Estimation of Near-Ground Path Loss for Wireless Sensor Networks

Thomas Jørgensen
7. semester, Wireless Communication Systems
Aalborg University
Email: tkjj13@student.aau.dk

Kemal Kapetanovic
7. semester, Wireless Communication Systems
Aalborg University
Email: kkapet08@student.aau.dk

Mads Gotthardsen
7. semester, Wireless Communication Systems
Aalborg University
Email: mgotth13@student.aau.dk

***Abstract*—This article focuses on developing a model that can be used to predict the path loss at near-ground. For this purpose four different path loss models have been investigated based on their accuracy and applicability in the near-ground case. A measurement campaign was conducted, in which several different parameters were included. Based on the measurements it was found that the path loss depend~~ency~~ s ~~was~~ mainly on ~~the~~ distance between, and the heights of, the antennas. From comparison between ~~the~~ measurements and ~~the~~ path loss models some weak points were discovered for the different models, which concurred with expectation from ~~the~~ theory. This lead to the development of an extended version of the two-ray propagation path loss model that account~~ed~~ s for some of these weaknesses.**

Key words: Path loss, Near-ground, ground wave, GWPL, FSPL, TRPL, NSPL, model validation, MSE, accuracy, extended model, direct wave, reflected wave, surface wave, surface wave attenuation factor, complex relative permittivity, minimum effective antenna height.

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, ~~where all of these nodes will have to report back to the base station, indicating if enemies are near~~. In such networks both power efficiency as well as reliability is key to maximise the performance. To estimate those, a reliable path loss (PL) model is needed. There ~~are~~ exists multiple models ~~made~~ for estimating the PL at low transmitter (Tx) or receiver (Rx) heights. Two articles found to have significant content on the subject are: Bullington's *Radio Propagation at Frequencies Above 30 Megacycles*, which has a theoretical approach to the problem and suggest a thorough, but complex solution to the problem and Chong and Kim's *Surface-Level Path Loss Modelling for Sensor Networks in Flat and Irregular Terrain*, which 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 ~~validating~~ evaluating existing PL models ~~and~~ based on 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 the existing models.

A. Path loss models

In terms of finding the PL different propagation models can be applied to calculate the power received, given different conditions. One of the more extensive models is the Ground Wave Path Loss (GWPL) model presented in (1). The GWPL model takes the three most dominant factors into account when calculating the power received; the direct wave, the reflected wave and the surface wave ~~[1], [2]~~ [1,2].

$$P_r = P_0 \cdot \Big| \underbrace{1}_{\substack{Direct\\wave}} + \underbrace{Re^{j\Delta}}_{\substack{Reflected\\wave}} + \underbrace{(1-R)Ae^{j\Delta}}_{\substack{Surface\\wave}} \Big|^2, \quad (1)$$

where

$$P_0 = \frac{P_t G_t G_r}{L} \left(\frac{\lambda}{4\pi d} \right)^2, \quad (2)$$

P_r and P_t are the power received and transmitted respectively, G_t and G_r are the gains in the transmitting and receiving antenna respectively, L is the system loss[1], λ is the wavelength of the transmitted signal, d is the distance between the transmitting and receiving antenna, Δ is the phase difference between the direct and reflected wave, R is the complex reflection coefficient and A is the surface wave attenuation factor [1], [2].

The complex reflection coefficient, R, given in (3) ~~is~~ depend~~ent~~ s on the incidence angle and the surface materiel.

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

where θ is the incidence angle of the signal and the surface, and z which is different from surface to surface is also different

[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.

for vertical and horizontal polarization, and respectively given as.

$$z_v = \frac{\sqrt{\epsilon_0 - \cos^2\theta}}{\epsilon_0} \quad (4)$$

$$z_h = \sqrt{\epsilon_0 - \cos^2\theta} \quad (5)$$

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

given in

÷ ord

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

As the GWPL model is quite complex 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 the Friss free space path loss (FSPL) model (7) which calculates the power received, given only free space loss [1]. This means that the reflected wave and surface wave can be set to 0 in (1).

shown in

$$P_r = \frac{P_t G_t G_r}{L}\left(\frac{\lambda}{4\pi d}\right)^2 \quad (7)$$

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 WSN.

A model that also accounts for the single point reflected wave is the two-ray-ground-reflection path loss model (TRPL) (8) [4].

$$P_r(d) = \frac{P_t G_t G_r}{L}\left(\frac{h_t h_r}{d^2}\right)^2 \quad (8)$$

where h_t, h_r are the heights of the transmitting and receiving antenna respectively.
The TRPL is a simplified version of (1). The approximations made to derive TRPL include $\frac{\Delta}{2} < \pi/10 \Rightarrow \sin\frac{\Delta}{2} \approx \frac{\Delta}{2}$ [1]. This approximation holds when (9) is true and thus the simplified TRPL (8) can be applied. If (9) is false FSPL (7) can be applied [4].

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

This fraction is often referred to as the critical distance, d_c, of the TRPL.
However when placing the antennas at ground level, the TRLP predicts that the power received is zero, which as the GWPL suggest is not the case with the introduction of the surface wave. The Norton Surface wave PL model (NSPL)(10) assumes a minimum effective height of the antennas.

$$P_r = \frac{P_t G_t G_r}{L}\left(\frac{h_0}{d}\right)^4 \quad (10)$$

where h_0 is the minimum effective height 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 [1]. The condition in terms of when to use the NSPL (12) is dependent on the height of the antennas and the wavelength og the signal [1].

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

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

II. Methods and Materials

This article has two parts to it the first is validation of PL models the second is to develop an extended PL model. The validation will be made over multiple steps, the first is to assume no knowledge of existing models and design a measurement campaign. The link of the measurement campaign can be seen in Tab. 1.

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	

Tab. 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 an empty parking lot as seen on Fig. 1 and inside a gym (45 by 25 meters) as seen on Fig. 2. 2) Both horizontal and vertical polarization are tested. 3) Two different antenna structures have been tested, a set of monopole antennas (858 MHz) a set of patch antennas (858 MHz). 4) and 5) The height of the Tx and Rx antennas are varied[2] between 0.04 m, 0.14 m, 0.36 m and 2.02 m. This is achieved by mounting the antennas on 2.5 m wooden poles using clamps. 6) The distance between Rx poles 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.

[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

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Fig. 1: Measurement at the empty parking lot

Fig. 2: Measurement at the gym

To minimize uncertainties at the individual test points a mean of 10 measurements is found. Next the received power is adjusted according to P_t, G_t, G_r and L to find the pure PL. The next step of the validation is to exclude parameters that have little to no statistical influence on the PL. Lastly the models will be used to predict the PL, which will be matched with the data to verify the accuracy of the predictions using the mean square error (MSE) method.

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III. Results

The results from the measurement campaign have been analysed, which can be seen in Appendix. The result of this is shown in Tab. 3, Tab. 4 and Tab. 5, where it can be seen that the environment, antenna type and polarization are less influential parameters (LIP). That makes it possible to take the mean across the LIP, and focus only on the different combinations of height and distances. To show the findings of the measurement campaign, Fig. 3 shows PL at equal height of the receivers and different distances, Fig. 4 shows PL with an Rx height of 0.04 m varying the Tx height and the distance, Fig. 5 shows PL at with an Rx height of 2.02 m varying the Tx height and the distance, in all cases a mean has been taken across the LIP.

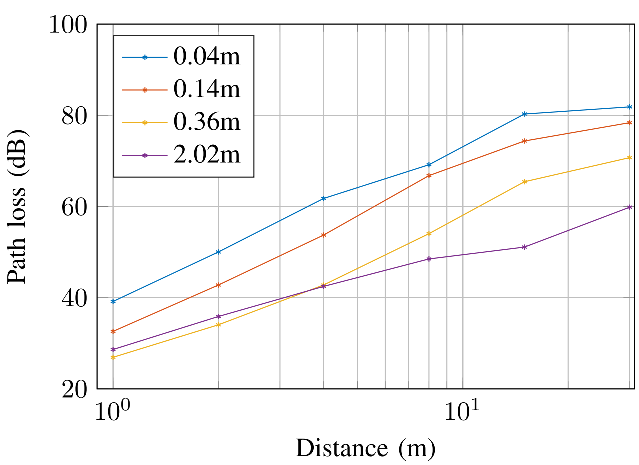

Fig. 3: Mean PL across LIP for transmitter and receiver antenna at the same height, at varying distance.

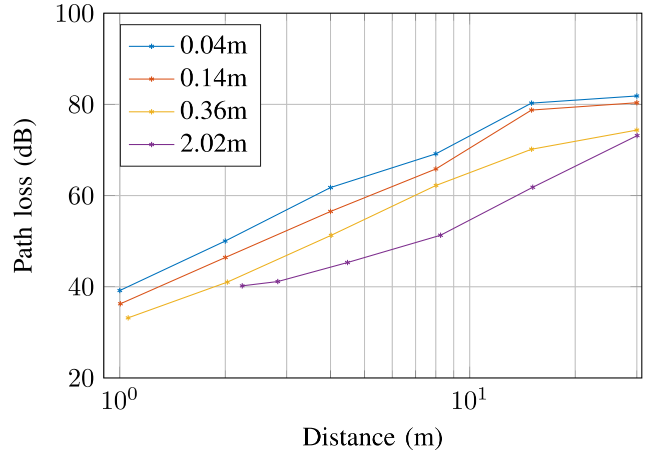

Fig. 4: Mean PL across LIP for transmitter at 0.01m and receiver antenna at varying heights

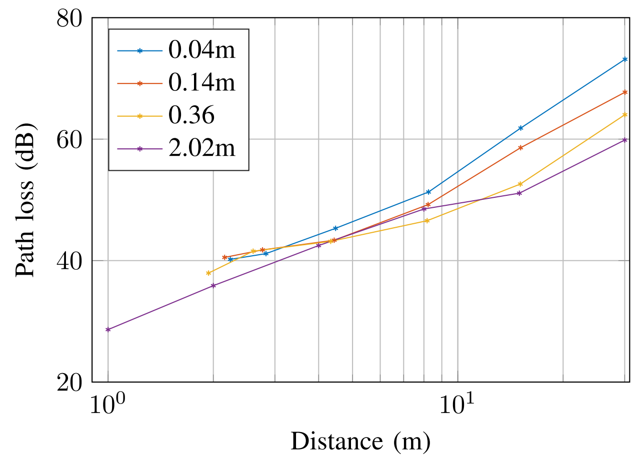

Fig. 5: Mean PL across LIP for transmitter at 2.00m and receiver antenna at varying heights

convergence?

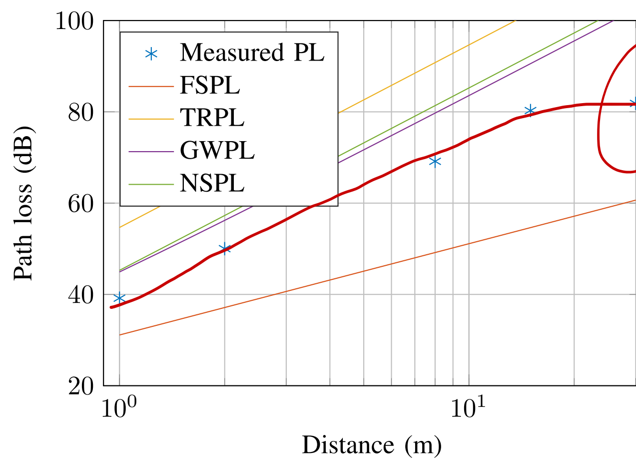

Fig. 6: Comparison between measured PL and predicted PL from models at a height of 0.04 m for both Tx and Rx.

Much too long sentence.

The measured PL, where the mean across LIP again has been taken, is now compared to predictions of the models described earlier, to see if the models predict the PL accurately, this is done at selected heights of the transmitting and receiving antenna, as seen on Fig. 6, Fig. 7 and Fig. 8.

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On Fig. 6 it can be seen that GWPL and NSPL predicts the PL best, as expected due to the conditions of the PL models, however both PL models overestimate the PL by ~~close~~ around 10 dB, which could indicate that the measurements of ϵ_0 might not be completely accurate, as it occurs in both PL models. Here the general problem with low height is also seen as FSPL greatly underestimate the PL where TRPL greatly overestimate the PL.

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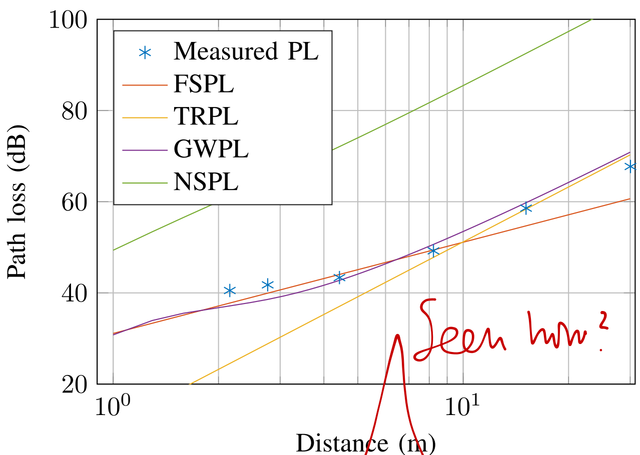

Fig. 7: Comparison between measured PL and predicted PL from models at a height of 0.14 m and 2.00 m for the Tx and Rx respectively.

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On Fig. 7 it can be seen that GWPL predicts the path loss across all distances, where the predictions from FSPL and TRPL crosses at a distance which matches the condition mentioned in (9). The NSPL greatly overestimate the PL which is expected since (12) is not true.

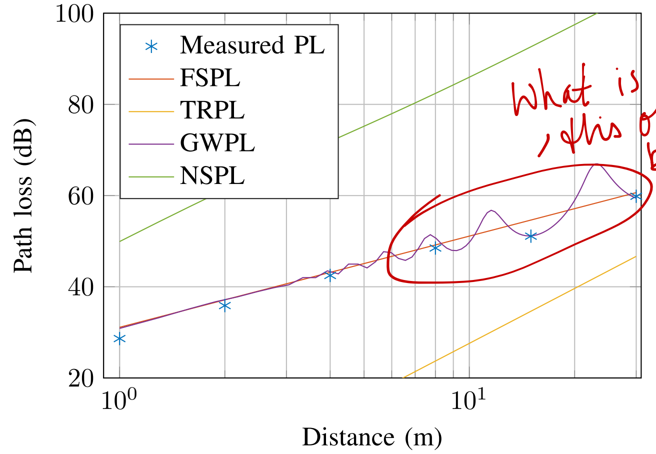

Fig. 8: Comparison between measured PL and predicted PL from models at a height of 2.00 m for both Tx and Rx.

On Fig. 8 it can be seen that GWPL together with the FSPL predicts the path loss across all distances, where the predictions from TRPL is underestimating the path loss which is because (9) is false. The NSPL greatly overestimate the PL which is expected since (12) is not true.

As it is seen from the figures Fig. 6, Fig. 7, Fig. 8, the different models, besides GWPL, have different areas where they are accurate, while having other areas, where they either over or underestimate the PL. To compare the different models accuracy the mean square error (MSE) is calculated based on the measured PL. To make this estimate valid it is necessary to work only inside the valid regions of the different models, which is found based on (9) and (12).

Models	**MSE**	**Covarge in %**
FSPL	15.95	35 %
TRPL	141.58	65 %
GWPL	35.49	100 %
NSPL	230.05	30 %

Tab. 2: The MSE of the different models, inside the areas, where the different models are valid. The coverage, is the percent of the measurement points, that is inside this area.

Summary

The most optimal PL model is the GWPL model (1) as it can be seen from the Tab. 2, the GWPL model gets the best coverage of 100%, as it takes all waves into account, and has a MSE of 35.49. But is also the most complex, as it requires to make measurements at desired locations. Further more by looking at Tab. 2 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 seem from Tab. 2, that the accuracy of the predictions decreases for the simplified PL models. It can be seen from Tab. 2 that the MSE for the NSPL is quite large, this is believed to primarily be due to measurement uncertainty of ϵ_0. But the general reason of the loss of prediction accuracy is due to some weak points of the simplifications made. 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. Where TRPL 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 go to zero so does the power received. The NSPL is worst off, lacking in both applicability as well as accuracy, the weak point here is primarily the need to measure z. This leaves all PL models with crucial weak points. This paper will now propose a model that accounts for some of these weak points.

IV. Discussion

In terms proposing a PL model all six parameters from the measurement campaign have been considered. In Appendix 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 is still firm. The aim is therefore to make a model that is ~~more~~ simple than the GWPL model, but has high applicability and high accuracy. The base of the model is the TRPL as it already has high applicability and simple structure. The weak point here is it inaccuracy at very low heights which could be accommodated by adding the NSPL.

weak definition

$$Proposed\ model = TRPL + NSPL \tag{13}$$

$$P_r = \frac{P_t G_t G_r}{L}\left(\frac{h_t^2 h_r^2 + h_0^4}{d^4}\right) \tag{14}$$

This model still suffer from the weak point of NSPL's dependency upon z. 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 our measurement 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 TRPL model which means it can be used if (9) is true else FSPL should still be used.

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 TRPL or NSPL it can therefore be concluded that the weak point of the TRPL 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 height is still affected by the magnitude of z as seen in Fig. 9. However as the heights increases the dependency of z lessen and the model is almost equal to TRPL as seen no Fig. 10. The model does still not perform as well as the GWPL, however that could not be expected.

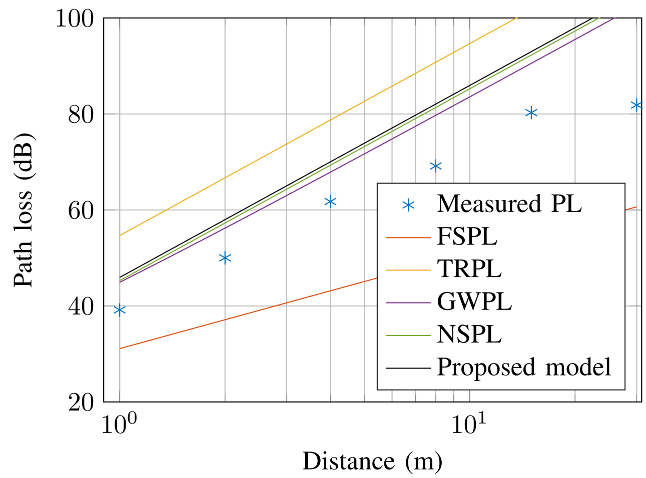

Fig. 9: Comparison between proposed model, measured path loss existing PL models at a height of 0.04 m for the transmitting and receiving antenna

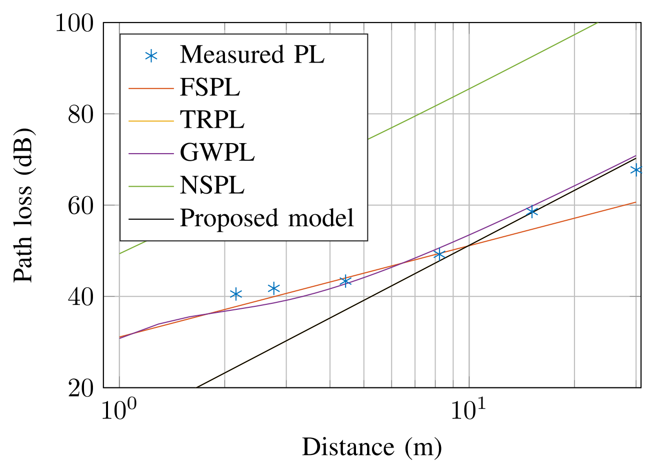

Fig. 10: Comparison between proposed model, measured path loss existing PL models at a height of 0.14 m and 2.00 m for the transmitting and receiving antenna respectively

PL is not an antenna feature!

V. Conclusion

The purpose of this paper was to get an better understanding of the PL of antennas when placed at ground level, and then to develop an simple PL model. This was done by conducting measurements of the PL, at two different locations a gym and an empty parking lot, two types of antennas, a patch and a monopole antenna, where used both at 858Mhz. The measurements were performed at both horizontal and vertical polarization, at different heights and distances. Four different PL models have been investigated, GWPL, FSPL, TRPL and NSPL, to get an better understanding of the different conditions given for the PL models. The PL results obtained from the measurement where used to estimate the accuracy of the different PL models, and to see the applicability of the PL models. The measurements also indicated that the polarization, antenna type and environment, where LIP compared to the distances and heights. The results also validated the conditions of the PL models. A model was developed based on the addition of the TRPL and the NSPL, still subject to the condition of the TRPL model. The prediction accuracy of the proposed model exceeded the individual PL models and the applicability was equal to the TRPL. Further investigation should however be focused on investigating the magnitude of z at different environments as this still is a critical point in the accuracy of the model at low heights for the Tx and Rx.

Acknowledgment

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providing access to   during the

References

[1] P. K. Chong and D. Kim, "Surface-Level Path Loss Modelling for Sensor Networks in Flat and Irregular Terrain," *ACM Transactions on Sensor Networks*, 2013, vol. 9, No. 2, Article 15.

[2] K. Bullington, "Radio Propagation at Frequencies Above 30 Megacycles," *PROCEEDINGS OF THE I.R.E*, 1947, årg. 35, hft. 10, 10-1947, s. 1122–1136.

[3] H.-S. Kim and R. M. Narayanan, "A New Measurement Technique for Obtaining the Complex Relative Permittivity of Terrain Surfaces," *IEEE Transactions on Geoscience and Remote Sensing*, 2002.

[4] UC Berkeley, LBL, USC/ISI and Xerox PARC, " 18.2 Two-ray ground reflection model," http://www.isi.edu/nsnam/ns/doc/node218.html, Nov 5, 2011.

Appendix 4 2

To make a simplified model, the influence of the different test parameters are analysed, to see if some of these parameters have significantly less influence on the path loss than some of the other test parameters. From the PL models it can be hinted at that the heights of the TX and Rx antennas along with the distance have more influence than the other parameters, as these influence almost all models where the other parameters only have some influence at very low heights.

Why an appendix in the first place?

When changing the distance from one measurement point to the next, there is an increase in PL of more than 6 dB across all distances point, which is shown in Tab. 3.

	1m	2m	4m	8m	15m	30m
PL (dB)	34.68	41.37	49.02	57.29	66.14	72.29

Tab. 3: PL across all measurements for different distances

In Tab. 4, the mean PL across all height setups is shown. It is seen that, at lower heights, the PL increases, which shows a dependency on the heights of the antennas.

Tx Rx	0.04m	0.14m	0.36m	2.02m
0.04m	63.71 dB	60.70 dB	55.37 dB	52.37 dB
0.14m	60.70 dB	58.11 dB	53.35 dB	50,20 dB
0.36m	55.37 dB	53.35 dB	48.99 dB	47.64 dB
2.02m	52.37 dB	50.20 dB	47.64 dB	44.41 dB

Tab. 4: PL across all measurements for different height combinations

Compared to these two parameters, the rest of the test parameters (Environment, Antenna type and Polarization) do have a lesser impact as seen in Tab. 5. It should be noted that even though only two setups have been tested of each parameter, these setups has been quite different so if the parameter has any influence it should show, however there is no significantly tendencies found in the data for these parameters.

Parameter	Environment	Antenna type	Polarization
Difference (dB)	2.23	4.18	3.32

Tab. 5: Difference bewteen setups of different 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 significant influence.