
An outdoor UWB tracking system to improve safety of semi-autonomous vehicle operations

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Abstract: UWB positioning systems show promise in improving navigational capabilities and safety of operations for semi-autonomous systems that are emerging in applications such as construction and agricultural vehicles. This paper describes an outdoor UWB positioning system used to measure the position of trucks in a semi-autonomous truck convoy. The system improves safety by providing position the vehicles control system with accurate position measurements. A measurement campaign was conducted to collect experimental range errors in open, forested and urban channels at distances ranging from 2 m to 40 m. The range errors are characterised and a model for range errors is proposed. Position errors using the proposed model are compared to the experimental data. Performance analysis regarding accuracy and position update delay is presented.

Keywords: ultra wideband; UWB; positioning systems; experimental analysis.

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1 Introduction

Semi-autonomous vehicles are emerging in defence, construction and agricultural applications with the aim of improving safety and reducing the amount of required personnel resources. These systems have varying levels of autonomy that range from tele-operated systems that are already fielded to experimental systems with fully autonomous navigation. This type of platform can benefit from a highly accurate positioning system to enhance

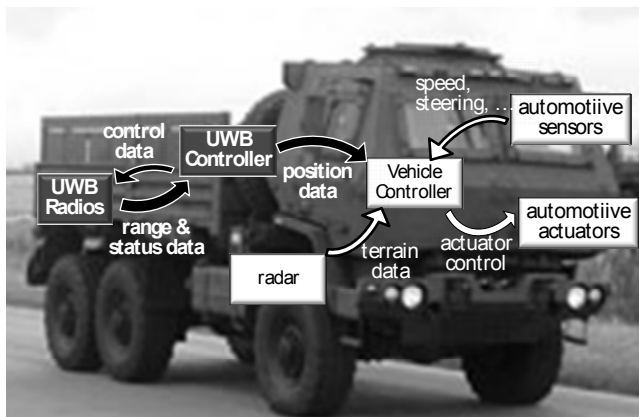
navigation, especially in GPS denied environments such as deep canyons or heavily forested terrain. Positioning data can improve safety of operations by providing operators and vehicle control systems with the position of nearby objects. This data can also facilitate certain autonomous applications such as 'leader-follower' wherein one vehicle will automatically follow another vehicle.

An ultra wideband impulse radio (UWB-IR) positioning system integrated into the control system of a

semi-autonomous vehicle shows promise to significantly improve the platform's navigation capability. UWB-IRs are able to achieve fine time resolution, which can be used to achieve accurate range measurements. These ranges measurements provide a building block for positioning systems. In this effort, we present an analysis of range and position measurement accuracy based on experimental data collected for an outdoor UWB-IR positioning system developed for such applications.

The UWB positioning system is used to implement a 'leader-follower' application for semi-autonomous medium tactical trucks (MTV), in support of the DoD Convoy Active Safety Technologies Program. The overall goal of the project is to have autonomous control systems improve the safety in truck convoy operations. Figure 1 shows a simplified diagram of the overall system's concept. The UWB positioning system determines position data for the truck in front of it and provides this data to the vehicle controller. The vehicle controller also accepts input from automotive sensors for power train status and radar for terrain information. The vehicle controller uses the inputs to determine the appropriate steering angle and velocity for the truck and actuates the steering, braking, transmission and throttle as needed.

Figure 1 Autonomous navigation system applied to an MTV convoys (background picture)



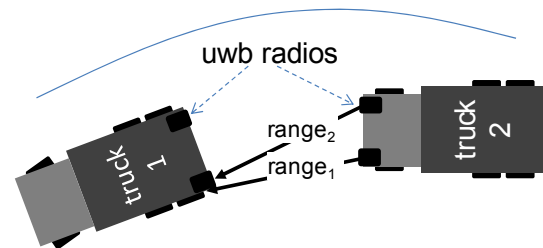
Notes: Vehicle controller supervises automotive functions. UWB positioning system provides the vehicle controller with the position information of leading truck.

Figure 2 shows a simplified diagram of the leader-follower operation in which the following truck, using UWB radios mounted on its cab, determines the position of the lead truck. In practice, each truck has four radios that allow the truck to simultaneously act as a leader and follower. A more detailed description of the UWB positioning system is given in Section 2.

This paper focuses on the range and position errors for the outdoor UWB positioning system. A measurement campaign was conducted that collected data in an open, forested and urban channels at distances between 2 m and 40 m. Based on this data collection, a Gaussian model is proposed for the range error distribution. Characteristics of position measurement errors from experimental data are

compared to those generated by the model in different channel conditions with different radio parameter settings. The performance of the system is analysed under static conditions with respect to position measurement error and position update delay. In this initial phase, we assume that terrain is relatively flat and only two coordinates are required. The data reported in this effort serves as a baseline for further studies into more complex channel environments (e.g., obstructed outdoor channels) and performance in mobile environments. This paper forms the foundation upon which future studies regarding mobile positioning, prediction and estimation.

Figure 2 Leader-follower concept: UWB radios on the following truck obtain range information of the lead truck (see online version for colours)



Notes: The UWB controller determines position of the lead truck from the range information.

The UWB positioning system uses commercially available UWB radios and achieves accurate positioning at distances up to 40 metres with update rates in excess of 50 Hz. The UWB radios are programmed and calibrated to optimise for high update rate and accurate range measurements in an unobstructed path. An integrated controller collects range data, calculates position measurements and controls system state. The system is capable of providing 360° coverage at distances between two and 40 meters from the vehicle's centre. This information is used to improve safety by limiting vehicle speeds based on proximity to other trucks.

1.1 Previous related work

UWB positioning and tracking systems are emerging in a diverse range of applications (Ni and Barton, 2005; Ni et al., 2006; Schwarz et al., 2005; Luediger et al., 2007; Riehle et al., 2008). The main focus of such systems has been for indoor environments, with scant data available for outdoor systems at longer ranges. UWB tracking has been explored for space applications (Ni and Barton, 2005; Ni et al., 2006), commercial asset tracking (Schwarz et al., 2005; Luediger et al., 2007) and assistance to disabled persons (Riehle et al., 2008). Mahfouz et al. (2008) describe a UWB indoor local positioning system that uses a 300 ps Gaussian pulse modulated on an 8 GHz carrier to provide accurate range measurements at short ranges in an indoor environment. The authors analyse errors caused by multipath interference, sampling rate limitations, tag synchronisation and antenna phase variations. Experimental data is presented and a path to achieve very high accuracy in an indoor environment is described. In Gremigni et al. (2006), a report of an indoor

range measurement experiment using UWB-IR radio is presented for LOS and NLOS intra-room propagation conditions.

Several projects (Yu and Oppermann, 2004; Navarro and Najar, 2007; Badorrey et al., 2008; Guoping et al., 2008; Youssef et al., 2008; Wann et al., 2006; Denis et al., 2005; Venkatesh and Buehrer, 2007) have addressed important issues regarding position estimation techniques. In Yu and Oppermann (2004), position estimates based on TOA signals are presented using classical filtering and an alternate approach that does not require knowledge of range error distribution. A novel joint position estimation approach using time-of-arrival (TOA) and direction-of-arrival (DOA) integrated with an extended Kalman filter is proposed in Navarro and Najar (2007) to achieve robust positioning. In Badorrey et al. (2008), analysis of TOA-based estimation mechanisms is provided that addresses design of receiver architectures for UWB systems and provides simulation of the architectures using the 802.15.4a channel model. In Guoping et al. (2008), the authors propose an adaptive combining approach to reduce position measurement uncertainty. The approach combines TDOA measurements and uses directional motion increments to reduce random channel noise and dilution of precision (DOP). The approach shows promise to improve performance over existing methods because of its low cost and battery life impacts. NLOS channels are studied in Youssef et al. (2008), Wann et al. (2006), Denis et al. (2005) and Venkatesh and Buehrer (2007). In Youssef et al. (2008), the authors address challenges for indoor NLOS channels using a hybrid TDOA/AOA positioning approach. An analysis using modified extended Kalman filter (MEKF) and modified regularised particle filter (MRPF) for position estimation in a mobile indoor environment is provided in Wann et al. (2006). In Venkatesh and Buehrer (2007), the authors propose the use of RMS delay spread to detect NLOS propagation conditions which enables effective use of algorithms developed to alleviate NLOS propagation effects.

This effort presents experimental data for an outdoor long range UWB positioning systems that have not previously been reported in the literature. We present the accuracy of range measurements based on experimental data collection and the ensuing impact on position measurements in static environments. In the next section, an overview of the UWB radios and tracking system is provided. Section 3 presents the characteristics of the range measurement error based on experimental data collection. The impact on position measurement error in a static environment is analysed in Section 4. Section 5 provides a summary and identifies areas of future work.

2 System overview

An overview of the UWB positioning system from the perspective of understanding the characteristics of range error measurements and delay and the affect on position measurements is provided in this section.

2.1 UWB radio description

The system uses the P210 UWB radio from Time Domain, a time hopped, impulse radio with capability for extended range measurements in outdoor environments. The radio transmits a time hopped pulse train with a 9.6 MHz pulse rate and time hop code of length 16. The pulse width at the internal SRD diode is 0.235 ns and has a centre frequency of $f_c = 4.26$ GHz. The pulse is high pass filtered in order to conform to the FCC mask for UWB at 3.1 GHz. Further filtering occurs at the antenna and the resultant pulse is elongated in the time domain. Measured 10 dB frequency response of the radio is from 3.1 GHz to 5.8 GHz. The radio has a wide range of parameter settings that provide flexibility for making trade-offs such as bit rate for bit energy and delay vs. accuracy. A description of trade-offs for several important parameters is provided in Section 3. The radio can operate as a conventional radio to send data packets or it can send special $\frac{1}{2}$ duplex range packets that measure time delay between any two radios. Higher layer services for data link control or networking must be provided by the user. The radio supports a 40 MHz strong arm processor with 32 MB RAM and an Ethernet 10 BaseT interface to host higher level services or user applications. The P210 data packet consists of an acquisition preamble and payload data segments. The parameter settings for packet acquisition determine the trade-off between packet loss rates, maximum distance and update delay. The primary parameters for acquisition include pulse integration, correlator step size and threshold settings. Additional segments to support upper layer services (e.g., MAC or network) can be added by the user.

The radios have I-Q correlator pairs that sample at the time hop intervals. The correlator outputs are integrated and compared to a threshold that detects acquisition. The correlator step size during acquisition can be adjusted from a very small size to increase the probability of acquisition to a larger size that speeds up the acquisition process, but decreases the probability of successful acquisition. The default correlator setup size is 235 ps or approximately one pulse width.

The symbol energy, E_s , during acquisition can be increased using a pulse integration process, wherein the number of pulses that represent an acquisition symbol is increased as a power of two from 2^4 to 2^{10} . Each increment in pulse integration doubles the accumulated signal voltage, providing a 6 dB increase in signal power. Gaussian noise increases by a factor of 1.41 dB for a 3 dB increase in power. Thus each doubling of integration yields approximately 3 dB increase in SNR. However, increasing integration also increases the transmission delay which causes the measurement update rate to decrease. The default number of acquisition symbols is 443 symbols, which allows the correlators to step for a duration of one pulse interval of 104 ns searching for a valid preamble as shown in (1).

$$\frac{\text{Pulse period}}{\text{Correlator step size}} = \frac{104 \text{ ns}}{235 \text{ ps}} = 443 \text{ symbols} \quad (1)$$

The transmission delay for the acquisition preamble is given by

$$\frac{AcqInt \times Num\ symbols}{Pulse\ rate} \quad (2)$$

The receiver threshold can be set either manually or automatically. The automatic mode sets the threshold based on correlator outputs during the first segment of packet acquisition. Autothresholding is effective in a dynamic channel environment, but uses an acquisition preamble that is 50% longer to estimate correct threshold value, resulting in increased transmission delay. The various methods to reduce packet error rate (e.g., increasing acquisition integration, reducing correlator step size, automatic thresholding) and the accompanying increase in transmission delay defines one of the key trade-offs in mobile positioning accuracy that must be carefully studied.

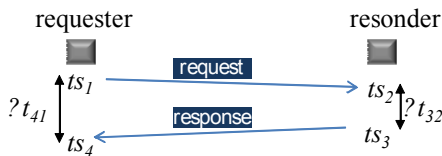
2.2 Range packets and measuring range

The range between two radios is determined by measuring the round trip delay between the radios via the exchange of special 'request' and 'response' packets. While this takes longer than simplex ranging systems, it has the benefit that it does not require central clock synchronisation. Range measurement consists of an initial coarse measurement and a fine adjustment step known as leading edge detection (LED). In the initial step (Figure 3), the requester time stamps the transmit time of a range request, at ts_1 and then transmits the packet. The responder time stamps the arrival of the range request at ts_2 , performs several processing steps and then returns the range response packet at time stamp ts_3 . The response packet contains the time delay on the responding radio, $\Delta t_{32} = ts_3 - ts_2$. The requester time stamps the arrival of the response packet, ts_4 . From Figure 3, we have $\Delta t_{41} = ts_4 - ts_1$ and $\Delta t_{32} = ts_3 - ts_2$, which yield coarse measurement of propagation delay, τ' .

$$\tau' = \frac{\Delta t_{41} - \Delta t_{32}}{2} \quad (3)$$

The coarse time stamps ts_4 and ts_2 are taken when the correlators achieve acquisition. Depending on the channel response, this may not be the leading edge of the pulse.

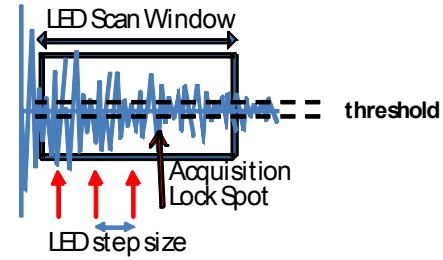
Figure 3 Half duplex range packets used to measure coarse propagation delay (see online version for colours)



Instead of conventional data, the payload of range packet contains the received analogue to digital conversion (ADC) outputs. This information is used to refine the coarse measurements for ts_2 and ts_4 using an LED algorithm supplied by the user. The current algorithm simply takes the squares of the ADC output and determines the earliest

amount of energy that crosses a specified threshold relative to the correlator lock spot, as shown in Figure 4. The LED algorithm parameters include LED scan window size and scan step size. The scan window size determines the time interval, relative to the lock point, that ADC outputs are captured. The scan step size determines the interval between samples when searching for the leading edge. A large scan window and small scan step size provides increased accuracy and robustness for LED, especially in a dense multipath environment. However, both settings also affect the delay to complete a ranging operation.

Figure 4 LED detection searches a scan window for the earliest received energy relative to the acquisition lock point (see online version for colours)



Note: Scan window size and step size are user specified.

As a figure of merit, the transmission delay for the preamble with automatic the holding and acquisition integration = 64

is determined from (2) as $\frac{64 \times 443}{9.6 \times 10^6} \times 1.5 \approx 4.43\ ms$. A scan

window setting of = 20 ns and scan step size = 54 ps leads to a 3.2 ms delay for LED. Practical values for a single range measurement at 40 m lead to delays ranging from 10 ms to 30 ms depending on the various parameter settings. Each setting offers a trade-off between better performances against increased delay.

2.3 Position measurements

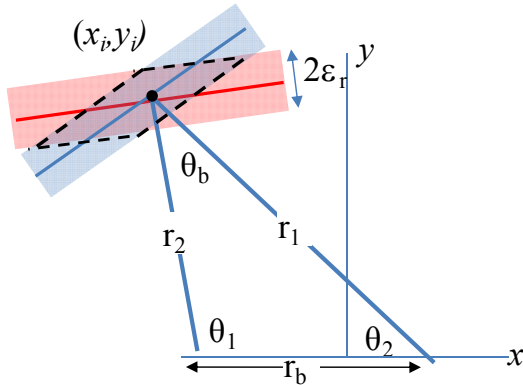
The current architecture uses a controller and four coordinate UWB radios mounted on each vehicle. The controller manages the operation of each coordinate radio and receives range data from each radio. An orthogonal time hopping channel is defined between each pair of vehicles to allow for simultaneous position updates in a convoy with multiple trucks. Each vehicle can use its radios to request ranges from a leading vehicle or respond to range requests from a following vehicle. Individual radios for requesting and responding are selected by the controller to minimise position errors due to geometry as discussed below. The coordinate nodes exchange data with the controller using UDP/IP over Ethernet. The UDP packets are used to monitor and control the system and to transfer range measurements from the coordinate nodes to the controller. Mean UDP packet delay was measured at 270 us with a variance of 40 us. Since range delays are on the order of $10^{-2}\ s$, the UDP packet delay is not a primary consideration.

As stated earlier, the initial assumption is for operations over relatively flat terrain, which requires only two

coordinates to define a position. To analyse position error in two coordinates, let the distribution of range errors be given by $\{\varepsilon_r\}$ and let each range measurement have a random error denoted by $\varepsilon_{r,i} \in \{\varepsilon_r\}$. The resulting position error can be analysed by examining the area created by the intersection of two measured ranges, $r_1 + \varepsilon_{r,1}$ and $r_2 + \varepsilon_{r,2}$ as shown in Figure 5. For simplification, we approximate the arcs representing the intersection of range measurements as straight lines. Then the parallelogram created by intersection of two measured ranges represents the distribution of the position error. It can be shown that the area of the parallelogram is given by $\left(\frac{\varepsilon_{r1}\varepsilon_{r2}}{\sin \theta_b} \right)$ and that this area, and

hence position error decreases as θ_b increases from $0^\circ < \theta_b \leq 90^\circ$ and it is minimised when $\theta_b = 90^\circ$. Decreasing either the separation distance between the platforms or $|\theta_1 - \theta_2|$ will cause θ_b to increase. The increased position error due to decreasing θ_b is known as geometric DOP (GDOP) and has been well studied (Venkatesh and Buehrer, 2007).

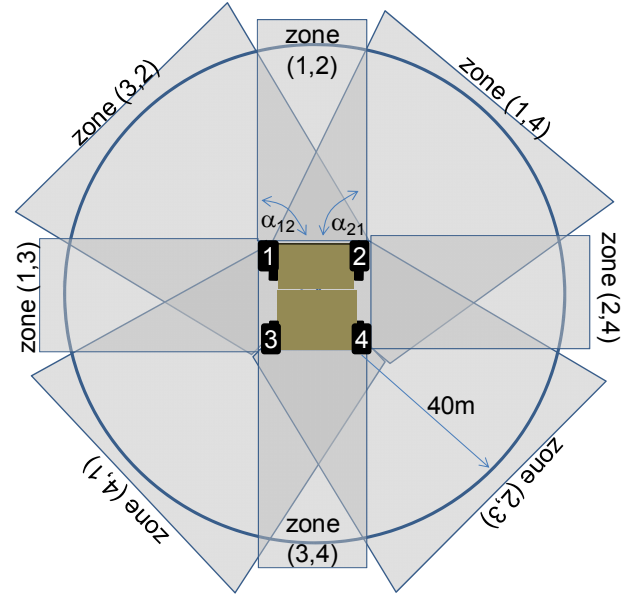
Figure 5 Parallelogram defined by range error, ε_r and angle θ_b , represents the magnitude of the position error (see online version for colours)



In this system, the four coordinate radios are spaced so as to limit DOP and eight zones are defined using radio pairings as shown in Figure 6 to balance the affects of DOP between zones. Zone boundaries are defined by the angles α_{ij} relative to the coordinate radio locations. We define the angles α_{ij} , such that the worst case (smallest) θ_b along any two bordering zones are equal, which balances the affect of DOP between zones and limits the affect of DOP in any one zone. At each position update, the controller on the following truck selects two radios to be requesters and two radios to be responders based on minimisation of DOP. The requesters and responders on one vehicle are set to different time hopping channels. For example, if the lead truck is turning to the right, then from Figure 6, the following truck will select zone (3, 2) and radios 3 and 2 are designated as requesters in the following truck to maximise θ_b . Factors, such as primary direction of travel and safety restrictions can be used to further refine zone boundaries. DOP is well studied (Venkatesh and Buehrer, 2007) and detailed discussion of DOP and zone coverage is not provided in this paper.

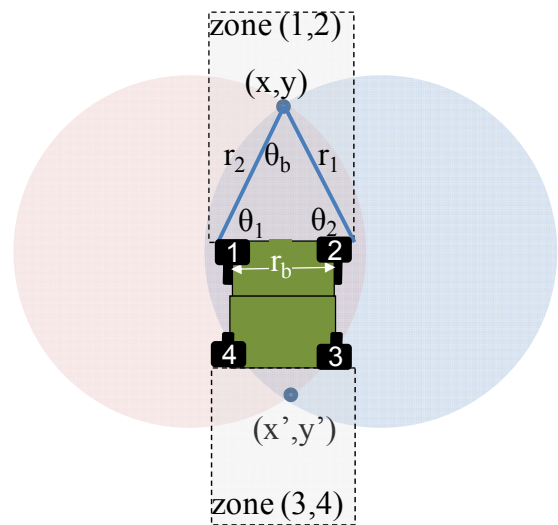
Normally, trilateration is required to eliminate an ambiguous position (x', y') that result in bilateration shown in Figure 7. However, the valid position between these two possibilities can be determined by using zones in such a way that GDOP is kept small and the history of the target's zone locations are recorded. For example, in Figure 6, the locations (x, y) and (x', y') are discernable because they are located in different zones. This allows us to measure position using only two range measurements which reduces the time to measure position by an average of 33%.

Figure 6 Eight zone definitions defined by coordinate radio pairs (see online version for colours)



Notes: Ambiguous positions resulting from bilateration will never be in the same zone.

Figure 7 Bilateration for position measurement in a plane (see online version for colours)



Notes: Ambiguous position at (x', y') is eliminated by assigning targets into zones based on last measurement.

From Figure 7, bilateration is used to determine a position, (x, y) , from two ranges, r_1 and r_2 as

$$\theta_2 = \cos^{-1} \left(\frac{r_1^2 + r_b^2 - r_2^2}{2r_1r_b} \right) \quad (4)$$

where the position in two coordinates is defined by $(x, y) = r_1 \angle \theta_2$. If ambiguity is introduced because of position measurement errors then historical position data or a third range can be used to determine a better measurement. If a range packet is dropped or detected to have a large error (outlier) then additional ranges can be requested. In practice, the number of retries is limited by an algorithm that looks at the delay impact to the target update rate for all other targets.

2.4 MAC and tracking multiple targets

Media access control (MAC) and data link layer services are required to coordinate range packets between various radios. The positioning system is inherently centralised about the following platform, so we opt for a centrally controlled, polling MAC for each time hopping channel that resides on the following truck's controller. The controller uses past position measurements to designate requesters and responders so as to minimise DOP. Source and destination MAC address are added to each range packet to identify responders on the lead truck. The link layer services are best effort and connectionless. The system is continuously ranging and dropped range packets are ignored. By design, we minimise computational delay on each controller and the processing time for various management tasks is less than 1 ms per position update. If we assume two range measurements for each position and a delay of 10–30 ms per range, then the system will have an overall position update rate of approximately 15 and 50 Hz per truck.

3 Experimental data collection

An experiment was conducted to establish a baseline assessment of performance limitations for range accuracy under the simplified conditions of an unobstructed channel on level terrain during the initial development of the system. Range data was collected in an open grassy field, in a canopied forest and in an urban environment at distances from 2 m to 42 m in 2 m increments. The height of the transmit antennae, h_{tx} , and receive antenna, h_{rx} , were both set to 1 m. Truth points were established using a high precision laser with a mean accuracy of 0.002 m and a variance of 0.001 m. At each truth point, 4,000 range samples were collected and the number of dropped range packets, outliers and successful range measurements was recorded as well as individual range measurements.

Generally, the attempt to measure a range can have one of three results: a dropped range packet, a large range error (outlier) or a successful range attempt. A dropped range packet occurs when acquisition is not achieved over the

preamble and the range attempt fails. This occurs when the received signal-to-noise (SNR) ratio is insufficient, either due to path loss or fading. A large range error can be caused by fading or by a system problem, such as the scan window being too small relative to channel delay spread. Typically, outliers have a measurement differential from the preceding range in excess of several metres. In our static data collection, we set a threshold of one metre for outliers. A successful range attempt will have some small error associated with fading or uncertainty in LED.

Preliminary experiments were conducted to evaluate a wide range of parameter settings. Parameters were selected that balanced accuracy of range measurements against time duration to complete a ranging operation. Automatic thresholding was selected as experiments verified that it is not possible to reliably cover distances from 2 m to 42 m using a static acquisition threshold. Experiments with correlator step size show significant increase in packet loss with step sizes greater than the default 235 ps. The acquisition integration was selected in order to minimise the effects of path loss on packet acquisition at a maximum range of 40 metres. The acquisition parameters for integration and step size were set to 64 and 235 ps, respectively. The symbol must have enough energy, E_s^{tx} to overcome path loss effects at $d = 40$ m. For analysis of path loss in a LOS channel over flat ground with $d \gg \sqrt{h_{tx}h_{rx}}$, we assume power falls off at 40 dB/decade (Massatt and Rudnick, 1989). Thus at $d = 40$ metres, we would expect pathloss, $L_p \approx -96$ dB. The average transmitted power of a pulse over the frequency range from 3.1 GHz to 5.8 GHz is given as

$$P_{TX} = 32 \mu W \quad (5)$$

If acquisition integration is set to 64, this yields transmitted symbol energy of

$$E_s^{tx} = -66.71 \text{ dBm} \cdot s \quad (6)$$

If noise power spectral density is assumed to be $N_0 = -174$ dBm · s then received bit energy to power spectral density is given

$$\frac{E_s^{rx}}{N_0} \approx -66.71 \text{ dBm} \cdot s + 174 \text{ dBm} \cdot s - 96 \text{ dB} = 11.29 \text{ dBm} \cdot s \quad (7)$$

The radios use BPSK modulation, hence the symbol error rate, P_e , is given as

$$P_e = Q \left(\sqrt{\frac{2E_s}{N_0}} \right) \approx 10^{-6} \quad (8)$$

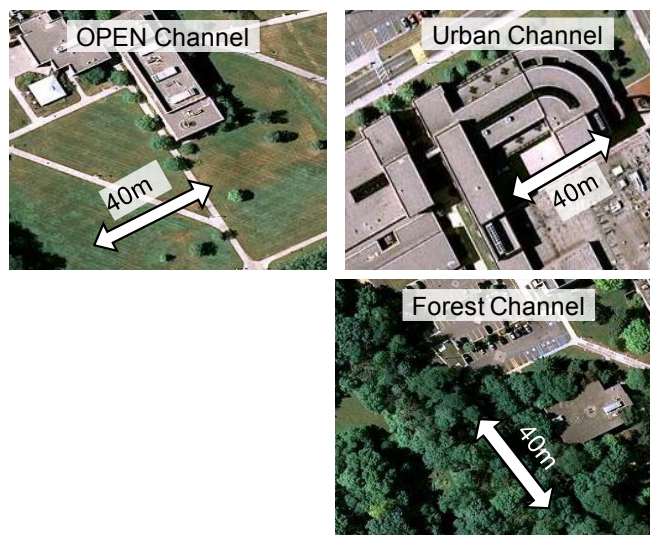
For a preamble length $n = 443$ symbols and if $n \cdot P_e \ll 1$ then the probability of dropping a packet is given by (Rappaport, 2001):

$$P_f \approx n \cdot P_e \approx 0.4\% \quad (9)$$

Thus if acquisition integration is set to 64, path loss should not be a significant factor in packet loss rate. Experimental data shows there is no significant correlation between distance and dropped packets and we conclude that dropped packets in an open channel at distances from 2 m to 40 m are primarily the result of fading.

The LED parameter for scan step size was set to $\tau_{step} = 54 \text{ ps}$ or 0.162 cm which is about 23% of a pulse width. If a sample misses the leading edge on average by $\tau_{step}/2$, then we would expect a mean bias of 0.08 cm for each of the LED operations, for a total mean bias of 0.162 cm. Multipath can obscure the leading edge also contributing to range errors. Measurements revealed a mean round trip bias of 0.18 cm using these settings. The scan window size was evaluated at two values, 20 ns and 100 ns. Preliminary experiments showed that 20 ns was the minimal window size that offered reliable performance in a wide range of conditions and has a delay of approximately 3.2 ms for LED with $\tau_{step} = 54 \text{ ps}$. The 100 ns window size was selected for the urban environment, where delay spread can be a very significant factor. The delay measured for the 100 ns window with $\tau_{step} = 54 \text{ ps}$ is 6.7 ms. The total delay for range measurement at 20 ns and 100 ns scan window is 20.1 ms and 27.1 ms, respectively. Assuming a successful range measurement, we expect range measurement errors to result primarily from LED sampling error and multipath fading. Experiments verify that the mean and variance of range errors are not correlated with distance.

Figure 8 Clockwise from top left, top view of open, urban and forest channels (see online version for colours)



Note: Arrows indicate 40 m channel where data was collected.

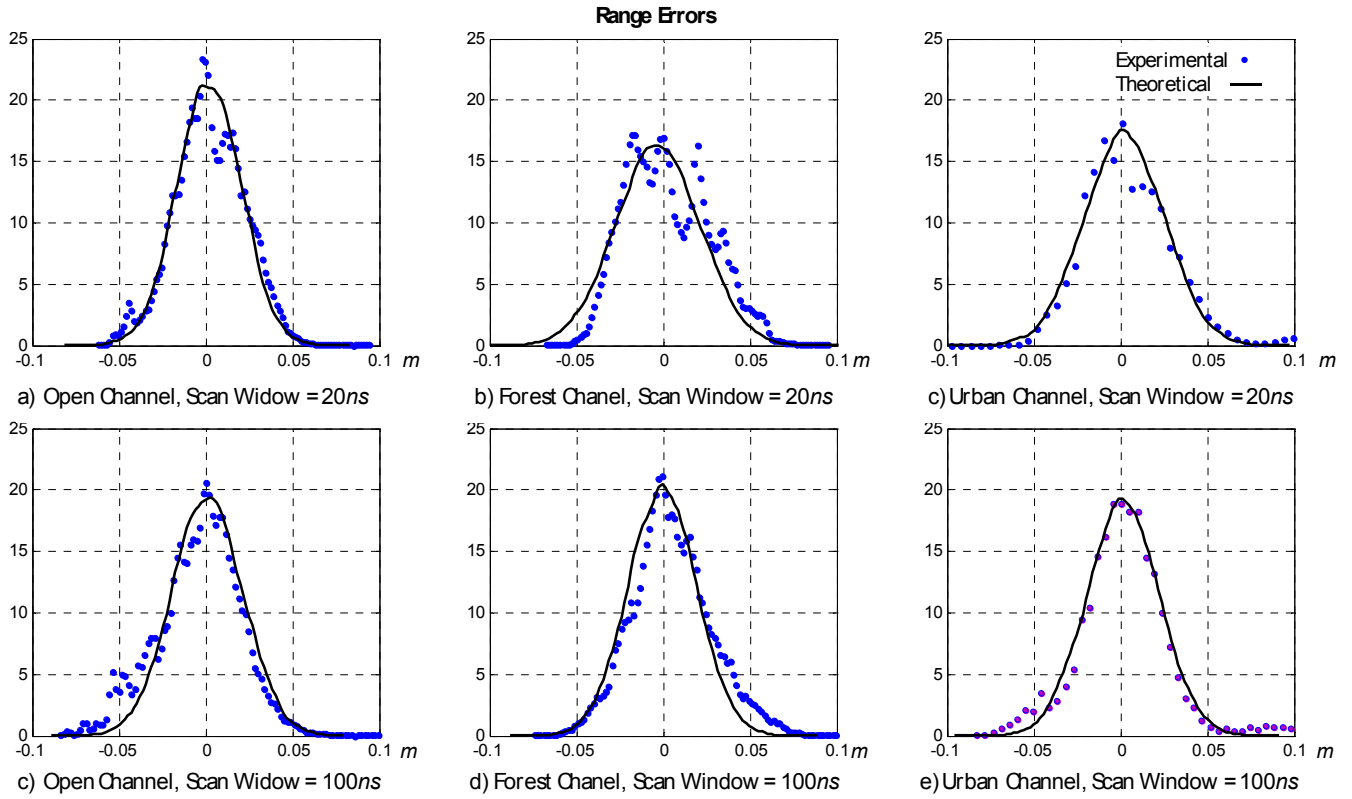
The open channel is in a 40 m grassy area with some trees and buildings at distances greater than 30 m on either side of the channel. There are several small trees within 20 m of the channel. The forested area had an unobstructed 40 m channel from antenna to antenna, an overhead canopy of mixed conifer and deciduous trees, and dense underbrush on all sides. The urban channel is enclosed on three sides with three to five story buildings. The fourth side is partially

obstructed by a three-storey building and has a narrow driveway extending for 25 m with two and three-storey buildings on either side. Figure 8 shows the open, forest and urban channel, respectively.

In Figure 9, dotted graph shows the distribution of experimental range errors for open, forested and urban channel with 20 ns and 100 ns scan window, adjusted for LED bias as described in the previous section. Figure 9(a) through Figure 9(c) shows the open, forest and urban channels for 20 ns scan window. Figure 9(d) through Figure 9(f) shows the open, forest and urban channels for the 100 ns scan window, respectively. It can be seen that the measured range errors closely follow a Gaussian distribution. A theoretical distribution was developed for each of the four cases and is shown in Figure 9 as the solid line.

The measured results are nearly zero-mean and slightly asymmetrical about the mean. The theoretical mean is symmetrical about the mean and the mean is adjusted to more closely match the asymmetry of the measured data. From the graphs, we propose that range errors can be reasonably modelled using a Gaussian distribution as shown. Table 1 shows mean and standard deviation of range errors for open, forest and urban channels with 20 ns and 100 ns scan windows for the measured data and theoretical model. In the next section, we will examine the position error generated by the experimental range data and the model.

Table 2 provides the percentage of dropped and outlier range packets. In the open channel, there are almost no outliers for either setting and both have similar percentage of dropped packets for the 20 ns and 100 ns scan windows. This indicates that multipath fading is not a significant issue in an open channel and that a smaller scan window is more effective because of the lower delay per range measurement. In the forested channel, there are also very few outliers. We assume that the size and material properties of the leaves, pine needles, branches, etc. lead to uncorrelated scattering (Rappaport, 2001) which diminishes fading effects at the receiver when compared to reflections from large, relatively smooth surfaces as found in an urban environment. The number of dropped packets is slightly lower for the forested channel, which can also be explained by the scattering effect of the forest. In the urban channel, outliers are 8% and 1.6% for the 20 ns and 100 ns scan windows, respectively. This shows the advantage of the larger scan window in a dense multipath environment. However, the percentage of dropped packets dominates the total lost ranges (drops and outliers) and both settings have similar percentage of dropped packets. A large scan window provides some advantage in a dense multipath environment with respect to range outliers, but this is not the dominant impairment. The 100 ns scan window also incurs an additional 35% delay over the 20 ns scan window. Thus, dropped packets due to multipath fading are a more significant impediment than outliers when ranging with UWB-IR systems and the scan window size does not affect this.

Figure 9 Distribution of range errors from experimental data and theoretical model for open, forest and urban channel and scan window = 20 ns and 100 ns (see online version for colours)**Table 1** Mean and standard deviation for range errors for open, forest and urban channels with 20 ns and 100 ns scan windows

Channel type	Open		Forest		Urban	
Scan window (ns)	20	100	20	100	20	100
Measured mean (m)	0.0022	-0.0043	0.0026	0.0048	0.0098	0.0032
Theoretical mean (m)	0.0200	0.0237	0.0240	0.0230	0.0384	0.0297
Measured std. dev. (m)	0.0023	0.0007	-0.0034	-0.0004	0.0021	0.0011
Theoretical std. dev. (m)	0.0183	0.0202	0.0239	0.0194	0.0230	0.0208

Note: Range error, mean and std deviation (m).

Table 2 % outliers, % dropped packets and % total lost ranges for open, forest and urban channel with 20 ns and 100 ns scan window

Channel type	Open		Forest		Urban	
Scan window (ns)	20	100	20	100	20	100
% range outliers	0.1	0.01	0.1	0.1	8	1.6
% dropped packets	7	8	4	7	26	27
% lost ranges	7.1	8.01	4.1	7.1	34	28.6

4 Position measurement errors and update delays

From two ranges, r_1 and r_2 , we can determine the angle θ_2 and position given by $r_1 \angle \theta_2$ as described in Section 2. Let $\{\varepsilon_r\}$ represent the range error distribution and $\varepsilon_{r,i} \in \{\varepsilon_r\}$ a sample from the distribution. Then the error in the angle θ_2 can be represented as

$$e_{\theta_2} = \cos^{-1} \left(\frac{(r_1 + \varepsilon_{r,1})^2 + r_b^2 - (r_2 + \varepsilon_{r,2})^2}{2r_b(r_1 + \varepsilon_{r,1})} \right) - \cos^{-1} \left(\frac{r_1^2 + r_b^2 - r_2^2}{2r_1 r_b} \right) \quad (10)$$

Then the measured position is given as

$$\hat{r}_1 \angle (\hat{\theta}_2 = (r_1 + e_{r,1}) \angle (\theta_2 + e_{\theta_2})) \quad (11)$$

For two coordinates, x_1 and x_2 with measured values $(\hat{x}_1, \hat{x}_2) = f(\hat{r}_1, \hat{r}_2)$, we can determine the error in position measurement as

$$\begin{bmatrix} \varphi_1 \\ \varphi_2 \end{bmatrix} = \begin{bmatrix} x_1 - \hat{x}_1 \\ x_2 - \hat{x}_2 \end{bmatrix} \quad (12)$$

Letting, μ_{φ_i} represent the mean value of φ_i , the RMS of the position error at time is given by

$$\varphi_{RMS} = \sqrt{\mu_{\varphi_1}^2 + \mu_{\varphi_2}^2} \quad (13)$$

Note that geometric affects will cause $\varphi_i(k)$ to grow as range and angle between the target and platform increase.

The position error and distribution of φ_{RMS} is determined for the case when angles $\theta_b = 90^\circ$ and $\theta_1 = 45^\circ$, which minimises geometric errors and allows us to focus on position errors due to range errors. Figure 10 shows the distribution of ε_{θ_2} , the errors for θ_2 . Figures 10(a)–10(c) show the open, forest and urban channel for 20 ns scan window. Figures 10(d)–10(f) show the open, forest and urban channel for 100 ns scan window. It can be seen that ε_{θ_2} generated using the theoretical model has close correlation to the experimental data. From Table 3, ε_{θ_2} is very close to zero mean error for both settings. The standard deviation for ε_{θ_2} is slightly larger for the theoretical case for all channels.

Figure 11 shows the distribution of φ_{RMS} for experimental and theoretical range errors for $\theta_b = 90^\circ$ and

$\theta_1 = 45^\circ$. Figure 11(a) through Figure 11(c) show the case for open and urban channel with 20 ns scan window and Figure 11(d) through Figure 11(f) show the case for open and urban channel with 100 ns scan window. The increased variance in φ_{RMS} due to dense multipath for the urban channel is evident both radio settings. It can be seen that φ_{RMS} generated from the proposed theoretical model closely follows the experimental data. This indicates the model using Gaussian range errors can provide reasonable results for analysing position error in open, forest and urban channels.

Table 4 shows the mean and standard deviation for all channels at both settings. Both experimental and theoretical yield zero mean error, within measurement tolerances. In all channels, the theoretical standard deviation is slightly larger than the experimental standard deviation.

Figure 12 shows the the distribution of φ_{RMS} for $2 \text{ m} \leq r_1 \leq 40 \text{ m}$ and $20^\circ \leq \theta_2 \leq 90^\circ$, which covers zone (1, 2) in Figure 7. Figure 12(a) through Figure 12(c) shows the case for open and urban channel with 20 ns scan window and Figure 12(d) through Figure 12(f) show the case for open and urban channel with 100 ns scan window. This graph shows the effect of geometric errors which increase with r_1 and θ_2 . It can be seen that even in the worst case of the urban channel, greater than 94% of all ranges are less than 1 m. There is no significant difference in position accuracy when comparing different radio settings. The theoretical models follow the experimental distributions closely in this case as well.

Table 3 Mean and standard deviation for ε_{θ_2} for 20 ns and 100 ns scan windows for open, forest and urban channels

	Scan window	20			100		
	Channel type	Open	Forest	Urban	Open	Forest	Urban
Mean	Experimental	−0.001	−0.001	−0.001	−0.001	−0.001	−0.003
	Theoretical	−0.002	−0.002	−0.002	−0.002	−0.002	−0.002
Standard deviation	Experimental	0.147	0.160	0.213	0.178	0.163	0.211
	Theoretical	0.211	0.257	0.246	0.228	0.221	0.234

Note: ε_{θ_2} (degrees).

Table 4 Mean and standard deviation for φ_{RMS} for 20 ns and 100 ns scan windows for open, forest and urban channels

	Scan window	20			100		
	Channel type	Open	Forest	Urban	Open	Forest	Urban
Mean	Experimental	0.003	0.003	0.005	0.003	0.003	0.004
	Theoretical	0.003	0.003	0.003	0.003	0.003	0.003
Standard deviation	Experimental	0.050	0.054	0.080	0.060	0.055	0.074
	Theoretical	0.074	0.094	0.088	0.081	0.078	0.085

Note: φ_{RMS} (m).

Table 5 Mean and standard deviation for position measurement update delay for open, forest and urban channel with 20 ns and 100 ns scan window

Channel type	Open		Forest		Urban	
Scan window (ns)	20	100	20	100	20	100
Mean update delay (ns)	43.23	59.29	41.25	58.74	54.81	71.31
Std. dev. Update delay (ns)	49.59	92.41	31.50	42.41	113.76	192.76

Figure 10 The distribution of errors for θ_2 in open, forest and urban channel for scan window = 20 ns and 100 ns (see online version for colours)

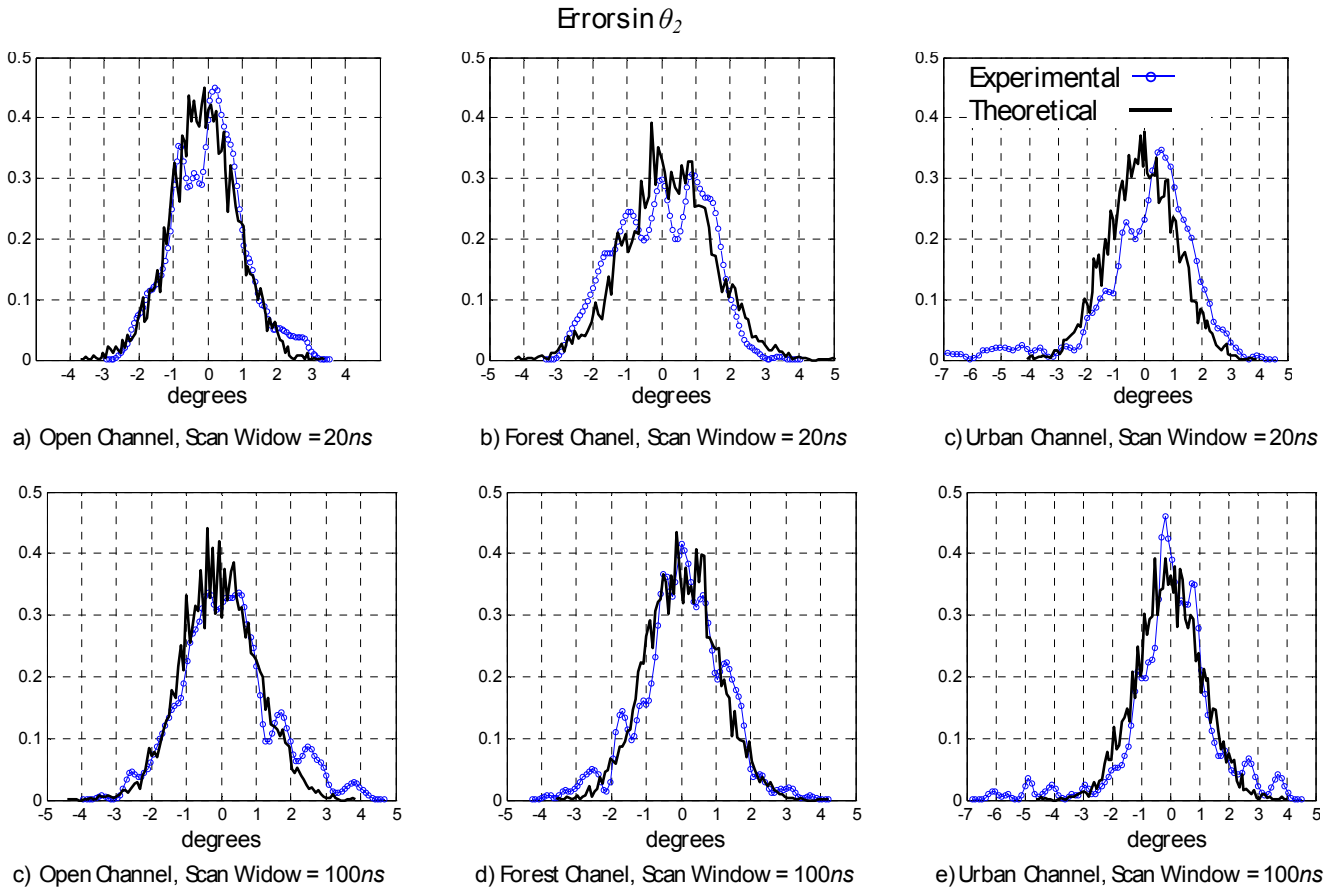


Figure 11 The distribution of ϕ_{RMS} in open, forest and urban channel for scan window = 20 ns and 100 ns (see online version for colours)

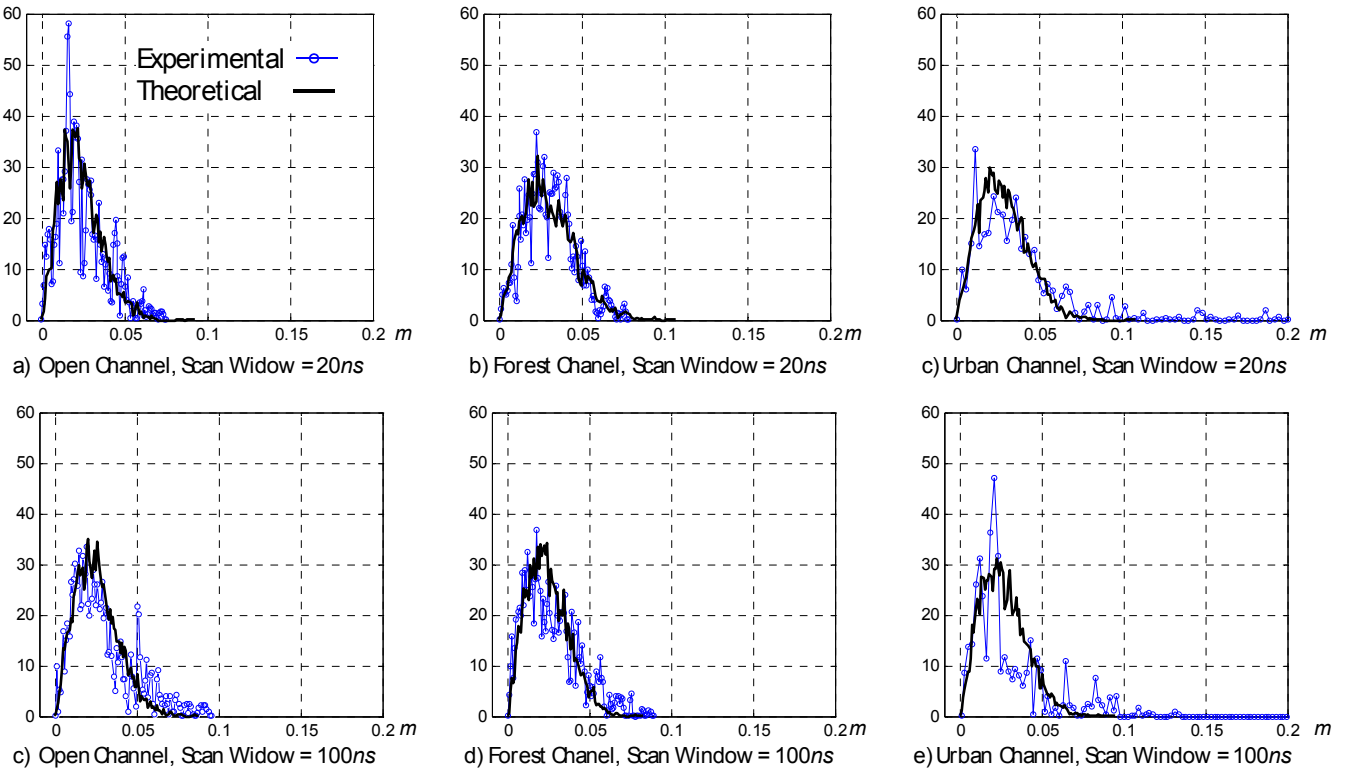


Figure 12 Distribution of static position errors for open, forest and urban channel and scan window = 20 ns and 100 ns for $20^\circ \leq \theta_1 \leq 90^\circ$ (see online version for colours)

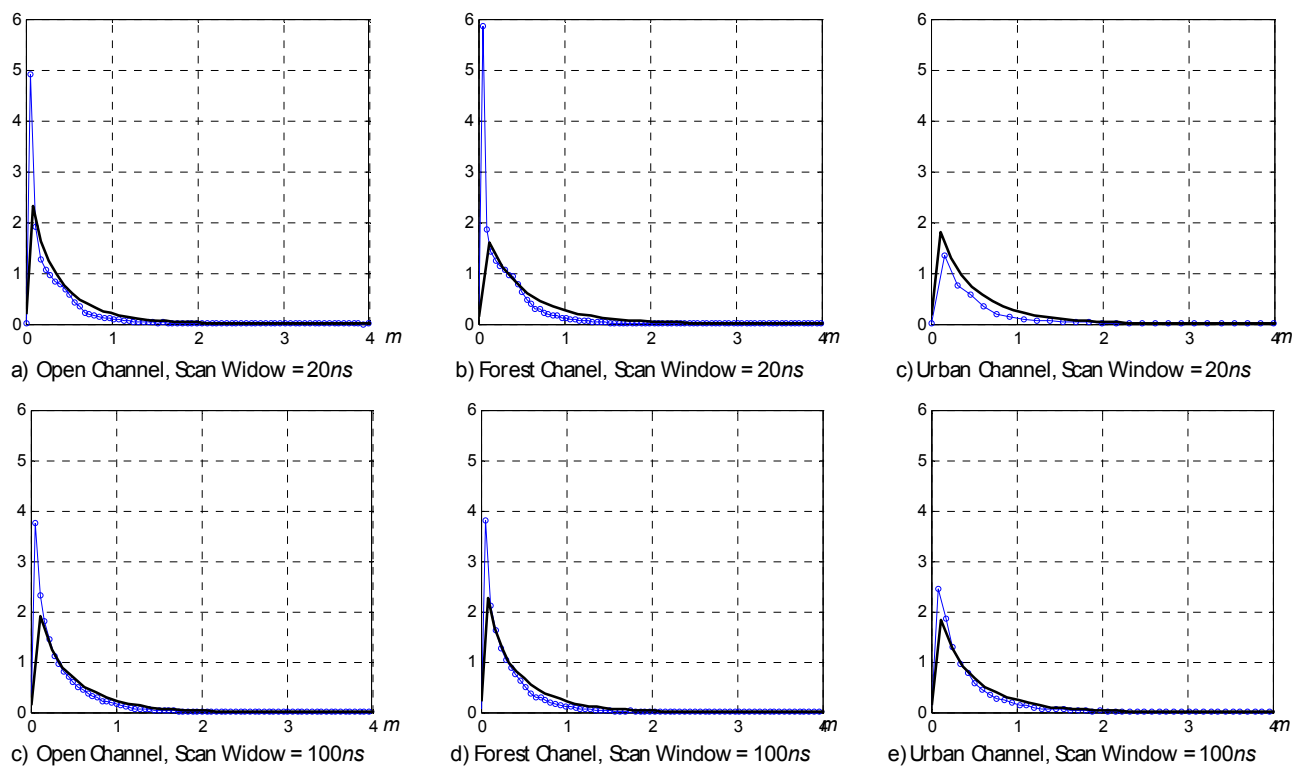


Figure 13 Distribution of position update delays for open, forest and urban channels with 20 ns and 100 ns scan window (see online version for colours)

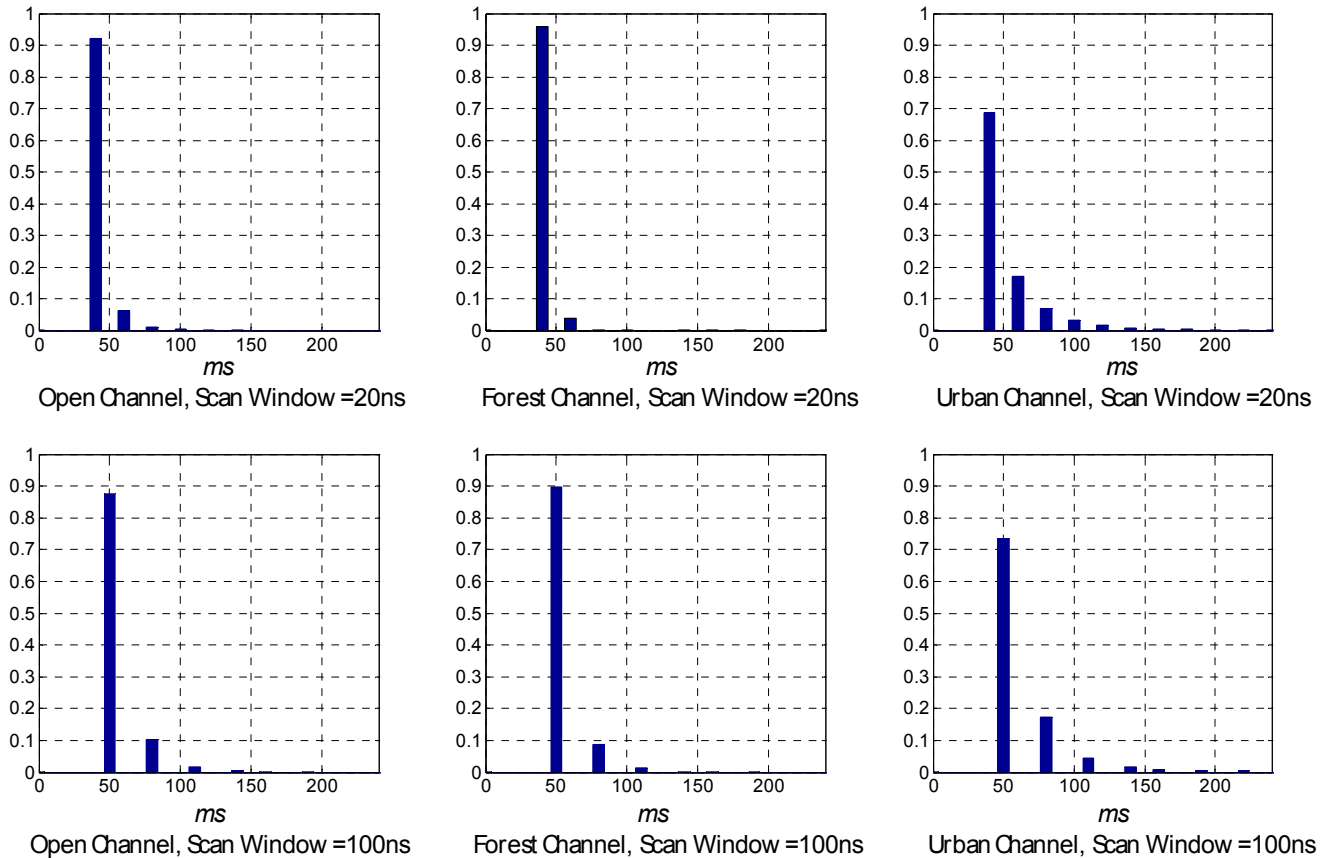


Figure 13 shows the distribution of the position update delays. In cases where two range measurements are needed to determine a position, the update delay is 40.02 ms for the 20 ns scan window setting and 54 ms for the 100 ns setting. Additional delay is caused by the need for additional range measurements, due to dropped packets or range outliers. For both settings in the open and forest channel, about 90% of the position updates require only two ranges. In this case, the 20 ns scan window setting provides an advantage of almost 14 ms in update delay. In the urban channel, only 70% of the position updates are completed in the minimal time. A little less than 20% of position updates require one additional range, which increases the delay advantage of the 20 ns scan window to 21 ms. In the worst case, position measurement required seven additional range measurements for both settings. For the 20 ns scan window setting this leads to a position update delay of approximately 180 ms and for the 100 ns setting, the update delay is 243 ms.

Table 5 shows the mean and standard deviation for position updates, which includes lost range packets due to drops or large errors. The 20 ns scan window has a clear advantage over the 100 ns scan window in terms of position update rate in

5 Summary and future work

This effort reports on the experimental range error characteristics for an outdoor UWB positioning system. A measurement campaign collected range data in open, forested and urban channels from distances of 2 m to 40 m. The range error characteristics were determined and from the results, we propose a Gaussian distribution for a range error model.

Position measurements determined from the experimental data and theoretical range error model show close correlation in the case where DOP is minimised ($\theta_b = 90^\circ$ and $\theta_2 = 45^\circ$) and in the more general case ($2\text{ m} \leq r_1 \leq 40\text{ m}$ and $20^\circ \leq \theta_2 \leq 90^\circ$). This indicates that a Gaussian model for range error is a reasonable choice and effective because of its simplicity.

Performance comparisons of %dropped packets, %outliers and overall position error indicate that range outliers are not a significant factor, even in a dense multipath environment. Thus while the 100 ns scan window has an advantage over the 20 ns scan window, it is not in a significant way. In terms of the more significant issues of dropped packets and accuracy, the performance levels are roughly similar for both settings. On the other hand, for time delay, which becomes critical in the event of a mobile system, the 20 ns scan window has a clear advantage over the parameters using a 100 ns scan window. Thus in the static environment, we can expect accurate position measurements of less than 1 m error with an update rate between 20 Hz and 25 Hz for the 20 ns scan window and between 14 Hz and 17 Hz for the 100 ns scan window and in ongoing efforts, we are analysing performance in more

challenging situations. We are pursuing meaningful study of positioning in a mobile environment with further analysis into delays during range and position measurements and the definition of a mobility model. Another important aspect being investigated is the obstructed channel in an outdoor, mobile channel. The work in this paper prepares the foundation for these further studies.

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