Modeling the Path Losses of Ultra-Wideband Signals in Multipath Propagation Channels

Sascha Schramm*, Sven Ole Schmidt† and Horst Hellbrück†
Luebeck University of Applied Sciences, Germany
Department of Electrical Engineering and Computer Science
* Email: sascha.schramm@stud.th-luebeck.de
† Email: sven.ole.schmidt, horst.hellbrueck@th-luebeck.de

***Abstract*—Recently, a single anchor localization system is a new scientific approach to localize a tag in a given room by utilizing only one anchor. For this new localization approach, a model for the impulse response is necessary that includes multipath propagation. Theoretically, each position has a unique signal response to a transmitter in a given room, which is called a fingerprint. A part of this fingerprint is the path losses of the original signal and the signal echo. The calculation of the distance between transmitter and receiver, based on a receiving signal, is a basic approach. However, this paper determines the path loss coefficient γ in a given room to obtain an approximate model that describes the path loss. The evaluation measurement shows a model accuracy of $\Delta d_1 = 11$ cm. In sum, this model is a good approximation, which needs further researching to improve the model.**

***Index Terms*—modeling path losses, path loss, channel impulse response, path loss coefficient, UWB impulse, multipath propagation, single anchor localization system.**

I. Introduction and Related Work

Localization is very important in different areas of application. In automation, there are often more than several thousand processing positions for raw, semi-finished, or finished items in production machines. A passive RFID transceiver is implemented at each of these positions [1] or a multi-anchor localization system is implemented for triangulation [2]. As known, this is very costly in time and money. For this reason, the goal of the research is to find a solution that minimizes installation costs while maintaining accuracy by reducing the anchor to a single anchor localization system[3]. Due to multipath propagation, a received signal of a transmitting ultra-wideband (UWB) impulse in a given room additionally has multiple components of these impulse echoes, which is called a fingerprint related to the position [4]. This fingerprint consists of a time delay and a reduced receive amplitude (caused by the path losses) at each pulse of a signal. Because of the fingerprint, we assume that indoor localization of a tag is theoretically possible. This approach of a mathematical model to describe the channel impulse response of a UWB multipath propagation is already introduced in [4]. The model of transmit power decrease due to the path losses is not only needed in localization. Also, path losses occur in further wireless communication systems like in medical implant communication. For this purpose, Sayrafian-Pour et al. modeled the path losses focused on the statistical analysis in [5].

In this paper, we discuss the path losses, especially the path loss coefficient, to further specify the experimental model for the line of sight path first.

The contributions of this paper are:

- We propose a model to determine the path losses of a UWB impulse response of a line of sight path.
- The influence of interference and path loss on a received signal is shown.
- We evaluate this model of the line of sight path.

The rest of the paper is organized as follows. Section II introduces multipath propagation, describes path losses, and shows the impact of path losses on signal transmission. Section III deviates the measurement setup for determining the path loss coefficient. Afterward, this section introduces the applied measurement devices. Finally, execute the determination of the path loss coefficient with the measured receiving voltage. Section IV provides the evaluation of the model with a measurement, which is not a part of the determination measurement series. Section V concludes the paper and provides an outlook on future work.

II. Theory

This section first introduces the multipath propagation of a transmitted signal. Then, path losses are explained and the equation model with the path loss coefficient is shown. Finally, the impact of path losses on the relationship between the original signal and the echo signal is visible.

A. Multipath propagation

In wireless communication, an omnidirectional transmitting antenna sends cubically in all directions. Based on this, there are several paths to the receiver. The first received impulse is transmitted on the line-of-sight (LOS) path, which is also called the original signal. The second one propagates on the non-line of sight (NLOS) path over a reflection on the ground which is called signal echo. A wall or ceiling reflection is neglected to obtain a simple model for the path losses, therefore in this paper, only two paths are considered as shown in Figure 1. This neglect has to be considered when determining the measurement setup.

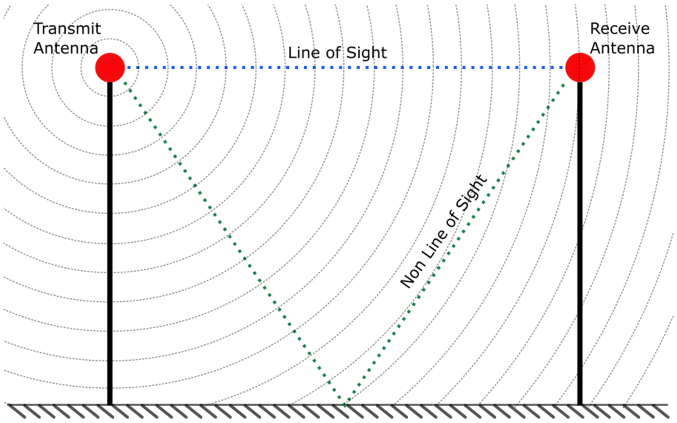

Fig. 1: Sketch of multipath propagation

B. Description path losses

The transmitting power is distributed over the theoretical area of a sphere and is called power density. With a larger sphere, the power density is lower because the power is distributed over a larger area. Due to this fact, a receiving antenna receives less and less power the greater the distance between the transmitter and receiver. More specifically, if higher received power is required, the antenna needs a larger antenna capture area to obtain the same power as when positioned close to the transmitter. In Figure 2, the sum of received power in the blue (A') and green (A") capture areas is the same, since the green one has a lower power density and a larger capture area.

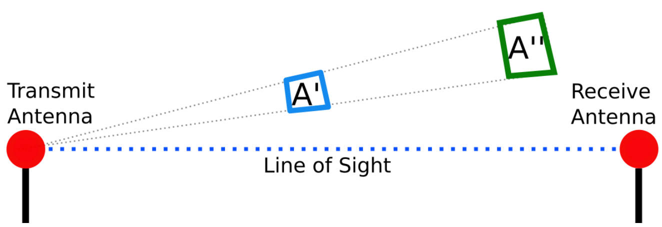

Fig. 2: Sketch of receiving power at different distances

The utilization of the same antenna capture area at these two distances results in a reduction of the receiving power at the green area (A") compared to the blue area (A'). This reduction is called path losses, which describes the relationship between transmitted and received power. As shown in Figure 2, the path losses are raising with increasing distance d (d is the radius of the sphere). Based on this derivation, the previously announced mathematical model of path losses is presented in eq.(1) [4].

$$P_{PL} = \frac{P_{Tx}}{P_{Rx}} = \left(\frac{4\pi f_c d}{c_0}\right)^{\gamma} \tag{1}$$

In Eq.(1), the speed of light c_0, carrier frequency f_c, and distance d are fixed at a measurement point. The γ is the so-called and sought after path loss coefficient, which we want to determine in this work. To keep this model as simple as possible, our goal is to determine the path loss coefficient with a constant value. When measuring a UWB signal, the voltage is measured in the oscilloscope after the input channel instead of the power. Therefore, the model has to be adapted accordingly. Thus, the eq.(1) has to be extended with the basic power formula $\sqrt{P \cdot R} = U$, which results in the eq.((2)). Finally, there is an eq.(3) with which γ is to be determined for a given position.

First, the equation is expanded with R and the square root $\sqrt{\cdot}$.

$$U_{PL} = \frac{\sqrt{P_{Tx} \cdot R}}{\sqrt{P_{Rx} \cdot R}} = \frac{U_{Tx}}{U_{Rx}} = \sqrt{\left(\frac{4\pi f_c d}{c_0}\right)^{\gamma}} \tag{2}$$

Then the equation is rearranged to the path loss coefficient γ.

$$\gamma = 2 \cdot \frac{lg(\frac{U_{Tx}}{U_{Rx}})}{lg(\frac{4\pi f_c d}{c_0})} \tag{3}$$

C. Impact of path losses on the received signal

A UWB channel 2 impulse is utilized in this paper [6]. This impulse has a bandwidth of $f_b = 499.2\,\text{MHz}$ and is describable as a rectangle in the frequency domain. The result of a transformation into time domain is a sinc-function that intersects the time axis at $\frac{1}{f_b}$ in positive and negative time. The Impulse duration T_p of this UWB signal is the difference between these two intersections and is noted as $T_p = \frac{2}{f_b} = 4\,\text{ns}$.

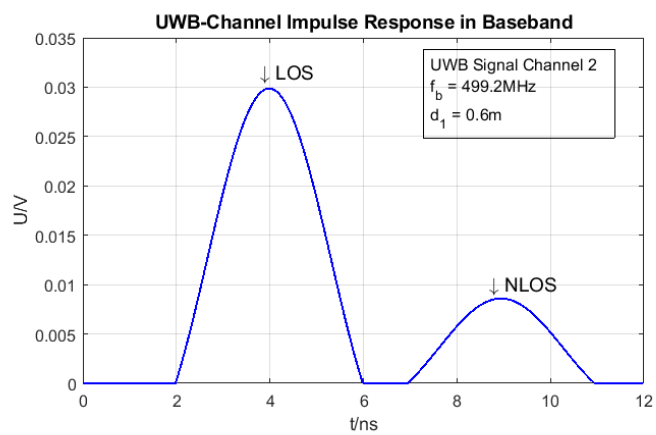

Fig. 3: Receiving signal with the influence of path losses

Figure 3 shows the channel impulse response in the baseband of a UWB channel 2 signal modeled with the equation from [2]. The original signal over the LOS path has the shortest path (earlier arrival time) and accordingly a higher amplitude. In contrast, the signal echo via the NLOS path has a longer propagation path (later arrival time) and correspondingly a lower amplitude.

In summary, it appears that path loss is directly related to distance.

III. Modeling Path Losses

First, the basic geometric measurement setup is derived in this chapter. Then, the path loss coefficient γ is determined with the derived measurement setup to obtain a model.

A. Deviation of the basic geometric measurement setup

For the determination of the path loss coefficient γ, a set of measurements is required. This set consists of the different adjusted distance between transmitter and receiver with the corresponding measured received voltage U_{Rx}.

First of all, the superposition of the original signal and the signal echo has to be prevented. For this reason, it is necessary to determine the arrival time (also called propagation time t_{prop}) of the signal echo. The so-called propagation time is the time needed for the transmission to a receiver. This is computable with the propagation distance over the speed of light $t_{prop} = \frac{d}{c_0}$. Based on this, the propagation time of the signal echoes t_{prop2} has to be larger than the propagation time of the original signal t_{prop1} and the already known UWB impulse duration $T_p = 4\,\text{ns}$ as already seen in Figure 3.

$$t_{prop2} > t_{prop1} + T_p \tag{4}$$

For the measurement setup, the distances are needed instead of the times. For this purpose, the time is replaced by $\frac{d}{c_0}$ and then multiplied by c_0 to obtain the relationship of these distances. Eq.(5) specifies the minimum required distance d_{2min} of the NLOS path that ensures superposition for a given distance d_1 via the LOS path. In order to be able to determine the maximum limit distance $d_{1,max}$, eq.(5) is changed to eq.(6).

$$d_{2min} > d_1 + 1.2m \tag{5}$$

$$d_2 = d_{1max} + 1.2m \tag{6}$$

A further equation is needed to determine the distances and the height h of the measurement setup. These correlations are derived with Pythagoras:

$$d_2 = \sqrt{4 \cdot h^2 + d_1^2} \tag{7}$$

We set the height of the measurement setup to $h = 1.0\,\text{m}$. Based on this selection, the adjustment range of d_1 has to be determined. For this purpose, the restriction from eq.(6) is applied and equated with eq.(7). From this equation, the maximum limit distance $d_{1,max} = 1.066\,\text{m}$ is calculated at the given height.

To obtain a distinguishable received signal between the original signal and the echo signal, a gap to the maximum limit distance is necessary. That is, the starting point of the measurement setup is set to $d_1 = 0.80\,\text{m}$. We assume that the number of forty-one measurements in $\Delta = 1\,\text{cm}$ steps to the endpoint $d_1 = 0.40\,\text{m}$ is sufficient. Figure 4 shows the certain measurement setup. At the execution of the measurement, the distances to the wall and ceiling have to be larger than the height to prevent a superposition with the original signal.

B. Measurement setup for determination path loss coefficient γ

Next, the applied laboratory equipment is mentioned and the measurement conditions are described. Finally, the path loss coefficient γ is determined.

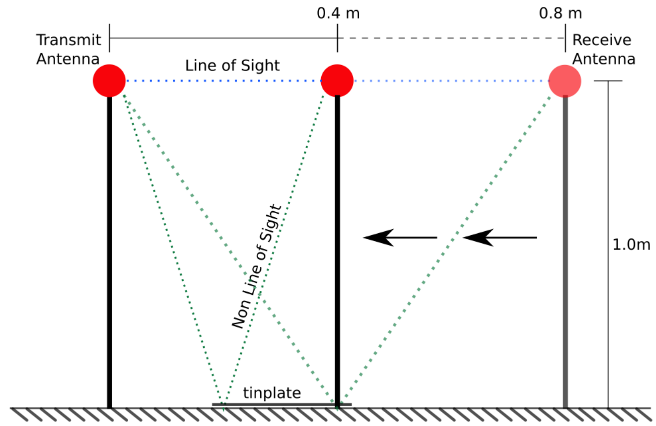

Fig. 4: Sketch of measurment setup

For this measurement, a UWB Channel 2 is applied as already mentioned. More precisely, the bandwidth is $f_b = 499.2\,\text{MHz}$ and the carrier frequency is $f_c = 3.9936\,\text{GHz}$, which is applied for this measurement series.

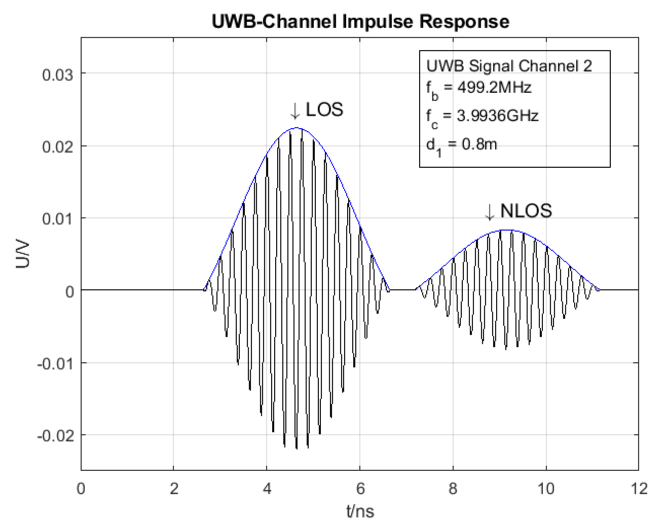

Fig. 5: Theoretical receiving signal at starting point

The UWB signal transmits in the frequency band with the carrier frequency f_c which represents the cosine oscillations in Figure 5. This figure shows the theoretical impulse response of the determined measurement start point at $d_1 = 0.8\,\text{m}$ with the original signal over the LOS path, the signal echo over the NLOS path, and a path loss coefficient of $\gamma = 2$ corresponding to the free space[7]. In this setup, we utilize Decawave WB002 antenna as transmitting and receiving antennas. The Tektronik AWG 70000a signal generator is applied to generate the UWB channel 2 impulse. The Tektronik DPO 70000dx oscilloscope measures the received signal at the receiving antenna. Furthermore, the amplitude of the transmit signal is set to $U_{Tx} = 300\,\text{mV}$. To keep the reflection losses constant and thus negligible for the signal echo, we apply a tinplate with a thickness of $thk = 0.7\,\text{mm}$. The execution room of this measurement has a height of $h = 2.8\,\text{m}$ and the wall has a minimum distance of $d_{min} = 2\,\text{m}$ in each direction. Based on this, there are no signal echoes from the wall and ceiling superimposed on the original signal from the LOS path. Last, we execute the measurement and determine the path loss coefficient γ of the original signal over the LOS path as announced.

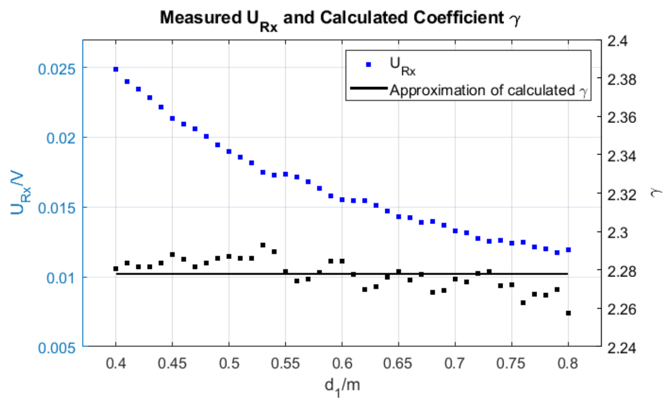

Fig. 6: Received Voltage U_{Rx} and calculated corresponding path loss coefficient γ

Figure 6 shows the measured received voltage U_{Rx} in blue. As expected, this decreases exponentially with distance d_1 and shows no abnormalities. The black dots represent the corresponding calculated path loss coefficient γ which is calculated via eq.(3). Unlike expected, these dots oscillate and decrease with increasing distance. The black line represents the constant approximation of these path loss coefficients γ, which is determined to a mean value and the standard deviation of $\gamma = 2.278 \pm 0.008$.

IV. Evaluation

As mentioned earlier, in this work we focus on the original signal pulse over the LOS path. Therefore, we mainly evaluate the original received signal. For the evaluation of this determined model, the comparison with an evaluation measurement is necessary. The setup is the same as the known setup in Figure 4. To obtain a meaningful evaluation, the distance for the measurement is set to $d_1 = 0.9\,\text{m}$, which is not included in the measurement series. The evaluation distance is also smaller than the maximum limit distance $d_{1,max}$ and also prevents superposition. The evaluation is performed 20 times and an averaged measurement curve is determined.

The black curve in Figure 7 shows the expected model (also utilized in Figure 3) at distance $d_1 = 0.9\,\text{m}$. The model contains the determined path loss coefficient $\gamma = 2.278$ and thus also the calculated path loss. The blue curve is the receiving UWB signal in baseband at $d_1 = 0.9\,\text{m}$. Between the modeling and the receiving signal, there is an amplitude difference of approximate $\Delta U_{Rx} = 1.8\,\text{mV}$ at the original signal, which we have not expected. The theoretical distance from the receiver to the transmitter is calculable by eq.(2). The received signal has a

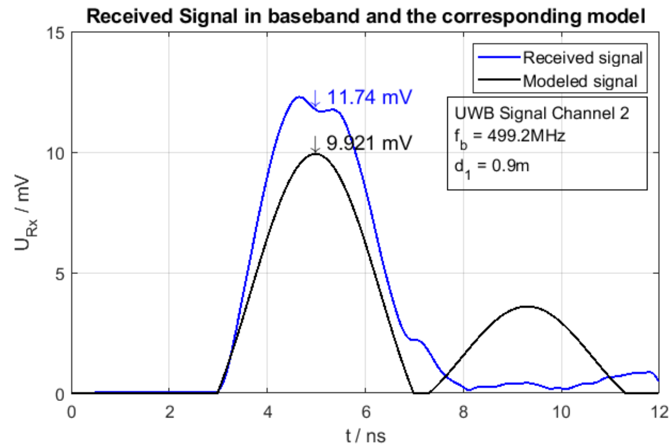

Fig. 7: Plot with receiving Impulse in baseband and the corresponding model

theoretical distance of $d_1 = 0.79\,\text{m}$. Thus, the difference from the model has an accuracy of $\Delta d_1 = 11\,\text{cm}$. The first signs of this discrepancy are visible in Figure 6 in the calculated gamma, as the gamma oscillates and decreases with increasing distance. The reason for this discrepancy are not clear. Technically, further interference or even antenna jitter could still be to blame. Antenna jitter means that there are some ranges, where the antenna does not send regular in all directions. Since the angle to the receiver does not change over the LOS path, we do not initially assume that jitter is to blame for the discrepancy. For this reason, we assume that other interferences interfere with the original signal. For this purpose, it is necessary to clarify where possible sources of interference could be located.

Nevertheless, the model is able to predict the position to the transmitter with an accuracy of $\Delta d_1 = 11\,\text{cm}$. Although we expected a better result, it is apparent from this model that it is theoretically possible to determine the position based on the path losses. For this reason, this model with a constant path loss coefficient is a good approximation for the time being.

V. Conclusion and Future Work

In this paper, it has been shown that it is theoretically possible to utilize a constant path loss coefficient to determine the position in a given room with respect to the transmitter. A fully applicable model is not created. From the evaluation, it is known that probably other interferences influenced the original signal. The influence of such interferences should be further investigated and implemented in this model. The goal of this scientific approach is to model not only the LOS path, but to include all signal echoes via floor, wall, and ceiling reflections. Due to the almost completely eliminated signal echo over the NLOS path, it is conceivable that the applied antennas have jitter or the tinplate does not reflect consistently as desired. A further step is to examine the antenna jitter and the reflection loss. The jitter and reflection loss are then to be implemented in the model or excluded as a cause. Finally, it is conceivable that this single-anchor localization system could be comparable to multi-anchor systems.

ACKNOWLEDGMENTS

This publication is a result of the research of the Center of Excellence CoSA and funded by the Federal Ministry for Economic Affairs and Energy of the Federal Republic of Germany (BMWi FKZ ZF4186108BZ8, MOIN). Horst Hellbrück is adjunct professor at the Institute of Telematics of University of Lübeck.

REFERENCES

[1] A. Russell, B. Moroz, and K. van Nes, "Rfid in manufacturing," *MANUFACTURING AUTOMATION*, 2006. [Online]. Available: https://www.automationmag.com/966-rfid-in-manufacturing/

[2] 4th KuVS/GI Expert Talk on Localization, Lübeck, Germany, 11.-12. Juli 2019, B. Matthews, S. O. Schmidt, and H. Hellbrück, "Understanding and prediction of ultra-wide band channel impulse response measurements," *Proceedings of the 4th KuVS/GI Expert Talk on Localization*, 2019. [Online]. Available: https://publikationsserver.tu-braunschweig.de/receive/dbbs_mods_00066765

[3] B. Großwindhager, M. Rath, J. Kulmer, M. S. Bakr, C. A. Boano, K. Witrisal, and K. Römer, "Salma: Uwb-based single-anchor localization system using multipath assistance," in *Proceedings of the 16th ACM Conference on Embedded Networked Sensor Systems*, ser. SenSys '18. New York, NY, USA: Association for Computing Machinery, 2018, p. 132–144. [Online]. Available: https://doi.org/10.1145/3274783.3274844

[4] S. O. Schmidt, M. Cimdins, and H. Hellbrück, "On the effective length of channel impulse responses in uwb single anchor localization," in *2019 International Conference on Localization and GNSS (ICL-GNSS)*, 2019, pp. 1–6.

[5] K. Sayrafian-Pour, W.-B. Yang, J. Hagedorn, J. Terrill, and K. Y. Yazdandoost, "A statistical path loss model for medical implant communication channels," in *2009 IEEE 20th International Symposium on Personal, Indoor and Mobile Radio Communications*. IEEE, 2009, pp. 2995–2999.

[6] "Ieee standard for low-rate wireless networks," *IEEE Std 802.15.4-2015 (Revision of IEEE Std 802.15.4-2011)*, pp. 1–709, 2016.

[7] N. Salman, A. H. Kemp, and M. Ghogho, "Low complexity joint estimation of location and path-loss exponent," *IEEE Wireless Communications Letters*, vol. 1, no. 4, pp. 364–367, 2012.