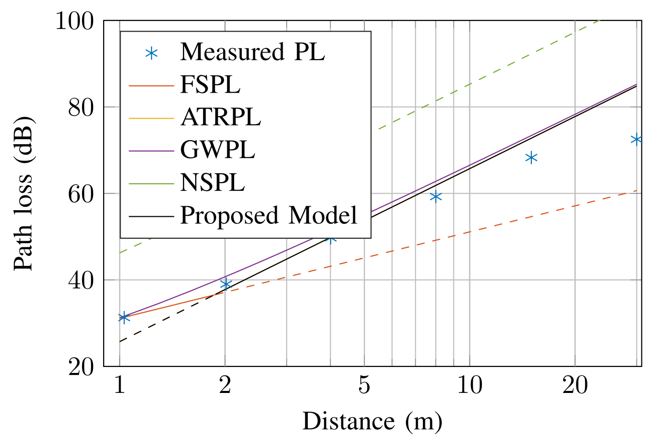

Fig. 7: Comparison between measured PL and predicted PL from models at a height of 0.14 m and 0.36 m for the Tx and Rx respectively.

IV. DISCUSSION

The accuracy is found on the same data set as the other models as none of the data points have been used for the derivation of any part of the model. The MSE is found to 87.66, which is significantly lower than either ATRPL or NSPL. It can therefore be concluded that the weakness of the ATRPL at very low Tx and/or Rx heights has been strengthened. The same can be said for the NSPL where the applicability has been greatly extended, the performance at low heights is still affected by the magnitude of z as seen in Fig. 8. However, as the heights increases the dependency of z lessen, as the contribution from the NSPL part becomes smaller. This can be seen as the model is almost equal to the ATRPL on Fig. 6 and Fig. 7. The model does still not perform as well as the GWPL, however that could not be expected, as the proposed model still uses approximations and simplifications. When comparing the proposed PL model with the GWPL, the part where the proposed PL model, has an edge over the GWPL, is in the determination of z. For the proposed PL model, only the magnitude of z is used, neglecting the complex part of z, meaning that the phase is not an issue. As for the GWPL z is also a part of R see (3) and A see (6), in where the magnitude of z is not taken, as the complex part also has an influence. However, with a better estimate of z both the proposed PL model and the GWPL might fit better at low Tx and Rx heights which can be seen on Fig. 9 in the case of the proposed PL model.

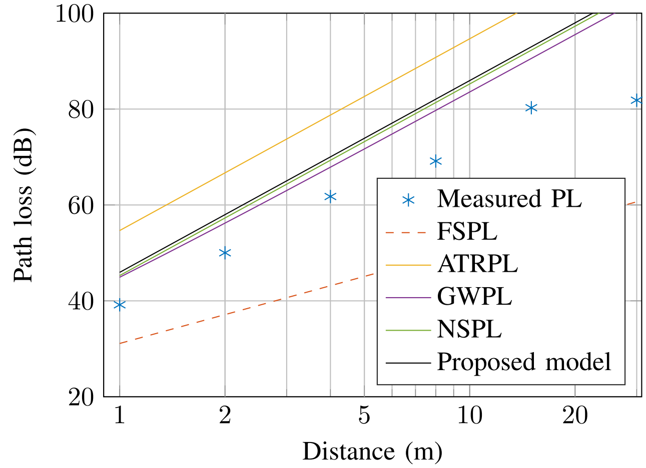

Fig. 8: *Comparison between proposed model, measured path loss existing PL models at a height of 0.04 m for Rx and Tx.*

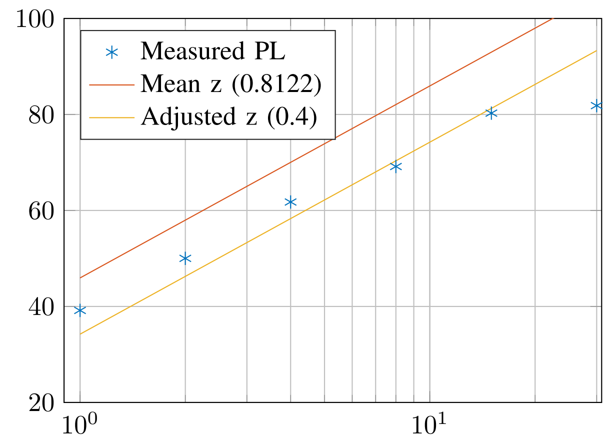

Fig. 9: *Comparison of the proposed model with the used z value and the adjusted z value at a height of 0.04 m for both Tx and Rx.*

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