

Empirical pathloss model for indoor geolocation using UWB measurements

N. Alsindi, B. Alavi and K. Pahlavan

A novel empirical approach is presented for modelling the path loss behaviour of the direct path (DP) between the transmitter and receiver, which is important for time-of-arrival-based indoor geolocation coverage characterisation. Using ultra wideband (UWB) measurements in four sites and three ranging scenarios, pathloss models at 500 MHz and 3 GHz system bandwidths are provided, centred on 4.5 GHz for DP and total signal power. In addition, ranging coverage analysis is provided using the DP models.

Introduction: Existing UWB indoor radio wave propagation measurements have focused mainly on determining the radio coverage in different environments [1, 2]. The reported results and models, however, are not adequate for predicting the coverage of time-of-arrival (TOA)-based UWB indoor geolocation systems because the performance in multipath rich indoor environments depends on the signal-to-noise ratio (SNR) of the DP between the transmitter and the receiver [3]. Unlike communication coverage, which is related to the received power of all the multipath components in a given distance, ranging coverage is related to the received power of the DP component. For a given system dynamic range ρ , we define ranging coverage, R_c , as the distance in which the maximum tolerable average pathloss of the DP is within ρ . This is represented by

$$\max\{\overline{PL_{DP}}\} = 10\gamma \log_{10}(R_c) \leq \rho \quad (1)$$

where $\overline{PL_{DP}}$ is the average pathloss and γ is the pathloss exponent. Note that ρ is related to the receiver sensitivity.

The pathloss behaviour of the DP is distance-dependant but, because of energy removed by scattering its intensity, decreases more rapidly with distance compared to total signal energy [4]. Operating out of ranging coverage, also known as undetected direct path (UDP) condition, causes large TOA estimation errors and degradation in the performance [5, 6]. The work presented in this Letter aims to provide novel characterisation of ranging coverage through large-scale UWB empirical measurement in different building environments and ranging scenarios.

Measurement campaign: The pathloss measurements were conducted at four building sites: Fuller laboratories (modern office), 17 Schussler Road (residential house), Norton Company (manufacturing floor) and Atwater Kent (AK) Laboratories (old office), all of which are in Worcester, MA, USA. Different ranging scenarios were conducted at the sites: indoor-to-indoor (ITI), outdoor-to-indoor (OTI), and roof-to-indoor (RTI). The measurements were conducted in the frequency domain similar to the setup in [2, 6], using an Agilent Vector Network Analyzer (VNA) sweeping 3–6 GHz and a pair of disc-cone UWB antennas with 30 dB power amplifier at the transmitter and low-noise amplifier (LNA) at the receiver. This setup provided 120 dB dynamic range. The VNA measures the S_{21} parameter, which is the frequency domain transfer function of the channel. From the measured 3 GHz bandwidth, 500 MHz bandwidth was parsed out of the same data, maintaining the same centre frequency of 4.5 GHz. The DP is extracted by converting the frequency domain data to the time-domain lowpass equivalent channel impulse response (CIR) using inverse Fourier transform (IFT). Then, with prior knowledge of measured distance between transmitter and receiver, the power and TOA of the DP are extracted by application of a peak detection algorithm. The undesirable effects of the cables, LNA and antennas are removed through system calibration. The height of the antennas was set to 1.5 m. For all the measurements, different receiver locations were measured for a fixed transmitter location. For ITI, the decision to measure line-of-sight (LOS) against non-LOS (NLOS) depended on the dimension of the building. OTI measurements were conducted in all sites except the AK building. Only RTI measurements were conducted in AK owing to roof accessibility. The transmitter was placed on the roof and the receiver was moved onto the floor directly beneath it.

Pathloss model: Using the same established pathloss modelling approach used in [1, 2, 6], we attempt to characterise the distance-pathloss dependence of the measured DP and total signal energy

through least-square (LS) linear regression. The pathloss expression in decibels at some distance d is given by

$$PL(d) = PL_0 + PL_p + 10\gamma \log_{10}\left(\frac{d}{d_0}\right) + \chi, \quad d \geq d_0 \quad (2)$$

where PL_0 is the pathloss at $d_0 = 1$ m, $10\gamma \log_{10}(d/d_0)$ is the average pathloss with reference to d_0 , γ is the pathloss exponent and PL_p is the penetration loss and both are functions of the measured scenario and building environment; and χ is the log-normal shadow fading.

Results: We present our results by grouping different ranging scenarios and environments. For both ITI and OTI we provide models for the Norton, Fuller and Schussler buildings, and the only RTI result is provided for the AK building. Fig. 1 shows a sample measured scatter plot of the pathloss against distance for Norton OTI at 500 MHz bandwidth. The straight line is the best-fit LS linear regression. As in many other models in the literature, the value of PL_0 is found through fitting the data to (2). We observed that the intercept value changed according to the ranging scenarios and building environments. Therefore, we measured PL_0 at 1 m free space to be 40 dB and added PL_p to compensate for the penetration loss.

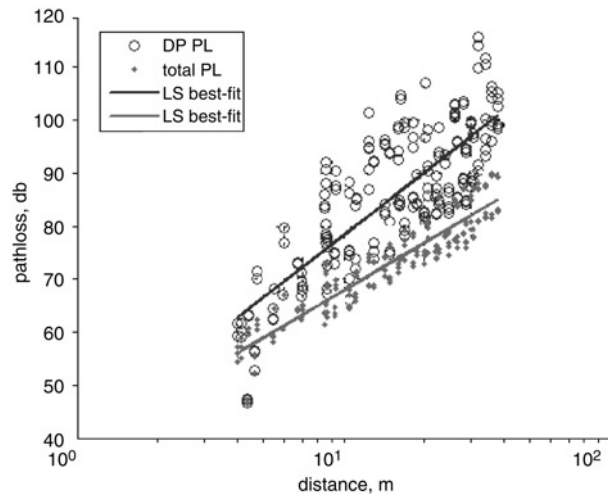


Fig. 1 Pathloss measurement data for Norton OTI at 500 MHz bandwidth

Table 1 provides a summary of the pathloss results. Several observations can be made from the Table and the Figure. The first is that for all the measurement data the pathloss exponent is higher for the DP compared to the total signal power, which justifies our modelling approach. Secondly, the DP power experiences greater fluctuations around the mean pathloss compared to the total signal power counterpart. This observation makes sense because small variations on the transmitter location affect the DP power more than the total power. Thirdly, PL_p changes for the different penetration scenarios. In the ITI scenarios only Schussler is NLOS and that is evident from the penetration loss due to the walls. Results of OTI measurements show that Fuller exhibits substantial penetration loss mainly because the signal had to penetrate a heavier building construction when compared to Norton and Schussler. RTI measurements experience the largest penetration loss and the highest pathloss exponent. Finally, note that the harsher the indoor environment the higher the pathloss exponent difference when moving to a higher system bandwidth. This is mainly due to the fact that larger system bandwidths provide better time-domain resolution at the cost of reduced power per multipath component. This implies that the advantage of higher time-domain resolution comes at a cost of shorter ranging coverage.

The models presented provide a powerful tool for simulating ranging coverage in different environments and scenarios, which is important for algorithm development and performance evaluation. Fig. 2 shows ranging coverage against different system dynamic ranges for 500 MHz (Fig. 2a) and 3 GHz (Fig. 2b) system bandwidths. As reflected in the measurement results, RTI faces the toughest constraint for ranging. The simulation reveals that for a realistic dynamic range of around 80 dB, ranging coverage from the roof is less than 5 m and for OTI it is around 15 m and ITI varies between 15 and 60 m, depending on the LOS or

NLOS conditions. Another observation made from the simulations is that the change in system bandwidth reduces the coverage substantially. This is less the case for *pure* LOS scenarios where the coverage is almost the same for both bandwidths, see ITI Fuller. The other ITI environments, however, are mixed LOS/NLOS for Norton and *pure* NLOS for Schussler and that can be clearly reflected in the change of their coverage between the bandwidths.

Table 1: Path-loss model parameters for different scenarios of measurement data based at 500 MHz and 3 GHz

Scenario	Environment	PL_p (dB)	Direct path				Total signal	
			500 MHz		3 GHz			
			γ	χ (dB)	γ	χ (dB)	γ	χ (dB)
ITI	Fuller (LOS)	0	3.2	8.9	3.3	7.1	2.4	5.5
	Norton (LOS/NLOS)	0	3.5	8.5	4.5	9.1	2.6	3.4
	Schussler (NLOS)	6	3.4	7.9	3.9	8.4	3.0	4.6
OTI	Fuller	14.3	3.4	13.7	3.7	14.1	2.5	7.7
	Norton	8.7	3.9	7.8	5.01	10.11	3.3	4.4
	Schussler	7.6	4.1	10.5	4.2	11.1	3.2	6.1
RTI	AK	24.5	4.3	7.6	5.3	8.8	2.9	1.7

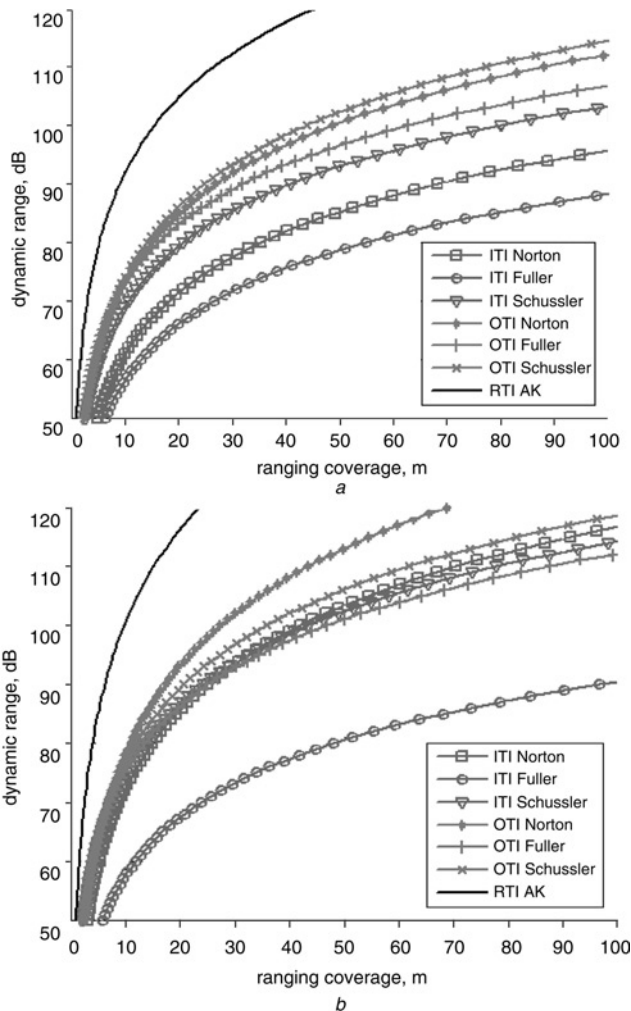


Fig. 2 Simulated ranging coverage
a 500 MHz bandwidth
b 3 GHz bandwidth

Conclusions: Novel empirical DP pathloss models based on indoor UWB measurements have been presented. In addition to the impact of system bandwidth, the results have shown that ranging coverage is environment and scenario dependent. The presented models provide tools to simulate and predict the ranging coverage for TOA-based indoor localisation algorithms.

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