Analysis of a UWB Indoor Positioning System Based on Received Signal Strength

Thomas Gigl[†], Gerard J.M. Janssen[‡], Vedran Dizdarević[†], Klaus Witrisal[†] and Zoubir Irahhauten[‡]
[†]Signal Processing and Speech Communication Laboratory, Graz University of Technology, Austria
[‡]Wireless and Mobile Communications Group, Delft University of Technology, The Netherlands

Abstract— **This paper explores the possibility to design an indoor ultra wideband (UWB) ranging and positioning system using the received signal strength (RSS). Due to the extremely large bandwidths, the effects of small scale fading are reduced to the level where the knowledge of the path loss model (PLM) can be employed for accurate and reliable distance estimation. This approach enables trilateration based position estimation while significantly reducing the synchronization effort. A limited number of measurements is necessary in order to calibrate the PLM parameters but no extensive database of measurements is required, such as in fingerprinting methods. Based on simulated UWB channels, the effects of uncertainties in the PLM parameters on the estimated distance are characterized. Data from a UWB measurement campaign in indoor line-of-sight (LOS) scenarios are used to verify the performance of such a system.**

I. INTRODUCTION

Emergence of location based services requires a technical solution for accurate indoor localization of persons and objects. As satellite based positioning does not work well inside buildings, new solutions are needed to tackle the problem. Indoor wireless systems have to cope with severe multipath situations. Due to the extremely large bandwidth ultra wideband (UWB) signals offer a good multipath resolution and enable accurate positioning. UWB positioning approaches can be divided into Time of Arrival (ToA), Angle of Arrival (AoA) and Received Signal Strength (RSS) based systems. ToA based ranging exploits the large bandwidth but imposes tight constraints on the synchronization between the nodes. A related time-difference of arrival (TDoA) method requires synchronization among the nodes of the reference infrastructure only. AoA employs antenna arrays to estimate the angular power spectrum and thus determine the directions of signal arrivals.

The system proposed in this paper deals with UWB positioning based on the received signal strength (RSS). The RSS of a UWB signal shows little small scale fading compared to narrowband signals [1]. Thus RSS methods indirectly exploit the high time resolution. The RSS metric is relatively simple to detect and no high synchronization effort or additional protocols are needed like in the ToA based solutions. Simple analog receivers with only one antenna can be used. It is not expected that RSS can match the precision of time based methods. The novel contribution of this paper is to explore the limits of accuracy achieved with RSS positioning. Many potential services do not need a centimeter level position accuracy [2], e.g. exhibit and museum commentary, goods and item tracking, hazard warnings, pedestrian route guidance, location based office services and in-building worker tracking. The expected absolute accuracy of 1m is needed for these applications. The achievable accuracy in RSS positioning decreases with the distance [3], which has be taken into account in the system design.

Positioning concepts in wireless LAN (WLAN) are based on the RSS, but detailed a priori knowledge of the channel is needed. The positioning area is divided into subareas. Calibration measurements are needed for every subarea and every receivable base station in these subareas. These RSS patterns are stored in a database, which is a time consuming process. The subarea with the best matching RSS pattern is the estimated location of the mobile. In contrast to this, the proposed positioning system estimates the coordinates of the mobile directly. Further it needs a smaller prior knowledge of the channel in comparison to WLAN concepts. Compared to an UWB system, the WLAN positioning suffers more from the small scale fading due to its much smaller bandwidth.

The paper is organized as follows: Section II describes the proposed system model. The factors, that are influencing the accuracy of ranging based on RSS, are analyzed in Section III. This Section is based on simulations with the IEEE 802.15.4a UWB channel model [5]. In Section IV an office LOS measurement scenario is presented. Here also the accuracy of the system is discussed. Finally, a brief conclusion will sum up the results and evaluate the potential of UWB positioning based on RSS.

II. PROPOSED SYSTEM MODEL

The UWB positioning system model uses impulse radio transmissions in the frequency band from 3.1 to 10.6 GHz providing for a signal bandwidth of 7.5GHz. It is designed as a beacon system, in which the mobile wants to determine its own position. This principle is well known from outdoor navigation systems such as GPS. The received signal strength P_r is defined as

$$P_r = \frac{1}{t_B - t_A} \int_{t_A}^{t_B} |p(t) * h(t) + n(t)|^2 dt. \tag{1}$$

The LOS component of the channel impulse response arrives at the time t_A and the last significant part occurs at t_B. A simple threshold detector is used to detect the LOS component. The received signal is modeled by the convolution of the transmitted pulse shape $p(t)$ and the channel impulse response $h(t)$. Additionally an additive white gaussian noise component $n(t)$ has to be taken into account.

The mean decay of the received signal strength is modeled with the pathloss model (PLM).

$$P_r = P_0 - 10\,n\,\log_{10}\left(\frac{d}{d_0}\right) + S \tag{2}$$

Where P_0 is the received signal strength at the reference distance d_0, n is the pathloss exponent and S is a zero-mean log-normal random variable with standard deviation σ_s accounting for the large scale fading [5]. In LOS indoor environments the pathloss exponent ranges from 1.0 in corridors to about 2 in office environments. In NLOS scenarios the pathloss exponent typically ranges from 3 to 7 [5]. Ranging based on the received signal strength is strongly dependent on the estimation of the parameters of the PLM. Thus in our system calibration measurements are needed in order to acquire accurate parameters of the PLM. The PLM can be rewritten with respect to d and the following ranging formula is obtained:

$$\tilde{d} = d_0\left(\frac{P_0}{P_r}\right)^{1/n} \tag{3}$$

S is discarded in the ranging calculation, because the deviation to the modeled received signal strength is unknown. Due to this uncertainty d becomes the estimated distance $\tilde{d}$. The ranging results to specific base stations enable multilateration to obtain the coordinates of the mobile.

Positioning Algorithm

A non-linear set of equations needs to be solved, to determine the position of the mobile.

$$\begin{aligned} \tilde{d}_1 &= \sqrt{(x_1 - x)^2 + (y_1 - y)^2} \\ &\vdots \\ \tilde{d}_N &= \sqrt{(x_N - x)^2 + (y_N - y)^2} \end{aligned} \tag{4}$$

(x_i, y_i) are the coordinates of the i^{th} base station, (x, y) are the unknown coordinates of the mobile and $\tilde{d}_i$ is the estimated range to the i^{th} base station. The set of non-linear equations is linearized using Taylor series expansion. After discarding all the higher order components we obtain Eq. (5).

$$\tilde{d} = f(x,y) = f(\underline{x}_0) + \left.\frac{\partial f}{\partial x}\right|_{\underline{x}_0}(x - x_0) + \left.\frac{\partial f}{\partial y}\right|_{\underline{x}_0}(y - y_0) \tag{5}$$

where $\underline{x}_0 = (x_0, y_0)$ is the linearization point. It is chosen as the mean of the base station coordinates. $f(x_0, y_0)$ is the value of the non-linear function at the linearization point. $\frac{\partial f}{\partial x}|_{\underline{x}_0}$ denotes the derivative of the function to x at $\underline{x}_0$. Only the terms with x and y are unknown, thus the other terms are included in $\underline{\tilde{d}}'$. The linearized equations are written in matrix form as

$$\underline{\tilde{d}}' = \mathbf{A}\underline{\tilde{x}} = \begin{pmatrix} \frac{\partial f_1}{\partial x}|_{\underline{x}_0} & \frac{\partial f_1}{\partial y}|_{\underline{x}_0} \\ \vdots & \vdots \\ \frac{\partial f_N}{\partial x}|_{\underline{x}_0} & \frac{\partial f_N}{\partial y}|_{\underline{x}_0} \end{pmatrix} \begin{pmatrix} \tilde{x} \\ \tilde{y} \end{pmatrix} \tag{6}$$

The weighted least squares (WLS) solution for the estimated coordinates is given by [9]:

$$\underline{\tilde{x}} = (A^{\mathrm{T}} W A)^{-1} A^{\mathrm{T}} W \underline{\tilde{d}}' \tag{7}$$

The weighting matrix W is a diagonal matrix with the elements w_{ii}. The weights are given by $w_{ii} = 1/\sigma^2_{d,i}$. $\sigma^2_{d,i}$ is the variance of the estimated distance at location i. σ^2_d is calculated for every base station of the calibration measurements. The base stations show different distances and the weights are related to the corresponding distances. Here a LS fitted exponential weighting function is calculated, that is related to $\tilde{d}$.

$$w(\tilde{d}) = a\exp^{-b\cdot\tilde{d}} \tag{8}$$

a and b are the parameters of the exponential fitting function and are obtained from the calibration measurements. If a signal is received from a specific base station, the corresponding weight is calculated using (8). An exponential weighting function is useful, because the weight should be high at short distances. The unweighted LS approach is given by discarding W in (7).

The estimated position coordinates of every iteration are used as a new linearization point. This procedure is repeated until the estimated coordinates of the mobile converges. For the given data no convergence problems occurred in the iterative procedure.

The positioning system uses estimated ranges to three or four base stations to obtain a position estimate using multilateration. Several ways to improve the accuracy of the positioning system are presented in Section IV.

III. ANALYSIS OF RSS RANGING PERFORMANCE

This section shows the factors that affect the accuracy of UWB ranging based on RSS. The simulations in this section are based on the UWB channel model 802.15.4a [5].

The PLM is not known and varies in every building or room. Therefore the parameters $\tilde{P}_0$ and $\tilde{n}$ need to be estimated. The distance error e_d introduced by estimation errors in the PLM parameters P_0 and n can be calculated as

$$\begin{aligned} e_d = \tilde{d} - d &= d_0\left(\frac{\tilde{P}_0}{P_r}\right)^{1/\tilde{n}} - d \\ &= d_0\left(\frac{\tilde{P}_0}{P_0\left(\frac{d_0}{d}\right)^n}\right)^{1/\tilde{n}} - d \\ &= \left(\frac{d^n\, {d_0}^{\tilde{n}-n}\,\tilde{P}_0}{P_0}\right)^{1/\tilde{n}} - d \end{aligned} \tag{9}$$

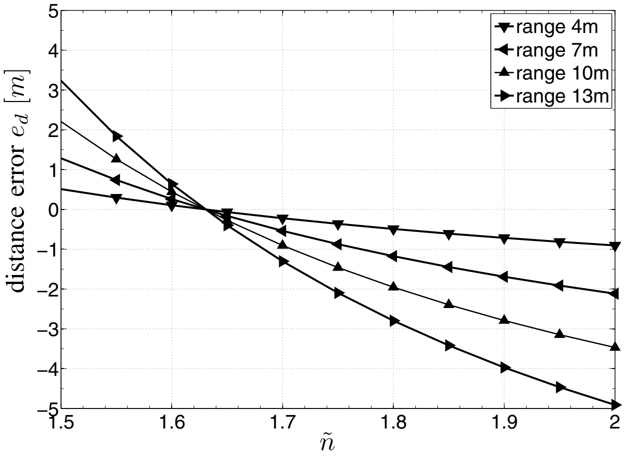

Fig. 1. Distance error introduced by inaccuracies in $\tilde{n}$ for different transmission distances d

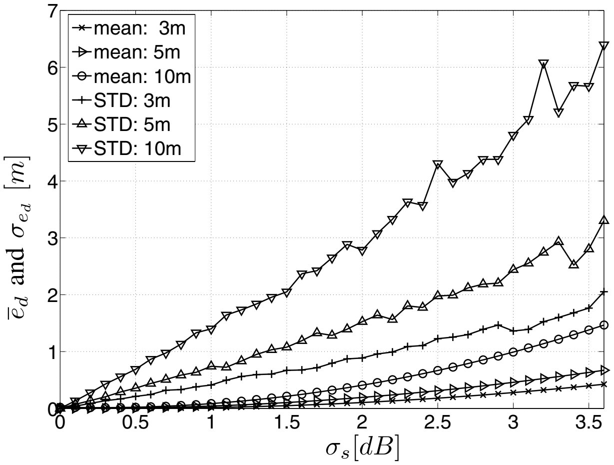

Fig. 2. The effect of large scale fading on the estimated distance

P_0, n and d are the true values and $\tilde{P}_0$, $\tilde{n}$ and $\tilde{d}$ are the estimated ones. The next subsection shows the effects of the error in estimation of n.

A. Prior channel knowledge

The following simulation assumes that P_0 is known. The analyzed environment is the office LOS scenario with $n = 1.63$ and $P_0 = -35.4dB$ of the IEEE office LOS channel model. Fig. 1 shows the range errors for different values of $\tilde{n}$.

If the reference distance is assumed to be 1m, then (9) simplifies to (10).

$$e_d = d(d^{\frac{n-\tilde{n}}{\tilde{n}}} - 1) \tag{10}$$

Note that the error also depends on the distance d. The legend denotes the different distances from the mobile to the base station. If $\tilde{n}$ is estimated too high, negative range errors are obtained. In order to obtain $|e_d| < 1m$ at range of 10m, n has to be known with an accuracy of 0.064 for $\tilde{n} < n$ and 0.078 for $\tilde{n} > n$. It is observable that a too small RSS, in comparison to the modeled RSS, introduces a higher distance error than a too large RSS, because the PLM is flatter for larger distances than for smaller ones. Another effect is that steeper pathloss models cause smaller distance errors than flatter ones. Measurements need to be performed to obtain calibrated PLM parameters. The least-squares (LS) fitting procedure yields $\tilde{n}$ and $\tilde{P}_0$. The effort for the calibration measurements of our system is much smaller than for WLAN based concepts. In WLAN the calibration measurements have to be done for every distinguishable subarea. In our system only measurement to calibrate the pathloss model are needed.

B. Small and large scale fading

The mean decay of the received signal strength can be modeled by the pathloss model, but the RSS shows random deviations around the PLM, which can be described as small scale fading (SSF) and LSF. Large scale fading is defined as the local mean variation around the pathloss model [5]. For small displacements of the receiver, on a scale comparable with one wavelength, fluctuations of RSS due to multipath effects can be observed and is called SSF [6]. The signal amplitudes affected by the SSF are modeled using a Nakagami distribution [5].

Fig. 2 shows the effect of LSF on the estimated distances based on Eq. (2). The results are averaged over 200 simulated channel impulse responses. $mean$ is the mean distance error $\overline{e}_d$, STD is the standard deviation of the distance error σ_{e_d}. These values are depicted for transmission distances of 3, 5 and 10m. The pathloss model is steeper for shorter distances than for longer ones, hence for shorter distances the same deviation to the pathloss model causes smaller distance errors in comparison to larger distances. The measurements reported in [7] show a σ_s of 1.06dB for the whole office building in a LOS scenario. This would cause a σ_{ed} of 1.4m at 10m and $\sigma_{ed} = 0.7m$ at 5m transmission distance. This indicates that in a positioning system based on the RSS close base stations have to be available. In a single room the measurements show a much lower σ_s between 0.39 and 0.78dB [7]. Although S is a zero mean Gaussian random variable, the mean distance error becomes positively biased, because the non-linear function (3) relates P_r to the estimated range $\tilde{d}$. This effect is negligible for low σ_s and becomes more important at $\sigma_s \geq 1.6dB$, where $\overline{e}_d$ exceeds 25cm for a range of 10m.

C. Integration limits

It is also important how the received signal strength is detected. The starting point of the integration and the integration time are of interest. In this work a simple threshold detector finds the LOS component and thus determines the starting point for the integration. The integration time is also very important, because all reflected energy should be taken into account. In UWB LOS signals a high percentage of the signal energy arrives in a very short time. If the receiver continues to integrate the energy after the last significant path, only

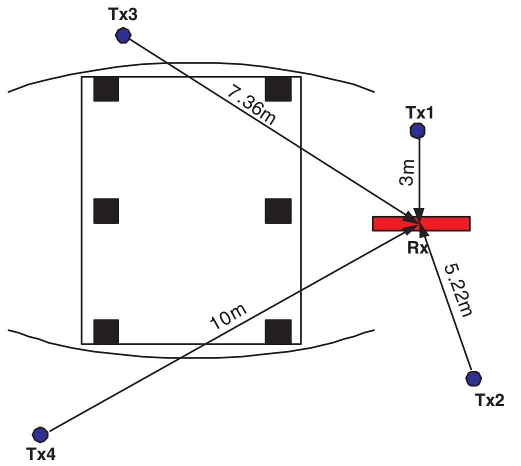

Fig. 3. Library positioning scenario (Source WMC)

noise energy is added to the measured RSS. This additional energy causes the distance to be estimated too short. On the other hand if the integration time is too short some signal energy is missing and the estimated distance is too long. The noise component originates mainly from the hardware. It is independent of the location in the positioning area and should not change under operating conditions. Several ways to handle this problem can be found, but the focus should be on simple concepts to keep the advantage of positioning based on the received signal strength.

Simulations have shown, that at $SNR > 20dB$ the influence of the noise is negligible if the integration time is less than 70ns [4].

IV. SYSTEM VALIDATION

A. Positioning scenario

The proposed system is validated with measurements of the WMC, Wireless and Mobile Communications Group of the Delft University of Technology. The description of the measurement setup can be found in [7]. The generator sends Gaussian-like pulses with a duration of approximately 50ps. The sampling rate is 10ps in a time window of 85ns. The measurements are taken in the library of the EEMCS building. The measurements scenario used in this work is shown in Fig. 3.

All transmissions have a strong leading edge component (LOS). Four transmitting base stations are located at 3m, 5.22m, 7.36m and 10m from the receiver. The receiver is moved on a 7x7 vertical grid with an antenna spacing of 5cm. These 49 local measurements enable small and large scale fading analysis. The black squares in Fig. 3 are concrete pillars.

The integration time is set to 70ns. According to the maximum excess delay reported in [8] this is enough to capture the entire impulse response.

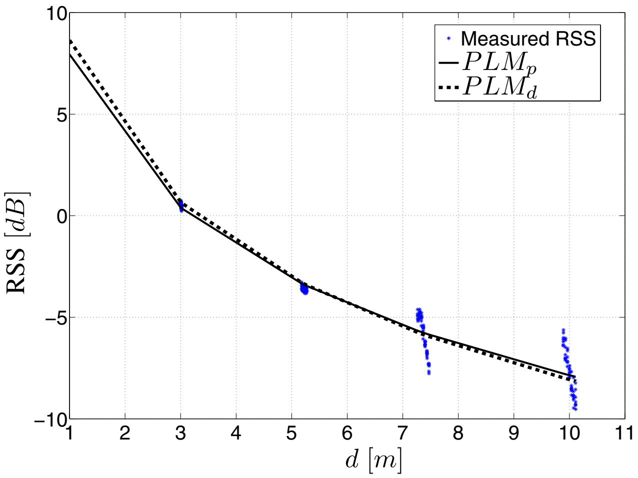

Fig. 4. Pathloss models for the library environment

B. Parameter estimation

Fig. 4 shows the measured RSS and the fitted pathloss models used in the positioning process. Distance dependency of the SSF can be observed. There are bookshelves in the library which contain metal parts likely to create a lot of multipath. These multipath components increase the small scale fading. The pathloss model can be fitted to the measurements in the LS sense to RSS or to the distance, in other words it can be fitted to the x-axis or to the y-axis of the available data set. The distance fitted PLMs show always higher pathloss exponents, because a steeper pathloss model will cause smaller distance deviations. Positions with higher SSF get a higher influence on the PLM. Tab. I shows the obtained values for the PLM fitted to the power PLM_p and for the pathloss model fitted to the distance PLM_d.

	$\tilde{n}$	$\tilde{P}_0$	a	b
PLM_p	1.58	7.94 [dB]	1896	0.5417
PLM_d	1.67	8.64 [dB]	1859	0.5227

TABLE I

PATHLOSS MODEL FITTED TO THE POWER AND TO THE DISTANCE

a and b are the calculated parameters of the weighting function according to (8). The weighting functions are very similar. It is observed that the weighting function of PLM_p is steeper than that of PLM_d, because PLM_d makes less distance errors at larger distances so higher weights for larger distances are obtained.

C. Positioning Results

The performance parameters are the mean distance error $\overline{e}_d$ and the circular error probability CEP [10]. This work uses CEP_{90}, which means that 90 percent of the estimated positions show an absolute distance error less than the specific value.

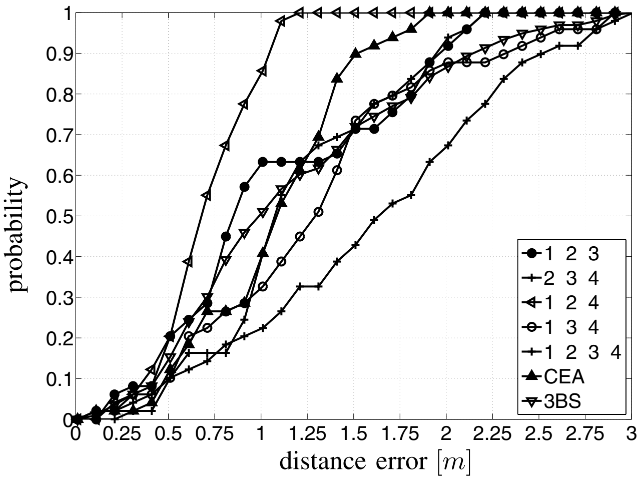

Fig. 5. Positioning results with PLM_d

Fig. 5 shows the positioning results using the PLM_d. The numbers in the legend show which base stations are used for the positioning. The choice of the base stations is very important, e.g. with base stations combination (BSC) 123 much better results can be achieved then with BSC 234. The average transmission distance of BSC 123 is smaller then that of BSC 234. As mentioned before the PLM is steeper for shorter ranges and causes smaller distance errors. Additionally the SSF is much higher for the base stations at 7.36m and 10m (BS 3 and 4). Comparing the two BSCs, the accurate ranging results of BS1 is substituted by the inaccurate ranging results of BS4. This leads to lower accuracy of BSC 234 compared to BSC 123. The BSC 124 yields the most accurate mobile position. Tab. II shows a summary of the simulation results for both PLMs:

	PLM_p		PLM_d	
base stations	$\overline{e}_d$	CEP_{90}	$\overline{e}_d$	CEP_{90}
3BS	112 (140)	204 (231)	115 (138)	193 (225)
1 2 3	100 (117)	183 (232)	107 (121)	198 (225)
1 2 3 4	106 (139)	186 (208)	119 (136)	195 (204)
CEA	103 (138)	162 (209)	106 (135)	147 (200)

TABLE II

POSITIONING RESULTS [CM]

The values in the brackets are the results for the unweighted LS positioning approach. It is observed, that the WLS approach leads to an significant improvement of the accuracy. The improvement for CEP_{90} is in the range from 27cm to 53cm, which is dependent on the selection of the BSC. *3BS* is the mean accuracy of all BSCs based on three base stations. WLS provides a mean accuracy of around 2m. In a relatively small area this is not sufficient for most applications. The first improvement is obtained when the three strongest signals are chosen for the positioning, assuming that the closest BSs provide for the highest RSS. This brings an improvement of about 20cm for PLM_p. The second approach is to take all 4 base stations into account. That delivers similar results as the use of the three strongest signals. The last improvement is the combined estimation algorithm (CEA). CEA averages over the obtained coordinates of all positioning results. The positioning is done for every possible BSC, also for all four base stations. It is very simple to include and exclude signals, e.g. if the estimated location is not in the positioning area or the algorithm does not converge, then it is possible to exclude the signal from the calculation. CEA yields the best results for the given positioning scenario with an accuracy of 1.5m with the PLM_d.

In general the two pathloss models PLM_p and PLM_d lead to quite similar results.

V. CONCLUSIONS

A new concept for UWB positioning based on received signal strength is presented. The factors that are influencing the accuracy of UWB ranging based on RSS are shown and analyzed using Matlab simulations. Ranging based on the RSS is very sensitive to the estimated pathloss model parameters. For this reason a number of calibration measurements in the positioning area are required. The pathloss model can be fitted to the power or to the distance, but both pathloss models lead to similar results. A system model was created and verified with office LOS measurements. In the best system setup a CEP_{90} of 1.5m was achieved in this measurement scenario. A better placement of the base stations could bring better accuracies through better geometrical conditioning. The achievable accuracy decreases with the distance, so close base stations have to be available in UWB positioning based on RSS.

ACKNOWLEDGMENTS

Special thanks to Christian Tiberius for his suggestions on this work.

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