WIRELESS SENSOR POSITIONING WITH ULTRAWIDEBAND FINGERPRINTING

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(*Invited Paper*)

Keywords: Localization, positioning, RF fingerprinting, ultrawideband (UWB).

Abstract

Ultrawideband (UWB) systems offer high spatiotemporal resolution and are therefore well suited to sensor localization applications. In this paper, we consider the use of UWB signals for positioning and ranging based on fingerprinting using a channel impulse response database. We use indoor measurements to demonstrate the reduction in the location estimation ambiguity and false alarm probability with an increase in the channel bandwidth.

1 Introduction

Accurate positioning is one of the major requirements for the next generation of wireless communications systems and sensor networks. Recently enacted regulations in the US and Europe now require cellular service providers to determine and report the location of a mobile transmitter in order to deal with emergency situations [1, 2]. There is also considerable interest in sensor localization by the military, since it can be useful for asset and personnel tracking, and covert communications. Finally, location-based billing, mobile yellow pages and intelligent transport systems are some of the major commercial applications.

Position estimation with the satellite-based Global Positioning System (GPS) is highly accurate in many situations, but suffers severe degradation when the receiver is in an urban canyon or an indoor environment. Ground-based stations use the received signal strength (RSS), time-of-arrival (TOA), time-difference-of-arrival (TDOA) or angle-of-arrival (AOA) for location estimation that usually involves triangulation [3]. These approaches are highly sensitive to the availability of line-of-sight (LOS), with positively biased range estimates in non-LOS (NLOS) situations. Multipath propagation also causes gross positioning errors, due to which systems with large bandwidth, and consequently fine multipath resolution capability, yield better performance [4, 5]. Furthermore, the geometric dilution of precision (GDOP) of many positioning techniques is small only when the positioning stations are mutually far apart, increasing significantly if they are spatially proximal.

RF fingerprinting is an alternative technique for location estimation [3, 6]. It consists of two steps: (1) *a priori* construction of a map relating various points in space to a given propagation parameter, and (2) run-time estimation of that parameter from the received signal and its correlation with the stored database. This signal parameter that acts as a unique location signature may, for example, be the RSS or the angular delay profile (ADP). The channel impulse response (CIR) may also be used for this purpose [7, 8], leading to greater accuracy than time-based approaches in urban but not suburban environments [9]. Compared to GSM systems, the accuracy of RF fingerprinting improves with UMTS due to its increased bandwidth and time resolution [9]. Further improvements can be obtained with adaptive approaches such as neural network training [10] or Kalman filtering [11] to increase the robustness. Fig. 1 illustrates the concept of sensor position estimation with fingerprinting and database correlation based on the spatio-temporal impulse response of the propagation channel.

CIR-based fingerprinting offers a potentially robust solution to some of the problems faced by the other positioning techniques. LOS blockage and dense multipath do not deteriorate its accuracy, which actually increases with greater scattering. On this basis, this technique is especially suited to indoor environments with dense, three-dimensional multipath propagation. As it does not involve triangulation or AOA estimation, the requirement for distributed or collocated antenna systems is also obviated. It performs better in wideband channels than in narrowband channels [9], and therefore may be a good choice for sensor localization using ultrawideband (UWB) technology [12, 13]. On the flip side, however, the construction of a high-resolution map based on measurements is a very time-consuming process and is feasible only in small regions with easy access. Also, the map is only valid for a radio propagation environment where the main features of the CIR, dependent on the dominant scattering centers, remain stationary, a condition that can be fulfilled by large buildings in outdoor environments, or walls and large objects in indoor channels.

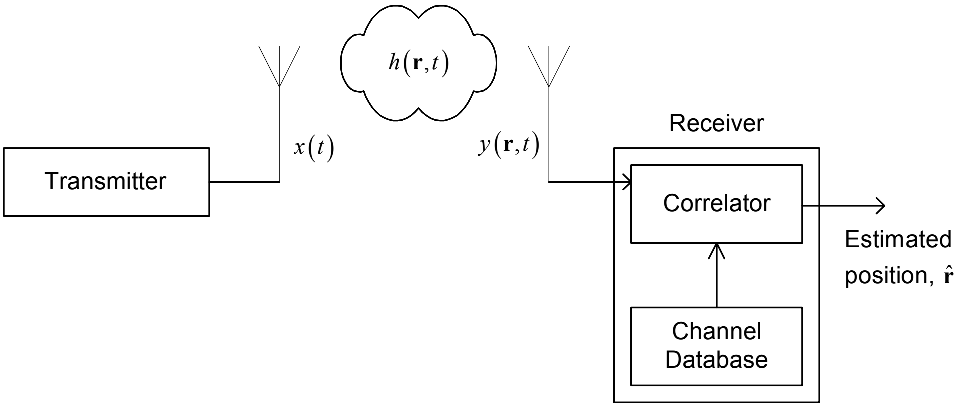


Fig. 1. Schematic representation of location fingerprinting based on database correlation.

In this paper, we investigate the use of UWB signals for sensor location fingerprinting in an indoor environment using CIR measurements. Of particular interest is the impact of LOS presence and channel bandwidth, which we consider in detail in our analysis. The rest of this paper is organized as follows. Sec. 2 gives an overview of the principle of wideband RF fingerprinting, Sec. 3. describes the indoor channel response measurement procedure used in the analysis in this paper, Sec. 4 discusses the key results from this analysis, and Sec. 5 summarizes the main conclusions.

2 RF Fingerprinting

We now present an analytical framework for location estimation using fingerprinting based on wideband radio signals. Let us consider a wideband wireless communications system operating in a frequency selective channel. The received signal is given in the general form by the expression

$$y(\mathbf{r},t)=\sqrt{E_x}h(\mathbf{r},t)*x(t)+z(t), \tag{1}$$

where $\mathbf{r}$ is the receiver location, $x(t)$ is the transmitted signal, E_x is the transmit signal energy, $z(t)$ is the additive white Gaussian noise, $h(\mathbf{r},t)$ is the spatio-temporal impulse response of the channel, and $*$ denotes convolution. Under the tapped delay line channel model, we can write

$$h(\mathbf{r},t)=\sum_{l=0}^{L_{\mathbf{r}}-1}\alpha_{\mathbf{r},l}e^{j\phi_{\mathbf{r},l}}\delta\left(t-t_{\mathbf{r},l}\right), \tag{2}$$

where $\alpha_{\mathbf{r},l}$, $\phi_{\mathbf{r},l}$ and $t_{\mathbf{r},l}$ denote the magnitude response, phase response and excess time delay of the l^{th} multipath component (MPC), and $L_{\mathbf{r}}$ is the number of resolved MPCs in the CIR corresponding to location $\mathbf{r}$.

The principle of RF fingerprinting involves the measurement and storage of $h(\mathbf{r},t)$ for $\mathbf{r}\in\mathcal{R}$, where $\mathcal{R}$ denotes the ensemble of locations in the region of interest. While fingerprinting can be used for volumetric localization, we will restrict our analysis to two spatial dimensions in this paper, so that $\mathbf{r}=\left(r_x,r_y\right)$ represents a point in the horizontal plane. When a pre-recorded CIR database is available, an estimate, $\hat{\mathbf{r}}_0$, of the true instantaneous position, $\mathbf{r}_0$, of a mobile can be obtained using the corresponding instantaneous estimated CIR, $h(\hat{\mathbf{r}}_0,t)$. Here we do not assume perfect channel estimation and allow for imperfections due to noise, unresolved multipath, interference, or synchronization errors. The position estimation problem can then be formulated as the maximization of the CIR cross-correlation coefficient, i.e.,

$$\hat{\mathbf{r}}_0=\arg\max_{\mathbf{r}\in\mathcal{R}}\left|R_{\mathbf{r}}^{m,n}\right|. \tag{3}$$

For $m=h(\mathbf{r},t)$ and $n=h(\hat{\mathbf{r}}_0,t)$, the complex correlation coefficient, $R_{\mathbf{r}}^{m,n}$, is the channel spatial correlation defined as

$$R_{\mathbf{r}}^{m,n}=\frac{\mathcal{E}\{m\bar{n}\}-\mathcal{E}\{m\}\mathcal{E}\{\bar{n}\}}{\sqrt{\left(\mathcal{E}\left\{|m|^2\right\}-\left|\mathcal{E}\{m\}\right|^2\right)\left(\mathcal{E}\left\{|n|^2\right\}-\left|\mathcal{E}\{n\}\right|^2\right)}}, \tag{4}$$

where $\bar{u}$ is the complex conjugate of u and $\mathcal{E}\{.\}$ denotes the expectation operator.

From (4), $R_{\mathbf{r}}^{m,n}=1$ corresponds to $\hat{\mathbf{r}}_0=\mathbf{r}_0$, leading to precise localization. The perfect correlation condition is, however, impractical due to imperfections in the channel estimation process at the receiver. A lower correlation threshold, R_{th}, can therefore be used instead, such as $R_{th}=$ 0.9, 0.7, or 0.5. The corresponding region in space is represented by $\hat{\mathcal{R}}\subseteq\mathcal{R}$ such that $\mathbf{r}\in\hat{\mathcal{R}}$ if $R_{\mathbf{r}}^{m,n}\geq R_{th}$ for $\mathbf{r}$ around $\hat{\mathbf{r}}_0$, and the span of $\hat{\mathcal{R}}$ defines the coherence distance, d_c, of the channel. Some sidelobes with varying amplitudes may be present in the spatial correlation function, as is typical for narrowband Rayleigh channels [14]. If the amplitude of any such sidelobe exceeds R_{th}, it may result in severe location estimation errors, and therefore R_{th} should be chosen carefully in accordance with the channel propagation conditions.

Analogous to this time-domain treatment, the frequency-domain channel transfer functions (CTFs) can also be used for fingerprinting. If $U = \mathcal{F}\{u\}$ denotes the discrete Fourier transform operation, then we can rewrite (4) as

$$R_{\mathbf{r}}^{m,n} = \mathcal{F}^{-1}\left\{M\bar{N}\right\} \tag{5}$$

where

$$\begin{aligned} M &= H(\mathbf{r}, f) = \mathcal{F}\left\{h(\mathbf{r}, t)\right\} \\ &= \sum_{k=0}^{K-1} a_{\mathbf{r},k} e^{j\theta_{\mathbf{r},k}} \delta(f - k\Delta f) \end{aligned} \tag{6}$$

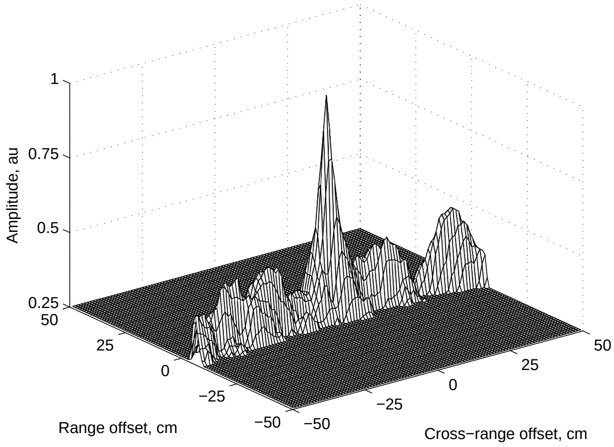
and $N = H(\hat{\mathbf{r}}_0, f)$ is defined similarly. In (6), $\alpha_{\mathbf{r},k}$ and $\theta_{\mathbf{r},k}$ denote the amplitude and phase of the k^{th} frequency component. For a channel with bandwidth W sampled at K frequency points, the frequency resolution is $\Delta f = W/(K-1)$.

3 Analysis Methodology

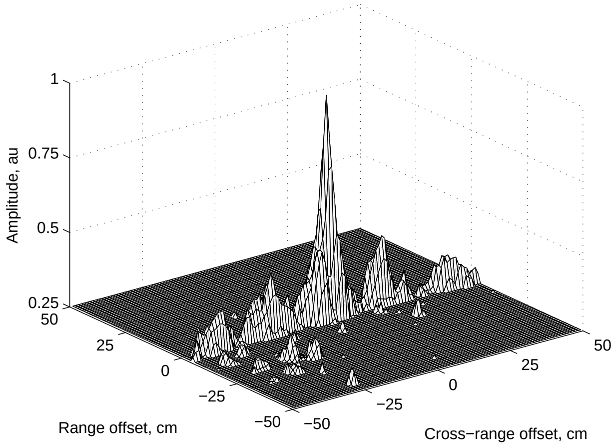
We conduct indoor channel measurements in a number of small office environments to evaluate the positioning ability of UWB fingerprinting. The measurements are in the FCC-allocated UWB band between frequencies f_l = 3.1 GHz and f_h = 10.6 GHz, with $K = W/\Delta f + 1 = 1601$ discrete frequency samples over the $W = (f_h - f_l)/2 = 7.5$ GHz bandwidth. A vector network analyzer is used to obtain the CTF, $H(\mathbf{r}, f)$, from the $S_{21}(f)$ measurement. LOS and NLOS channel datasets are obtained in multiple rooms, each comprising of the CTFs measured in a local region using a rectangular grid positioner spanning 1 m × 1 m with 0.01 m resolution. For each dataset, the transmitter is fixed at one location while the receiver is translated horizontally using the positioner. Discone antennas are used for omnidirectional transmission and reception. From each measured $H(\mathbf{r}, f)$, we obtain the corresponding reduced-bandwidth CTFs, $H_b(\mathbf{r}, f)$, with bandwidth W_b, using ideal bandpass filters centred at f_c, such that $H_b(\mathbf{r}, f) = H(\mathbf{r}, f)$ if $|f - f_c| \le W_b/2$, and 0 otherwise, where $f_c = (f_l + f_h)/2 = 6.85$ GHz is maintained in each case. The number of frequency points, K, is kept constant for fair comparison by zero-padding the discretized CTFs in the interval $W_b/2 < |f - f_c| \le W_b$, similar to [15]. Further details of the channel measurement procedure, the propagation environment, and basic data processing can be found in [15].

4 Results

The measurement-based analysis of fingerprinting with UWB signals demonstrates the effectiveness of this technique. We find from the complex spatial correlation magnitude, $\left|R_{\mathbf{r}}^{m,n}\right|$, in Fig. 2 that in the 7.5 GHz wide UWB channel, there is little probability of false position estimation if the correlation threshold is chosen carefully. From our analysis, a small number of false matches may occur at R_{th} = 0.5 for some CIRs due to the correlation sidelobes, but R_{th} = 0.7 provides more reliable results. Significant sidelobes, which decay with distance, are observed only along the cross-range direction, indicating that the propagation is not perfectly isotropic. The comparison of Figs. 2(a) and (b) reveals that the positioning accuracy is higher and the incidence of false a alarm lower in NLOS than in LOS, due to the more pronounced sidelobes in the latter, establishing that the performance of UWB fingerprinting improves under increased scattering. The position ambiguity region has a radius of approximately 2 cm with R_{th} = 0.5. This accuracy is comparable to that obtained from TOA-based UWB positioning with triangulation in [5].



(a) Line-of-sight environment



(b) Non-line-of-sight environment

Fig. 2. An estimate of fingerprint ambiguity in terms of the channel impulse response spatial correlation for a 7.5 GHz wide UWB channel. The true sensor location is $\mathbf{r_0}$ = (0,0).

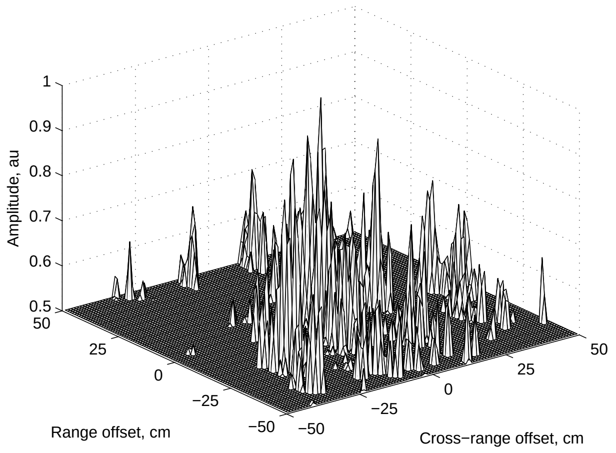
Fig. 3 depicts the correlation magnitudes in the NLOS channel for various values of the channel bandwidth, W_b. It is found that the localization accuracy depends significantly on W_b. As W_b increases, the robustness of the correlation measure also increases, with fewer false estimates appearing above the appropriately selected correlation threshold at very large bandwidth. We also find that at low W_b, the correlation threshold must be increased to a value approaching unity in order to reduce the occurrence of false position estimates. A consequence of this observation is that the conditions on channel estimation quality can be relaxed when the bandwidth is large, leading to reduced requirements for the associated hardware complexity. The width of the correlation function mainlobe does not appear to vary substantially with W_b, and the main contribution of increasing bandwidth is thus the improved discrimination from distant locations.

We now investigate the dependence of correlation on channel bandwidth in further detail by examining the spatial correlation function at various values of W_b. The mean correlation behavior is analyzed along the range and cross-range directions separately. In this analysis, the cross-range correlation, $R_x^{m,n}$, is obtained as a function of the cross-range offset, r_x, for a given set of fixed-range CIRs using (4) with $m = h(\mathbf{r}_x, t)$ and $n = h(\hat{\mathbf{r}}_{0x}, t)$, where $\hat{\mathbf{r}}_{0x}$ denotes the estimate of the true position. We then average this correlation function over the range, y, to obtain $\bar{R}_x^{m,n} = \mathcal{E}_y\left\{\left|R_x^{m,n}\right|\right\}$. A similar procedure is adopted to evaluate of the mean range correlation, $\bar{R}_y^{m,n}$, and the process is repeated for various W_b.

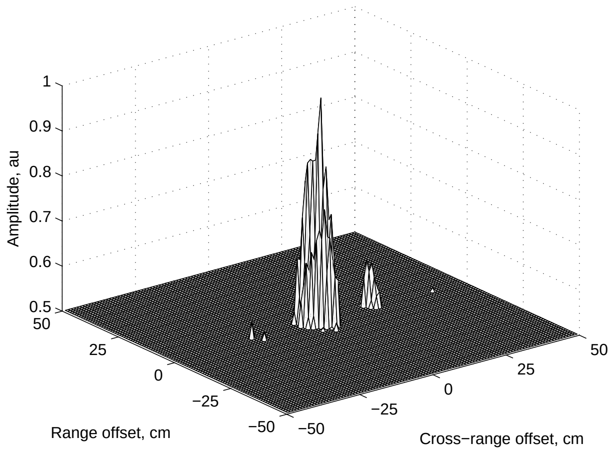
Fig. 4 shows that both the mean range and cross-range correlation sidelobes decay sharply with W_b. The correlation decay is larger in range than in cross-range. The cross-range sidelobes observed in Fig. 3 are most noticeable at low W_b. The mean width of the correlation function mainlobe, which determines the spatial resolution of the sensor position estimate, is also found to be smaller in the range direction than in the cross-range direction. When the correlation threshold is taken as 0.5, this positioning ambiguity region spans approximately $d_r = 4$ cm and $d_x = 6$ cm along the range and cross-range directions, respectively, at the UWB bandwidth ($W_b \geq 500$ MHz), so that the area of the ambiguity ellipse is $\pi d_x d_r / 4 = 18.8\ \text{cm}^2$.

5 Conclusion

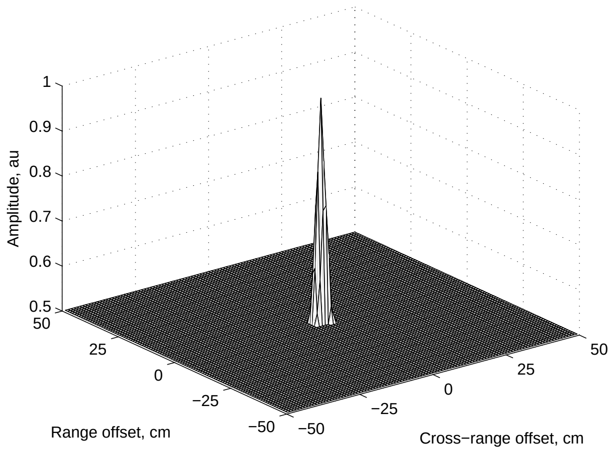
Sensor position estimation with fingerprinting provides a viable alternative to other positioning techniques based on TOA, TDOA and AOA estimation, providing a suitably detailed signature database is available. Its accuracy, achieved with a single antenna, is comparable to the other candidate techniques. It is also robust to harsh propagation conditions such as NLOS channels with dense multipath. Our analysis has shown that the positioning accuracy and reliability obtained with CIR-based fingerprinting is improved substantially with an increase in the signal bandwidth. As accurate position estimation can then be achieved even with relatively low correlation, the UWB channel estimation requirements can be relaxed and system complexity reduced. In conclusion, UWB fingerprinting is well suited to sensor localization applications in static indoor environments.



(a) W_b = 500 MHz



(b) W_b = 2 GHz



(c) W_b = 7.5 GHz

Fig. 3. Fingerprint ambiguity in terms of the channel impulse response spatial correlation for a UWB channel with bandwidth W_b in NLOS. The true sensor location is $\mathbf{r_0} = (0,0)$.

Acknowledgement

This work was supported by the Engineering and Physical Sciences Research Council, UK, via Grant GR/T21769/01.

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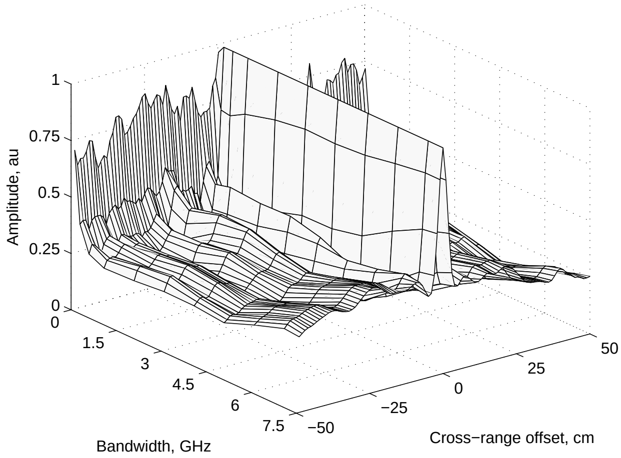
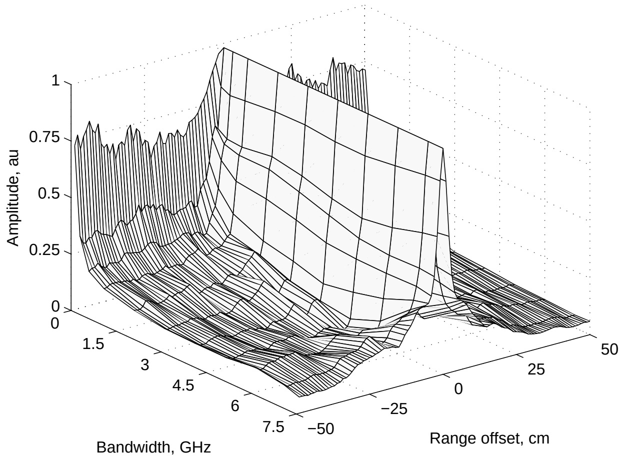


(a) Cross-range direction



(b) Range direction

Fig. 4. The variation of fingerprint ambiguity with channel bandwidth, in terms of the UWB channel impulse response spatial correlation, along cross-range and range directions in NLOS. The true sensor location is at offset 0.