2009-10-01

Efficient UWB Indoor Localisation Using a Ray-tracing Propagation Tool

Tam Huynh
Ho Chi Minh City University of Technology, tamhuynh@hcmut.edu.vn

Conor Brennan
Dublin City University, brennanc@eeng.dcu.ie

Recommended Citation

Huynh, T., Brennan, C. (2009). Efficient UWB indoor localisation using a ray-tracing propagation tool. *Ninth IT & T Conference*, Technological University Dublin, Dublin, Ireland, 22nd.- 23rd. October. doi:10.21427/mb8m-b230

Efficient UWB indoor localisation using a ray-tracing propagation tool

Tam N. Huynh[1], Conor Brennan[2]

[1] Faculty of Electrical and Electronic Engineering,
Ho Chi Minh City University of Technology,
Vietnam
tamhuynh@hcmut.edu.vn

[2] Network Innovation Centre,
Research Institute for Networks and Communications Engineering (RINCE),
Dublin City University
Ireland
brennanc@eeng.dcu.ie

Abstract

A novel method of applying Ray Tracing to the problem of Ultra-wide Band (UWB) indoor user-localization is presented. This novel method for UWB localization is based on correlation between the received signal and a database of pre-computed ray-traced signals computed on a search curve. In the absence of real data the technique is validated by generating synthetic received signals using ray tracing plus Rayleigh distributed random multipath clusters as well as random amplitude and delay factors which account for database uncertainty. Results are presented that indicate that acceptable location and tracking performance can be achieved with a single sensor.

Keywords: Ray Tracing, Semi-Deterministic model, UWB localization

1 Introduction

Ultra wideband communication is based on the transmission of very short pulses with relatively low energy [Molisch, 2006]. Among the variety of potential UWB applications, precision indoor localization has been one of the most obvious for impulse radio (IR) UWB technology. These applications exploit the fine time resolution of UWB signals. The ultra short pulse waveform enables UWB receivers to accurately determine the Time of Arrival (TOA) of the transmitted signal from another UWB transmitter. For example, the accuracy of TOA measurements up to $40ps$ has been achieved, which corresponds to 1.2cm spatial uncertainty as mentioned in [Shen et al., 2006].

There are several methods for UWB-based indoor localization. Most of them are based on the Time-of-Arrival (TOA) or Time-Different-of-Arrival (TDOA) and the Direction-of-Arrival (DOA) of the received signal at a collection of UWB sensors. The basic method based on the TOA or TDOA estimation is presented in [Kang et al., 2006, Molisch, 2006, Shen et al., 2006]. In this approach, the TOA or TDOA of received signal at a certain number of sensors (at least 3) is used to create a nonlinear system of equations which is solved to produce an estimate of the position of the object. Another approach was based on DOA and TOA at a monostation (or single sensor) to predict the position of the object [Sun et al., 2008]. The TOA is used for estimating the distance from object to the base-station and the DOA is used for specifying the angle of the object in polar coordinates. Some other methods can be found in [Pierucci and Roig, 2005, Jo et al., 2005] .

In this paper, we propose a novel method which utilises UWB Ray Tracing channel simulation in the localization process. Simulation results show that the new method is a potential avenue for energy-efficient UWB localization applications using fewer sensors. This paper is organized as follows. In section 2, the application of the Ray Tracing algorithm for a multi-path UWB channel is introduced. This deterministic channel model is used to compute the "map" of received signal in the time domain which in turn is used during the localization process in the next sections. Then, in section 3, the proposed method for UWB localization based on the idea of signal correlation is presented. Section 4 introduces and investigates some models for generating received signals based on a semi-deterministic channel model. These are used to generate synthetic received signals for testing the proposed localization method. The results of these tests are presented in in section 5.

2 Ray Tracing for UWB channel modelling

In this approach, a discrete time, multi-path, impulse response for modelling the UWB channel is used. Signals arrive at the receiver with different amplitudes and delays with respect to the L ray-traced paths yielding

$$h\left(t, \mathbf{r}_n\right) = \sum_{l=1}^{L} \alpha_l \delta\left(t - \tau_l\right) \tag{1}$$

where $\mathbf{r}_n\left(x_n, y_n, z_n\right)$ is the receiver location. The attenuation coefficient α_l is caused by path loss, reflection, transmission and diffraction loss and, as it is frequency dependent, leads to some distortion in both amplitude and shape of the received signal. If the pulse $x(t)$ is transmitted, the received signal at $\mathbf{r}_n$ can be obtained by

$$y\left(\mathbf{r}_n, t\right) = x(t) \otimes h\left(\mathbf{r}_n, t\right) \tag{2}$$

In the frequency domain this is simplified using the Fourier transform

$$Y\left(\mathbf{r}_n, f\right) = X(f) H\left(\mathbf{r}_n, f\right) \tag{3}$$

where

$$H\left(\mathbf{r}_n, f\right) = \sum_{l=1}^{L} H_l\left(\mathbf{r}_n, f\right) \tag{4}$$

where $H_l\left(\mathbf{r}_n, f\right)$ is the frequency response of the l^{th} ray obtained by the ray tracing algorithm. In UWB systems, the transmitted pulse $x(t)$ spreads over a very large bandwidth (up to $7.5GHz$). Consequently the calculation of the frequency response $H(f)$ is an essential part of propagation modelling. In our simulation, we assume that a Gaussian Sinusoidal Pulse is generated at the transmitter. This is given by

$$x(t) = A_0 e^{-\frac{1}{2}\left(\frac{t-\mu}{\sigma}\right)^2} \cos\left(2\pi f_c t\right) \tag{5}$$

where A_0 is the amplitude of the transmitted signal, σ is the standard deviation of Gaussian distribution and is used to manage the width of the pulse in the time domain (or the bandwidth of the signal in frequency domain). μ is the mean of the Gaussian distribution and is used to adjust the position of the Gaussian pulse in the time domain. f_c is the carrier frequency and used to adjust the position of the signal spectrum in the frequency domain. These values should be chosen so as to satisfy the EIRP regulation for UWB signals as specified by the FCC. In this work the current amplitude A_0 is chosen as 1.4×10^{-8} Amps in order to conform to this regulation. σ, μ, and f_c are chosen with values $120 \times 10^{-12} s, 1 \times 10^{-9} s$ and $7 \times 10^9 Hz$ respectively so that the spectrum of the transmitted signal satisfies the definition of a UWB signal. The Gaussian Sinusoidal pulse and its one side frequency spectrum are shown in figures 1 and 2. It should be noted that the nature of the transceiver antenna also has a big impact on UWB systems modelling. In this paper, we simplify the effect of the antenna by modelling the transmitter as a set of dipoles. In this study, a simple room $10m \times 10m \times 5m$, with 6 planes as in figure (3), has been constructed in the simulation. The planes present for ceiling, floor and 4 walls are assumed to be

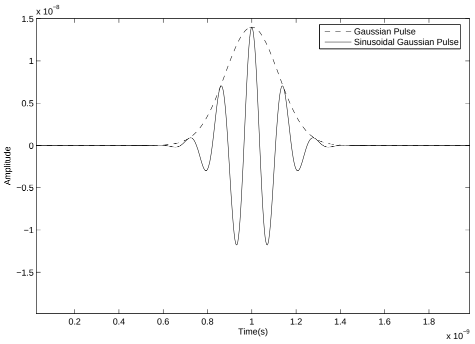

Figure 1: Gaussian and Gaussian Sinusoidal pulse in time domain

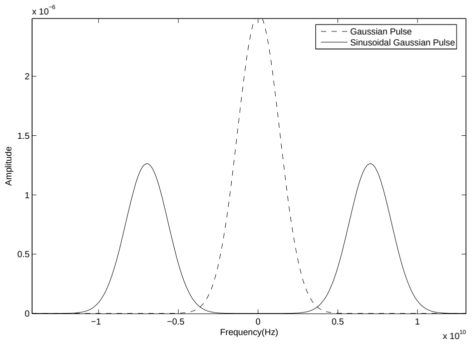

Figure 2: Frequency spectra of Gaussian and Gaussian sinusoidal pulses

made from concrete. It is worth mentioning that we assume the electrical properties of dry concrete do not depend appreciably on frequency within the band of interest, although such frequency variation is readily incorporated into our model if necessary. The relative permittivity, ϵ_r and conductivity, σ of dry concrete [Yao et al., 2003] are 5 and 0.7, respectively. Figure (4) shows an example of the multi-path signal generated by the ray-tracing code at a specific receiver point.

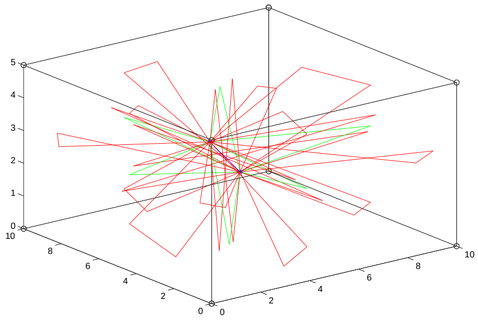

Figure 3: The multipath channel in $10m \times 10m \times 5m$ room

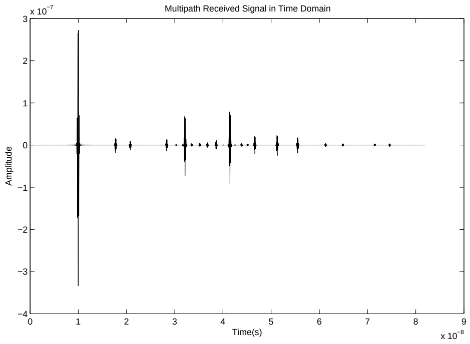

Figure 4: The received signal up to second order reflection

3 Proposed method for UWB ray tracing localisation

In this paper, we propose a novel method that computes the correlation between the signal received at a single UWB sensor and the signal computed by a ray-tracing simulation on a regular grid of points. The point at which this correlation value is maximised is deemed to be the location of the transmitter. The method reduces the cost and complexity of the localization system as only a single UWB sensor is required. Referring to figure (5), the localization process is set out below:

1. The TOA of the received UWB signal is used to estimated the distance d from the Base Station (BS) to the localized object or Mobile Station (MS)

2. The ray-tracing simulation is implemented at all points a distance d, as obtained from step (1), from the BS. To make this step more efficient these ray-tracing received signals should be pre-computed on a regular grid and loaded into RAM as required.

3. Correlations are computed between the received signal and the simulated received signals at all

points along the curve as specified in step (2)(hereafter referred to as the search curve). The point which displays the best correlation is chosen as the estimated location of the MS.

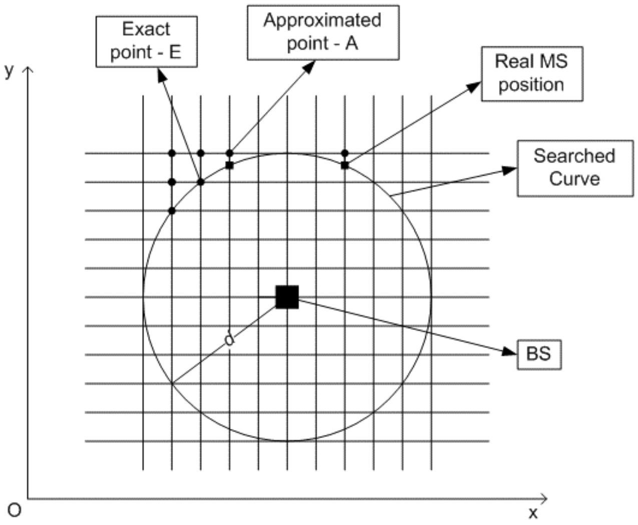

Figure 5: Approximation on the pre-computed ray-trace grid.

The discrete signal correlation in step (3) can be obtained from

$$Corr\left(y_r(t), y_s(t)\right) = \frac{1}{M}\sum_{m=0}^{M-1} y_r^{(}m)y_s(t+m) \tag{6}$$

where $y_r(t)$ and $y_s(t)$ are the actual received signal and ray-trace simulated received signals, respectively. M is the length of the sampled signal in the time-domain. In practice, the correlation in (6) is implemented by taking the inverse Fourier Transform of the product of the signals in the frequency domain

$$Corr\left(y_r(t), y_s(t)\right) = \mathcal{F}^{-1}\left(Y_r(f)Y_s(f)\right) \tag{7}$$

Referring to Fig (5), the pre-computed ray-trace data is available for a regular grid of points. In this paper, for an area of $10m \times 10m$, we used a resolution of $0.1m$, and $M = 2^{12}$. The size of the resultant database is roughly 600 MB. Problems obviously occur in that we only have signal information at a fixed grid of points which will necessarily lead to errors in localization as our accuracy is restricted by the grid resolution. However this was considered to be an acceptable trade off as the use of a pre-computed database reduces the computation time significantly. Calculation time is reduced from tens or hundreds of second (when directly computing ray-traces for each point on the search curve) down to less than $3s$.

The main idea of this localization method is based on correlation as introduced above. So the manner in which this correlation varies along the search curve, and whether a unique maximum is attained, is central to whether the method will succeed or fail. An example of a simulation is shown in figure 6. It is clear that as we traverse the search curve the correlation value is distributed into distinct groups, and each group has its local maximum. The actual position of the MS is the point which yields the global maximum correlation. However, when the grid-resolution (and hence the resolution of the search curve) is reduced to save computation time, the sampling distance between two adjacent points on the search curve (in Fig 4) will be increased which leads to another problem in that the global maximum correlation may be missed and another local maximum (not associated with the real position of MS) is wrongly interpreted as the global maximum.

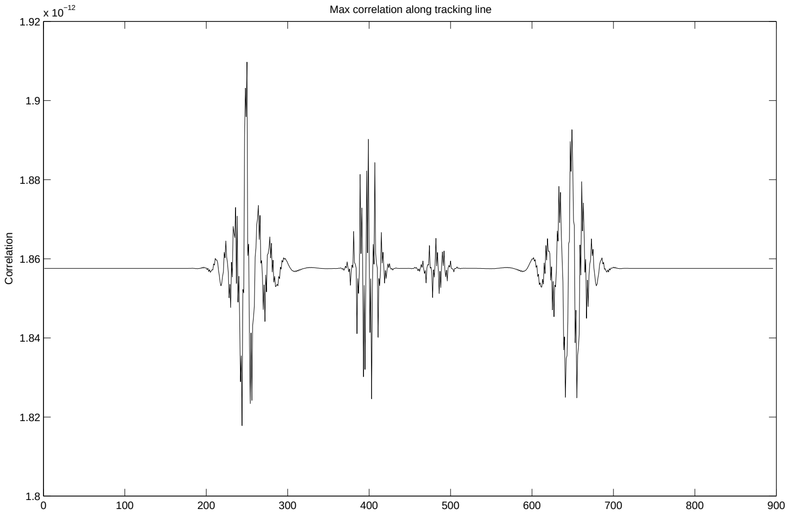

Figure 6: Correlation values along the search curve

4 Pseudo received signal using semi-deterministic channel model

In the absence of measured data it was necessary to generate some synthetic received signals in order to validate the method outlined in the previous section. A procedure for generating a synthetic received signal is implemented, called “Semi-Deterministic” UWB channel modelling. In this approach, we combine the ray-trace channel model which is presented in section 2 and ray cluster theory following the Saleh-Valenzuela (SV) model as described in [Molisch, 2006, Kunisch and Pamp, 2002]. The “main” rays of the clusters are obtained using the ray-trace algorithm and the other rays in each cluster are obtained from a Rayleigh random process. The channel impulse response of our proposed model can be expressed as

$$h(t) = \sum_{l=0}^{L} \alpha_{0,l}\zeta_l \delta\left(t - T_l - v_{rnd}\right) + \sum_{l=0}^{L}\sum_{k=1}^{K} \alpha_{k,l}\delta\left(t - T_l - \tau_{k,l}\right) + n(t) \tag{8}$$

where $\alpha_{k,l}$ is the tap weight of the k^{th} component in the l^{th} cluster, T_l is the delay of the l^{th} cluster. $\tau_{k,l}$ is the delay of the k^{th} multi-path component relative to the l^{th} cluster arrival time T_l. $n(t)$ represents additive white Gaussian noise (AWGN) within the channel. In (8), the “main” rays of each cluster $(k = 0)$ are represented by the first term. In this term, the attenuation and the cluster delay T_l (or delay of “main” rays) is obtained from ray-tracing simulation. To make the synthetic received signal more realistic we model database uncertainty. To do this a random amplitude coefficient ζ_l, uniformly distributed in the interval of $(0.5, 1)$, is included (to account for imprecise knowledge of material electrical properties as well as shadowing effects etc). A random amount v_{rnd} was also added to the cluster delay T_l (to account for imprecise information about the exact location of reflecting walls and ceilings etc). This was also uniformly distributed.

The second term in equation (8) represents the “auxiliary” rays in each cluster which are grouped around the main ray. The delay of each auxiliary ray is given by a Rayleigh distribution as mentioned above. The attenuation $\alpha_{k,l}$ for $k > 0$ can be obtained as

$$\alpha_{k,l} = \alpha_{0,l} R_{rnd} e^{-\frac{\tau_{k,l}}{\gamma}} \tag{9}$$

R_{rnd} represents a random amplitude reflection coefficient caused by unknown material electrical properties. In this paper, we assume that R_{rnd} is uniformly distributed in the range $(0.5, 1.2)$. The last term

$\exp(-\tau_{k,l}/\gamma)$ is the exponential decay in amplitude of each cluster. The coefficient γ is quite important in our model. Increasing γ leads to higher random scattering and consequently a high level of error in the localization. The total number of rays K in each cluster is also an important parameter of the model. In this paper, we let it range from 7 to 10 rays.

Figures (7) and (8) illustrate two example of synthetic received signals generated by the Semi-Deterministic model, assuming $K = 10$ and $K = 7$ respectively. In both cases γ was set to 0.2. AWGN noise with a SNR of 10dB was added in the case of figure (8).

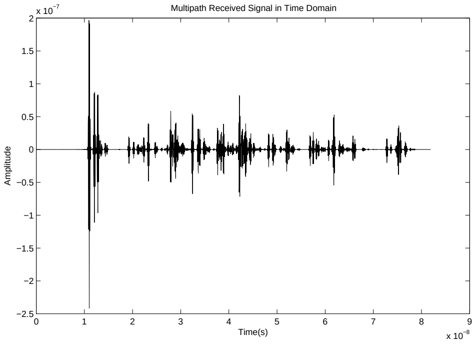

Figure 7: Received signal from semi deterministic channel model up to second order reflection $\gamma = 0.2, K = 10$ without AWGN noise

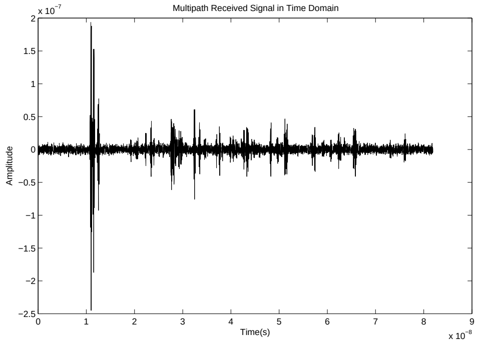

Figure 8: Received signal from semi deterministic channel model up to second order reflection $\gamma = 0.2, K = 7$ with AWGN noise

5 Simulation Results

The error metric used was the distance between the actual position of the MS and that predicted by RT localization. The percentage of cases in error (i.e. error greater than the grid resolution) and the mean error were also evaluated and are presented in Table 1. In the absence of real data synthetic received signals were generated using the Semi-Deterministic model discussed in the previous section. 100 random MS positions were created in the room and the localization algorithm was implemented to specify the object positions. It is worth noting that the resolution for the searching process is $0.1m$ (limited by the resolution of pre-computed RT grid) and that we assume that in all cases we have the exact TOA (i.e. we obtained the exact distance d between MS and BS from the UWB sensor). K, the number of rays per cluster was fixed at 7 for these results. Simulation results suggest that the "main" rays with their database uncertainty parameters (ζ_l, v_{rnd}) and the cluster decay γ of the pseudo received signal contribute the most significant effect on the localization error. The effects of the coefficient γ are shown in figures (9) and (10)

Examining figures (9) and (10), when γ increases from 0.2 to 0.5, the error in localization increases significantly from 3% cases in error (with a mean error = $0.188m$) to 23% incorrectly specified points (with a mean error of $1.236m$). Moreover, both figures show that, sometimes, large errors of over $8m$ are obtained. These occasions can be explained by the global correlation maximum being missed due to an overly coarse sampling resolution.

The effect of the database uncertainty parameters γ_l and v_{rnd} are shown in figures (11) and (12). Fixing $\gamma = 0.2$ we let γ_l vary uniformly within $(0.5, 1)$ while v_{rnd} was allowed to vary uniformly in the range $(-33 \times 10^{-11}, 33 \times 10^{-11})$ corresponding to a uncertainty in the distances travelled by the main rays of $\pm 1cm$.

From figures (11) and (12) the presence of uncertainty in the ray delays (v_{rnd}) plays a more significant role than the noise in ray amplitudes, increasing the error rate from 9% to 44% as shown in Table 1. However, if we assume that the delay uncertainty does not affect the LOS ray (which is reasonable given that one does not need knowledge of the building database to get this right) the results are improved considerably.

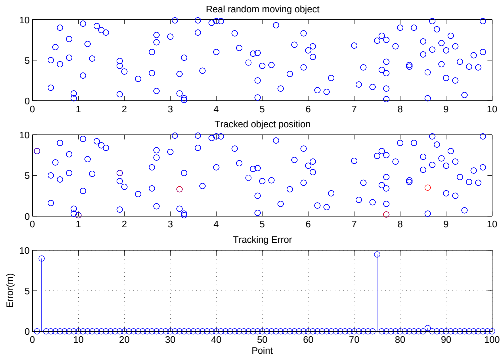

Figure 9: Localisation error when the pseudo received signal model has $\gamma = 0.2$

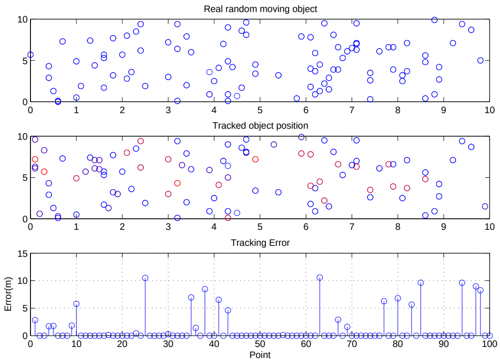

Figure 10: Localisation error when the pseudo received signal model has $\gamma = 0.5$

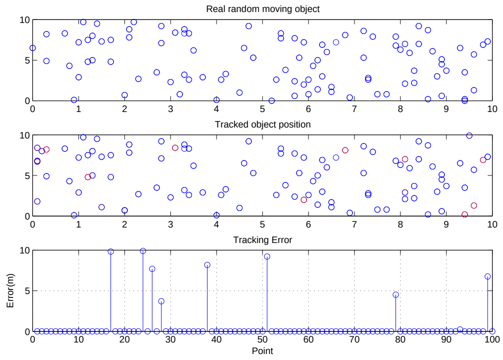

Figure 11: Localisation error when the pseudo received signal model includes γ_l only

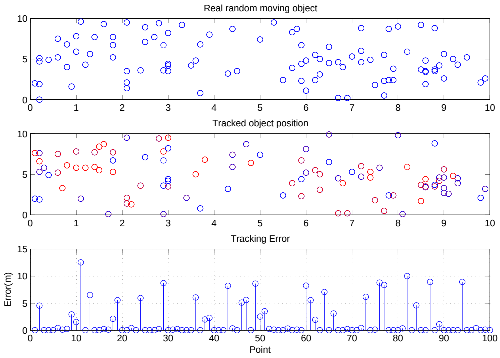

Figure 12: Localisation error when the pseudo received signal model includes γ_l and delay uncertainty v_{rnd}.

Essentially the ray-trace localisation procedure works well when the ray-trace accurately models the real life signal as generated synthetically using the Semi-Deterministic model. When this occurs it is possible to pick out a unique global maximum along the search curve which corresponds to the actual MS location (See figure (13) for an example). In contrast when the ray-trace result deviates significantly from the received signal due to the presence of too much unknown multipath or database error in the ray-trace result it is impossible to identify a unique global maximum (See figure (14) for an example).

6 Conclusion

A novel method of applying Ray Tracing in UWB localization has been presented. A database obtained by exhaustive ray-tracing UWB channel simulation is created and is used to identify the most likely receiver location by computing correlations between the received signal and the simulated signals along a search curve (specified by the TOA). In the absence of real-data the method is validated using synthetic received signals which are generated using semi-deterministic channel models. In addition the effect of inaccuracies in the building database, resulting in incorrect amplitudes and delays, are investigated. As expected the results indicate that the methods accuracy depends on how well the ray-traced signals match the actual received signals. It should be noted that even in the worse case the match is, on average, reasonable and could be improved by imposing physical constraints on motion and smoothing filters when tracking a user through the environment.

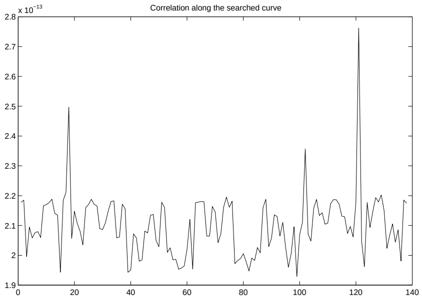

Figure 13: Correlation values along the search curve in the case of correct localisation.

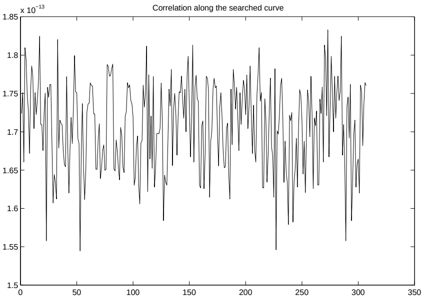

Figure 14: Correlation values along the search curve in the case of incorrect localisation.

Table 1: Summary of numerical results for various setups

Synthetic Received Signal	Percentage cases in error	Mean error (m)
With $\gamma = 0.2$	3	0.188382
With $\gamma = 0.5$	23	1.235583
with $\gamma = 0.2$, amplitude uncertainty γ_l	9	0.60004
with $\gamma = 0.2$, amplitude uncertainty γ_l delay uncertainty v_{rnd}	44	1.810008
with $\gamma = 0.2$, amplitude uncertainty γ_l delay uncertainty v_{rnd} (except LOS)	18	1.09179

References

[Jo et al., 2005] Jo, Y., Lee, J. Y., Ha, D. H., and Kang, S. H. (2005). Accuracy enhancement for uwb indoor positioning using ray-tracing. In *Proceedings of the IEEE/ION Position, Location and Navigation Symposium 2005*.

[Kang et al., 2006] Kang, D., Namgoong, Y., Yang, S., Choi, S., and Shin, Y. (2006). A simple asynchronous uwb position location algorithm based on a single round-trip transmission. In *Proceedings of the 2006 International Conference on Advanced Communication Technology ICACT2006*.

[Kunisch and Pamp, 2002] Kunisch, J. and Pamp, J. (2002). Measurement results and modeling aspects for the uwb radio channel. In *Proceedings of IEEE Conference on Ultrawideband Systems and Technologies*.

[Molisch, 2006] Molisch, A. (2006). *UWB Communication Systems: A Comprehensive Overview*. New York: Hindawi.

[Pierucci and Roig, 2005] Pierucci, L. and Roig, P. J. (2005). Uwb localization on indoor mimo channels. In *Proceedings of the International Conference on Wireless Networks, Communications and Mobile Computing 2005*.

[Shen et al., 2006] Shen, X., Guizani, M., Qiu, R., and Le-Ngoc, T. (2006). *Ultra-wideband wireless communications and networks*. Boston: Prentice Hall.

[Sun et al., 2008] Sun, X., Ma, Y., Xu, J., Zhang, J., and Wang, J. (2008). A high accuracy monostation uwb positioning system. In *Proceedings of the 2008 IEEE International Conference on Ultra-Wideband ICUWB2008*.

[Yao et al., 2003] Yao, R., Zhu, W., and Chen, Z. (2003). An efficient time-domain ray model for uwb indoor multipath paropagation channel. In *Proceedings of the 58th IEEE Vehicular Technology Conference*.