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UWB Ranging Based on Partial Received Sub-Band Signals in Dense Multipath Environments

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***Abstract*— In this paper, an Ultra-Wideband (UWB) receiver scheme with very low sampling rate is proposed for ranging in indoor multipath environments. The idea underlying the proposed scheme is that, instead of processing the whole UWB band, only partial sub-bands are considered at the receiver. The missing sub-bands are estimated by exploiting an estimate of the frequency correlation properties of the channel to reconstruct the signal over the whole UWB band. For the simulations, the IEEE UWB channel model is used and the range error using the proposed receiver scheme is obtained and compared to that of conventional UWB receivers which require very high sampling rates. Furthermore, a large number of UWB channel measurements in an office environment has been used to validate the accuracy of the obtained results. These results show that the range accuracy strongly depends on the number of received sub-bands and the spacing between them. For instance, using 1% of the total UWB bandwidth, an average range error of less than 10 cm is obtained. Furthermore, unlike conventional UWB receivers, the proposed technique performs better (in terms of range error) for low signal-to-noise ratios.**

I. Introduction

Positioning information in indoor environments is becoming more important and attractive especially for wireless ad-hoc networks and location based services, logistics and emergency management. One of the main issues in positioning is how to achieve a good range estimation. Usually, the required range accuracy depends on the application and can range from a few centimeters to meters.

Current positioning systems, such as GPS, or future systems, like the European GALILEO, may not be available or do not have sufficient accuracy in specific areas where these future applications will operate, e.g. in city-centers and indoor locations. The poor performance of satellite systems in supporting those applications is mainly caused by attenuation due to signal blocking and/or multipath signals which cause distortion of the direct signal path. The primary reason of performance degradation is not the presence of multipath itself but the fact that multipath cannot be resolved due to the (relatively) small signal bandwidth used by current positioning systems.

UWB radio seems to be a favorable solution for achieving a high accuracy [1]–[6]. Clearly, the huge bandwidth available for UWB systems allows a fine time resolution of the received multipath signal. Accordingly, it is possible to reach accurate range estimation when TOA/TDOA (Time Of Arrival/Time Difference Of Arrival) techniques are used to detect the first path of the received signal [7]. However, the implementation of the receiver remains challenging since usually very high sampling rates and processing power are required. To make the system feasible, a trade-off between receiver complexity and range accuracy has to be addressed regarding the system design.

The aim of this paper is to propose a new receiver scheme to reduce the sampling rate needed to acquire the UWB signal which also allows the use of commercialized ADCs (Analogue-to-Digital Converters). This is done by processing only partial sub-bands of the whole UWB band at the receiver. The basic idea of the proposed technique renders itself from sampling theory which is further elaborated in this work. While in this paper TOA or range is important, the proposed receiver can also be used for data transmission with lower complexity. It should be noted at this juncture that the proposed method can be utilized for both UWB technologies (i.e. Impulse Radio and MB-OFDM). The paper is organized as follows. In section II, we describe the UWB receiver scheme, point out some advantages of this approach and related implementation issues, and propose the estimation method used for the missing sub-bands. In section III the proposed receiver is applied to ranging and important parameters with respect to the range accuracy are discussed and evaluated. In section IV, UWB channel measurements are used to validate the accuracy of the proposed technique. Finally, in section V conclusions are provided.

II. Proposed receiver scheme

A. Description and Implementation

Although the huge bandwidth of UWB allows for high data rate communication and accurate positioning applications, it requires high sampling rates. This may put some limitations/constraints regarding the receiver design especially for the ADC. Here, we propose a new receiver scheme for ranging applications which requires only a moderate sampling rate. In the proposed technique the whole UWB band is divided into sub-bands and only a number of these sub-bands is used for processing at the receiver. In this method, using the received sub-bands and some limited a priori "statistical" knowledge of the UWB channel, the whole UWB signal is reconstructed. Besides the reduction of the high sampling rate, this scheme may provide several advantages with respect to actual UWB receivers. Since UWB systems operate over extremely wide frequency bands, they have to coexist with other narrow-band systems which may operate with much higher power levels. This may completely jam the UWB signals [8]. Therefore, the introduced scheme can avoid narrow-band interference by skipping (i.e. not measuring) the frequency bands with narrow-band interference. It means that only measurements over the sub-bands outside the interfered band need to be performed and of course, the missing information associated to these bands should be predicted separately. While the implementation and complexity of the proposed technique is not the focus of this paper, below we shortly discuss some implementation aspects of the technique.

In this work, two receiver architectures are proposed according to the complexity, cost and power consumption of the ADCs. The first one is depicted in Fig. 1(a) and consists of a bank of parallel narrow-band bandpass filters, low frequency oscillators (LFOs) and ADCs. The local oscillator before the bank allows us to use LFOs which are low power consuming and easy to design. Concerning the antenna, since only narrow-band signals are received, the UWB receiving antenna may consist of different narrow-band antennas which are easy to design and implement. The parallel structure is investigated for a broadband multi-carrier communication receiver in [9], [10] and it has been shown that it can give a better performance when compared to the conventional UWB receiver structure with a high sampling rate. Here we expect much more complexity reduction compared to [9] as we only use partial branches. A further improvement of the receiver scheme is depicted in Fig. 1(b) in which only a single ADC is used. The required sampling rate of the ADC is $f_s = 2N_c b$ (b is the width of each sub-band and N_c is the number of received sub-bands.) which is much lower than that needed for the full UWB signal (e.g. at least 1 Gsample/s for a UWB signal of 500 MHz). The number of oscillators can be reduced in two ways. The first one is to use a voltage-controlled oscillator (VCO) and hence N_c transmissions are needed to measure all sub-bands. The second solution is to use a harmonic oscillator which allows bandwidth compression as illustrated in Fig. 2. A simple example of a harmonic oscillator is a step recovery diode or Schottky diode. In Fig. 1(b) it is assumed that the filters are ideal which is not the case in practice. Filters with stepwise slopes are hard to make and costly. Thus, to avoid this constraint we can design a simpler filter by adding a guard interval between the compressed sub-bands as shown in Fig. 3. Another solution is to use the filtering effect of the antenna (i.e. the antenna acts as a filter).

B. Cramer-Rao Lower Bound (CRB)

As already mentioned, the proposed technique is used for ranging in indoor environments. In order to have a clear idea of the range error in case of using the proposed approach, the CRB is determined. The lower limit for the delay estimation error variance $\sigma^2_{\hat{\tau}}$ in the presence of AWGN is given by the

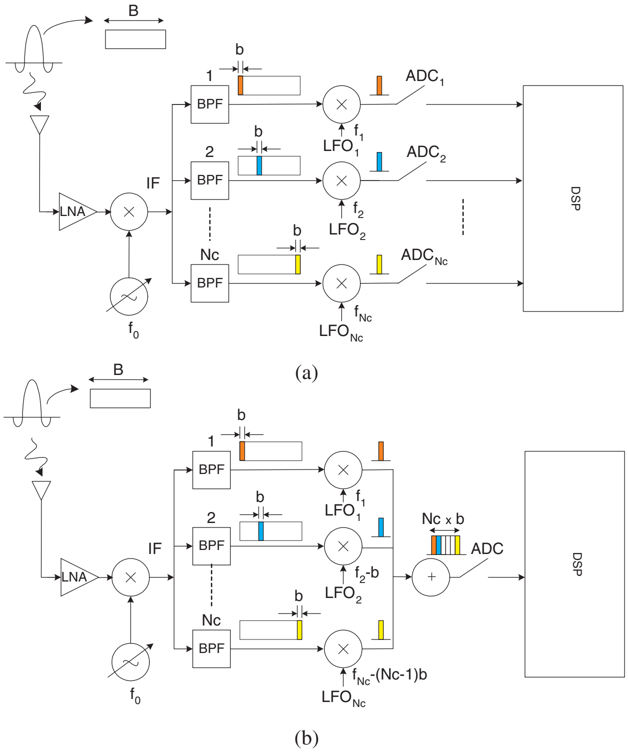


Fig. 1. Proposed receiver scheme based on a) several ADCs b) one ADC. The parameter b is the width of each sub-band, B is the bandwidth of the UWB signal and N_c is the number of received sub-bands.

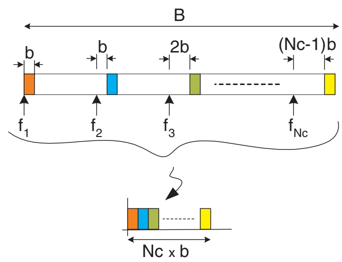


Fig. 2. Illustration of the compression effect using an oscillator with different harmonics.

following CRB [11]:

$$\sigma^2_{\hat{\tau}} = \frac{N_0}{2\int_{-\infty}^{+\infty}(2\pi f)^2|P(f)|^2 df} \tag{1}$$

where f is the frequency, and $|P(f)|^2$ and N_0 are the power spectral density (PSD) of the transmitted signal and noise, respectively. Let's assume a UWB signal with a flat spectrum expressed as:

$$|P(f)|^2 = \begin{cases} K & \text{if } f \in [f_L, f_H] \cup [-f_H, -f_L] \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

where K is a constant and f_L and f_H are the lower and higher frequencies of the UWB signal, respectively. Then, (1) can be written as:

$$\sigma^2_{\hat{\tau}} = \frac{N_0}{16\pi^2 K \int_0^{+\infty} f^2 df} = \frac{N_0}{\frac{16\pi^2 K}{3}(f_H^3 - f_L^3)}$$

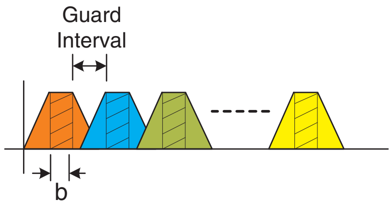


Fig. 3. Guard interval for the filters.

For the case of partial sub-bands (1) can be written as:

$$\sigma^2_{\hat{\tau}_c} = \frac{N_0}{16\pi^2 K \left[\sum_{i=1}^{N_c} \int_{f_L+\Delta f_i}^{f_L+\Delta f_i+b} f^2 df\right]} \quad (3)$$

where Δf_i is the frequency spacing between the first sub-band and the i^{th} sub-band with $\Delta f_i < \Delta f_{i+1}$. Let's assume that the total UWB bandwidth B is divided into N sub-bands each having a width of b. For a good understanding of the method, the concept of percentage bandwidth $B_{\%}$ is introduced. This parameter gives the percentage of used bandwidth in the available UWB band:

$$B_{\%} = \frac{N_c}{N} 100\% \quad (4)$$

where N_c is the number of considered received sub-bands. Table I compares the CRB of the proposed approach for different percentage bandwidths. It can be concluded that the error using the proposed approach increases when the $B_{\%}$ decreases. In order to reduce the complexity of the approach and hence use a smaller number of sub-bands while having a good error performance, an estimation of the UWB signal over its whole spectrum is needed. In the next section, the estimation method for the missing sub-bands is discussed.

TABLE I

THE CRB AS A FUNCTION OF THE PERCENTAGE BANDWIDTH (HERE IT IS ASSUMED THAT $B = 500$ MHZ, $f_L = 3.1$ GHZ, $b = 1$ MHZ AND THE RECEIVED SUB-BANDS ARE UNIFORMLY DISTRIBUTED WITH THE FIRST AND LAST SUB-BANDS ALWAYS AVAILABLE.

$B_{\%}$	1%	5%	10%	50%
N_c	5	25	50	250
$\sigma^2_{\hat{\tau}_c}/\sigma^2_{\hat{\tau}}$	100	20	10	2

C. UWB Received Signal Estimation

As stated before, in the proposed approach the UWB band is divided into small portions (sub-bands), and only a small number of these sub-bands is received. Now, the main issue regarding the receiver scheme is how to estimate the missing information associated to the not-received sub-bands. Here we make use of the correlation properties of the channel between all sub-bands. It turns out that based on the knowledge of the received sub-band at a particular frequency f_0, and incorporating the correlation with an other sub-band at frequency f_i, the received sub-band at frequency f_i can be predicted.

Let's assume that $\mathbf{h}_{f_0}$ and $\mathbf{h}_{f_i}$ are the frequency responses of the received and not-received sub-bands, respectively. Then the missing sub-bands at f_i can be estimated as:

$$\hat{\mathbf{h}}_{f_i} = \mathbf{W}^*\mathbf{h}_{f_0} \quad (5)$$

where $\mathbf{W}$ is the linear filter that has to be designed, $(^*)$ denotes the Hermitian transpose. In the following, vectors and matrices are represented with boldface small and capital letters, respectively. It should be noted that the estimation of the missing sub-band channels can be performed in the time-domain or frequency-domain. In this work, the estimation is done in the frequency-domain and hence the estimated channel impulse response can be obtained using the IFFT. Our objective is now to minimize the error in the estimation of $\mathbf{h}_{f_i}$. A widely used method is the Minimum Mean Square Error (MMSE) cost function:

$$J(\mathbf{W}) = E\left\|\mathbf{W}^*\mathbf{h}_{f_0} - \mathbf{h}_{f_i}\right\|^2 \quad (6)$$

where $E\{.\}$ denotes the expected value. Working out (6) we get:

$$\begin{aligned} J(\mathbf{W}) &= E\left\{\|\mathbf{W}^*\mathbf{h}_{f_0} - \mathbf{h}_{f_i}\|^2\right\} \\ &= \mathbf{W}^*\mathbf{R}\mathbf{W} - \mathbf{W}^*\mathbf{Q} - \mathbf{Q}^*\mathbf{W} + \mathbf{P} \end{aligned} \quad (7)$$

where $\mathbf{R}$ and $\mathbf{P}$ are the covariance matrices of the received and not-received sub-bands, respectively, and $\mathbf{Q}$ is the cross-covariance matrix between the received and not-received sub-bands. To minimize this function, we have to compute its derivative with respect to $\mathbf{W}$ and set it to zero. From [12] we have:

$$\nabla(\mathbf{W}^*\mathbf{Q}) = \mathbf{Q}, \;\; \nabla(\mathbf{Q}^*\mathbf{W}) = \mathbf{0}, \;\; \nabla(\mathbf{W}^*\mathbf{R}\mathbf{W}) = \mathbf{R}\mathbf{W} \quad (8)$$

Thus, by differentiating with respect to $\mathbf{W}$ and using (8) we obtain:

$$\nabla J(\mathbf{W}) = \mathbf{R}\mathbf{W} - \mathbf{Q} \quad (9)$$

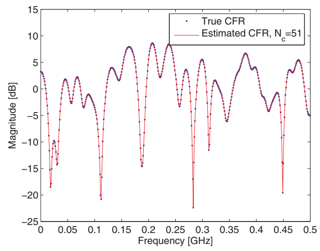
The minimum of $J(\mathbf{W})$ is attained for:

$$\nabla J(\mathbf{W}) = \mathbf{R}\mathbf{W} - \mathbf{Q} = \mathbf{0} \;\; \Rightarrow \;\; \mathbf{W} = \mathbf{R}^{-1}\mathbf{Q} \quad (10)$$

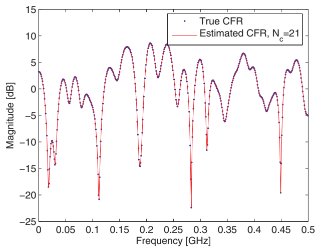
This result is also known as the Wiener filter. According to (10), if the matrices $\mathbf{R}$ and $\mathbf{Q}$ are known, the missing sub-bands can be estimated. The estimation accuracy for the missing sub-bands depends on the accuracy of $\mathbf{R}$ and $\mathbf{Q}$. As these matrices have to be statistically determined, enough measured/simulated data are required.

D. Simulations and Comparison

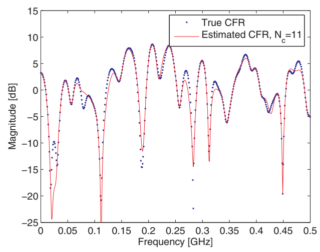
To validate the proposed ranging receiver scheme, the IEEE UWB channel model 802.15.4a is used for the simulations. For each generated UWB channel impulse response, 90% of the total signal energy is considered so that only important multipath components are accounted for. Based on the simulations both matrices $\mathbf{R}$ and $\mathbf{Q}$ are statistically computed, averaged over 10,000 iterations for each environment and saved. Thus, for each specific environment the corresponding $\mathbf{R}$ and $\mathbf{Q}$ are called and used in the estimation process. Then, independent channel impulse responses are generated for further simulations. Without loss of generality, we assumed the IEEE CM4 channel model which stands for NLOS office propagation [13]. The delay spread for CM4 is about 15 ns, i.e. the coherence bandwidth is 10-15 MHz. CM4 is used because it represents a dense NLOS scenario, which is the worst case scenario. A total bandwidth of 500 MHz, which fulfills the UWB definition, is assumed. The width of each sub-band is 500 KHz with a frequency resolution of 100 KHz ($N_s = 5$ samples per sub-band). We also assume that the starting and ending sub-bands are always present. For different percentage bandwidths the sub-bands are assumed to be uniformly distributed along the frequency axis. Fig. 4 shows the generated UWB frequency response and the estimated one for different percentage bandwidths. To quantify how accurate the missing sub-bands are estimated, we define the error ϵ_{h_f} as the *average* of the difference between the whole complex UWB channel frequency response $\mathbf{h}_f$ and its estimate $\hat{\mathbf{h}}_f$.



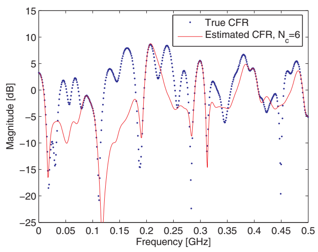
(a) $B_{\%} = 5.1\%$



(b) $B_{\%} = 2.1\%$



(c) $B_{\%} = 1.1\%$



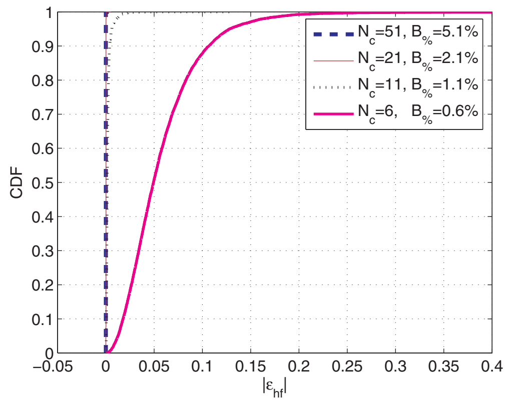
(d) $B_{\%} = 0.6\%$

Fig. 4. Comparison between true and estimated UWB channel frequency response (CFR) for different numbers of received sub-bands.

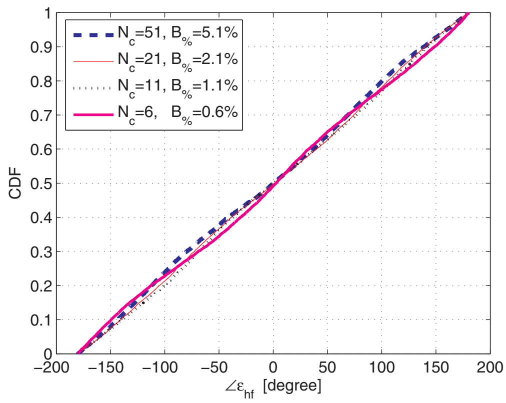
Fig. 5 gives the cumulative distribution function (CDF) of ϵ_{h_f} (i.e. magnitude and phase) for different percentage bandwidths. From this figure it can be concluded that the larger the percentage bandwidth the smaller the error. This can be explained by the fact that when the frequency spacing between the available sub-bands is large the correlation between them reduces (which of course depends on the coherence bandwidth of the channel) and hence the estimation of the UWB channel becomes less accurate.

III. Ranging using the Proposed Receiver Scheme

In this section, the new approach is applied to UWB ranging. Here, only the time of arrival estimation method is used. This method is based on the estimation of the time of



(a) Magnitude



(b) Phase

Fig. 5. CDF of the estimation error using different percentage bandwidths.

arrival of the first path, which is usually assumed as the one corresponding to the direct ray coming from the transmitter. From the travel time the estimated distance $\hat{d}$ can be derived:

$$\hat{d} = c.\hat{\tau} \tag{11}$$

where c is the speed of light and $\hat{\tau}$ is the estimated travel time. To estimate the time of arrival of the first path, a back search algorithm is used. This means that the strongest path is first estimated and then we look back to all paths within a threshold from this maximum. Here we used 15 dB below the maximum. To quantify the use of the proposed approach in UWB ranging applications, we define an estimation error ϵ as the difference between the estimated ranges when a full and partial bandwidth are measured:

$$\epsilon = |\hat{d}_{FB} - \hat{d}_{PB}| \tag{12}$$

where $\hat{d}_{FB}$ and $\hat{d}_{PB}$ are the estimated distances using the full and partial bandwidth, respectively. The same simulation assumptions and procedure as described in section II-D are used. Fig. 6 shows the range error for different percentage bandwidths. It is clear that the range error decreases with increasing the percentage bandwidth. Another important parameter is how many samples are needed to represent one sub-band. This parameter is investigated in Fig. 7. It can be observed that 5 samples per sub-band are enough to get the same performance than when a higher number of samples is used.

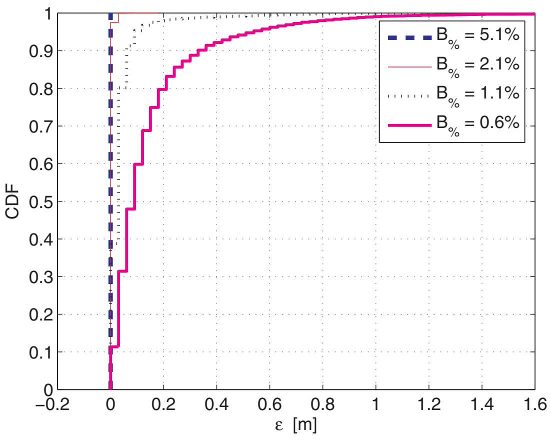


Fig. 6. Range error for different percentage bandwidths.

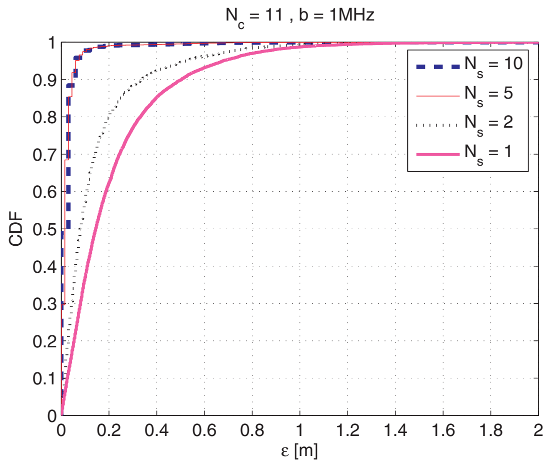


Fig. 7. Effect of the number of samples per sub-band on range error. It should be noted that there is no considerable difference in the results between using a 0.5 or 1 MHz sub-band width because the correlations in an interval of 0.5 or 1 MHz are very similar.

In the following, the effect of the noise on the range error using the proposed receiver scheme is investigated. We define the signal-to-noise ratio (SNR) as follows:

$$SNR = \frac{\|\mathbf{h}_t\|^2}{\|\mathbf{n}_t\|^2} = \frac{P_s}{L\sigma_n^2} \tag{13}$$

where $\mathbf{h}_t$ and $\mathbf{n}_t$ are the channel impulse response and noise, respectively, σ_n^2 is the noise variance, P_s is the signal power and L is the length of the total sequence [1]. It should be noted that the first time of arrival is differently estimated than before. This is because in this case the received signal is corrupted by noise and for low SNR the back search method may not be valid as only noise will be detected. Therefore, we have used another method based on noise estimation. Clearly, we first estimate the variance of the noise by using the first signal part (noise only). Then we set the threshold level at $4\sigma_n$. The first path which appears above this threshold level is assumed to be the direct path. Here, we first estimate the distance using the full band noiseless channel impulse response and then compare it to the estimated one corrupted by noise for both full band and partial band, as e_{snr} in Fig. 8. From this figure it can be concluded that the range error decreases with SNR and is higher for the case when the full UWB band is used. It can also be observed that for small SNR the range error decreases with decreasing the number of available sub-bands. This is because of noise filtering of the missing sub-bands. However, for high SNR the range error decreases with increasing number of available sub-bands. This is because with the considered coherence bandwidth the correlation between the received and estimated sub-bands is high. Furthermore, it is interesting to note that the proposed scheme is more robust against noise and this can be illustrated when the SNR is 0 dB.

[1]This definition for SNR depends on the length of the signal sequence. However, this seems not to be a problem as the same definition is kept for the same simulation and also because we are interested in the difference in the range results.

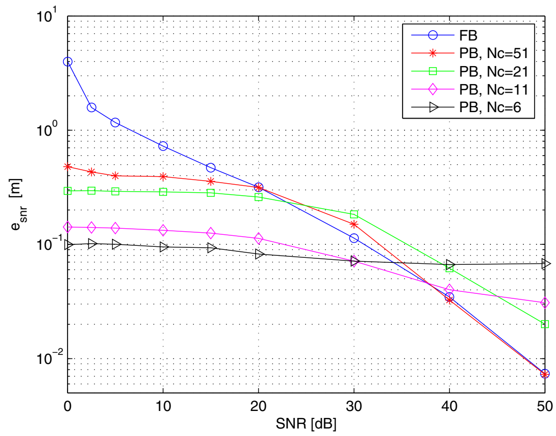


Fig. 8. Effect of SNR on range error for different percentage bandwidths (FB: full band, PB: partial band).

IV. Measurement Campaign and Validation

In order to validate the proposed approach, a set of UWB channel impulse response measurements has been performed at different distances using a time domain technique. The generator fires a Gaussian-like pulse with a duration of 50 ps, allowing measurements in the bandwidth of 0.1-12 GHz. More details on the setup and its operation can be found in [14]. The received signal is sampled at a rate of 1 sample per 10 ps. An acquisition time window of 85 ns is used. The measured signal is then transferred to a PC where the data is stored for later processing and analysis.

The measurements were carried out in the Electrical Engineering building of Delft University of Technology at different floors. The external walls are made of concrete and the floors of reinforced concrete. Different scenarios are considered for LOS and NLOS situations. A maximum distance of 10 m is measured. In each scenario, the receiver is kept in a fixed position and the position of the transmitter is changed. For each position, 49 local measurements are performed with a spacing of 5 cm, in a grid of 7x7 elements, placed in the vertical plane and perpendicular to the line with the receiver. In total 30 positions (i.e. 12 LOS and 18 NLOS) are recorded which leads to a total of 1470 channel impulse responses. A detailed description of the measurement scenarios can be found in [14].

The matrices **R** and **Q** are first determined based on 20 positions (i.e. 980 measurements including LOS and NLOS and different distances) which are randomly selected. Then, the other 10 positions (i.e. 490 measurements which are not used in the estimation of **R** and **Q**) are used in the estimation process. Here we selected a band of 500 MHz (i.e. 3.1-3.6 GHz). Fig. 9 shows an example of the measured channel impulse response and its estimate for two different locations. The obtained range error is shown in Fig. 10. From this figure, it can be concluded that with using 6 sub-bands, the range error does not exceed 5 cm for a probability of 90%, which validates the results obtained from the simulations and of course the accuracy of the proposed technique.

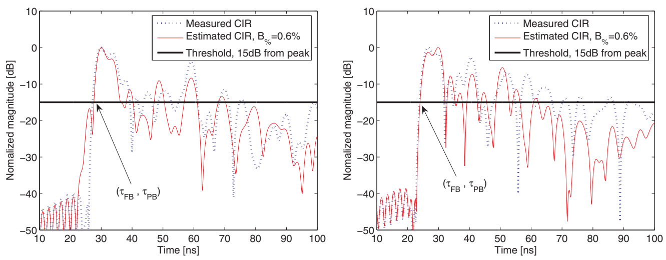


Fig. 9. Example of real measured channel impulse response (CIR) and its estimate using the proposed scheme for different measured positions.

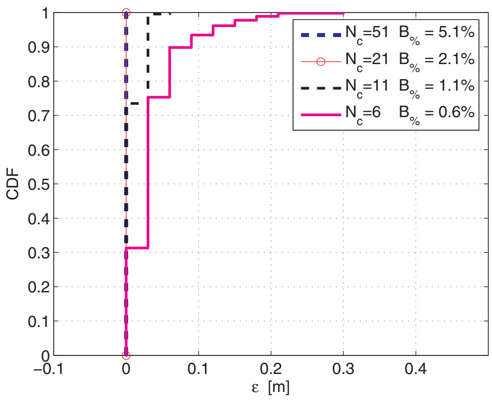


Fig. 10. CDF of range error as a function of $B_{\%}$ using real measured data.

V. Conclusions

In this work, a new UWB receiver scheme for ranging in multipath environments, operating at very low sampling rate, is proposed. The scheme is based on receiving partial sub-bands of the whole UWB band whereas the rest of the band is estimated using the channel correlation properties of the environment. The proposed approach is verified by means of a large set of simulated data using the standard IEEE UWB channel model. Here only the CM4 channel model (i.e. office NLOS) is considered, however, the concept can be applied to all kinds of UWB channel models. The results are collected in terms of range error. It can be concluded that the scheme provides accurate ranging using low sampling rate which makes it easy to use commercial of the shelf ADCs. The range error depends on the percentage bandwidth and the number of samples representing each sub-band. Using a percentage bandwidth of 1%, range errors of less than 10 cm can be obtained. For low SNR, the proposed approach shows a better performance than when the full band is used, and hence a small percentage bandwidth is more appreciated. The reason for this is that at low SNR with lower percentage bandwidth, more noise power is filtered. However, for high SNR the range error decreases with the decrease of percentage bandwidth. This is because at high SNR with more accessible sub-bands, more correlation data is available to estimate the missing sub-bands. Real UWB channel measurements performed in an indoor office environment at different positions confirmed the validity of the proposed technique.

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