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IR UWB TOA Estimation Techniques and Comparison

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ABSTRACT: *In the recent times Impulse Radio-Ultra wide bandwidth (IR-UWB) positioning techniques have been gaining interest especially in agglomerated environments where signals from satellite navigation systems are not reliable. Range measurements required by UWB positioning systems are usually obtained from the time-of-arrival (TOA) estimation of the first path, which could be a challenging task in the presence of multipath and interference. In this paper we discuss various Time of Arrival (TOA) estimation techniques which include De-convolution, Maximum Likelihood (ML) estimation, Pseudo spectrum multiple signal classification (MUSIC) and Two stage estimation algorithms, their performances against different signal to noise(Eb/No) ratios and also their complexities. The performances of the proposed algorithms are investigated via simulations using IEEE 802.15.4a UWB channel model in Line of Sight (LOS) environment.*

KEYWORDS: *UWB, TOA, ML estimation, MUSIC Pseudo spectrum, DE convolution, Two Stage Estimation.*

I. INTRODUCTION:

In the recent times the need for accurate location has been gaining interest.Especially in cluttered environments (inside buildings, in urban areas, tree canopies etc.), where Global Positioning system is inaccessible.The ultra-wide band-width (UWB) technology offers potential for achieving high accuracy in such cluttered environments [1]-[4] . Most positioning techniques are based on, the first path is often not the time-of-arrival (ToA) estimation of the first path [2],[5]-[6]. TOA based position estimation systems measure the distance between transmitter and receiver based on the estimation of propagation delay which is affected by multi path channel and noise. In dense multipath channels, the first path is often not the strongest making the TOA estimation challenging [7]-[8]. The Direction of Arrival is also used for the estimation position The Direction of Arrival (DOA) based positioning technique involve the use of antenna arrays. Due to the large bandwidth of the UWB signal, the number of paths may be very large, especially in indoor environments. Therefore, accurate angle estimation becomes very challenging due to scattering from objects in the environments. Moreover, time-based approaches can provide very precise location estimates, and therefore they are better motivated for UWB.An UWB signal is defined as signal that possess an absolute bandwidth larger than 500Mhz or fractional energy bandwidth about 0.2-0.25 .The short pulse duration of UWB offers a lucrative application which is positon estimation especially indoor positioning. In the following estimation techniques LOS scenario is assumed. In general different measures are used to evaluate a TOA estimation algorithm in wireless channel like noise sensitivity, complexity of the algorithm and priori information.

Many high resolution time delay estimating algorithms have been proposed in order to accurately measure TOA by determining the delay of the first incoming signal path. These techniques can either be performed in time domain or in frequency domain. Energy detection(ED) based estimations are growing popular due to their low complexity implementation at sub-NY Quist sampling rates.The main purpose of our work is to investigate the effects of multipath propagation on ToA estimation using real measurement data by considering different algorithms with different levels of complexity. The trade-off between estimation accuracy, complexity and sensitivity to parameter choice for different propagation conditions is discussed.The outline of this paper is as follows. Section-II introduces the IR UWB signal model. Different estimation techniques like DE convolution, ML correlation, pseudo spectrum MUSIC and Two step coarse-fine estimation techniques are discussed in section III. Numerical analysis and conclusion are discussed in section IV and section V respectively.

II. SYSTEM MODEL:

We consider an IR UWB system where transmission of symbol happens in repeated pulses N_f . The mathematical model for transmitted signal is given as

$$S(t) = \sum_{k=-\infty}^{\infty} \sum_{j=0}^{N_f-1} p\big(t - (kN_j + j)T_f - c_j T_c - b_k T_\delta\big) \qquad (1)$$

p(t) refers to a Gaussian pulse or one of its derivatives with a pulse duration of T_p. Symbol duration $T_{sym}=N_f :T_f$ which is much greater than the pulse duration T_p ,where N_f is number of frames and T_f is frame duration. T_δ is Pulse position Modulation (PPM) interval. N_c is the number of chips per frame c_j which is the time hopping sequence which takes values from {0, N_c-1}. An ideal received wideband signal template with T_p = 0.77 ns is shown in Fig.1.

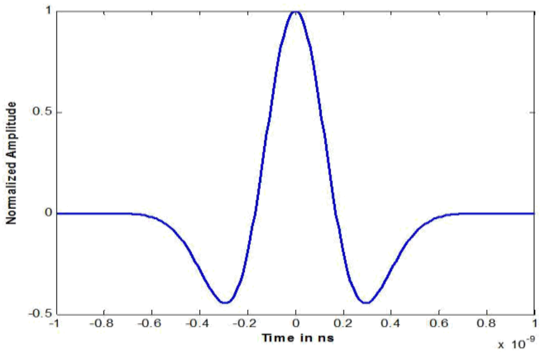

Fig. 1. An ideal UWB pulse template

Mathematical model for the general considered multicluster, multipath fading channel [9] is given by

$$h(t) = \sum_{k=1}^{L} \alpha_k \delta(t - \tau_k) \qquad (2)$$

In the above equation, L represents the number of multipath components, α_k and τ_k are the complex attenuation and propagation delays of the k^{th} path respectively and $\delta(t)$ is the unit impulse response. In general, due to the mobility of the transmitter, the receiver, and objects in the environment, the parameters α_k and τ_k are time varying random variables. A realization of the Amplitude response of IEEE 802.15.4a is shown in Fig.2

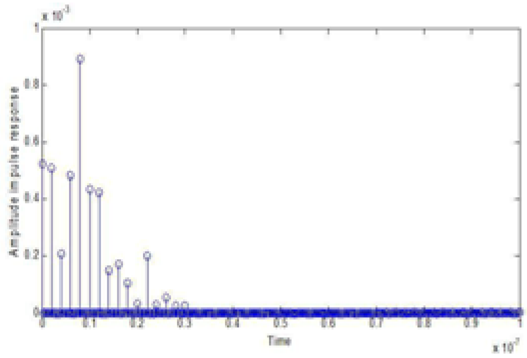

Fig. 2.Amplitude response of the channel.

The multipath affected received signal r(t) consists of superimposition of several attenuated delayed and eventually distorted replicas of a transmitted wave from s(t).When propagation fluctuation with in an observation time T>>T_{sym} and path dependent distortions can be neglected.r(t) can be expressed as follows

$$r(t) = \sum_{k=1}^{L} \alpha_k s(t - \tau_k) + n(t) \qquad (3)$$

Where s(t) is the transmitted signal. L is is the number of multipath components. α_k and τ_k are the complex attenuation and propagation delays of the k^{th} path respectively. n(t) is the Gaussian noise present during the transmission.

III. TOA ESTIMATION TECHNIQUES:

A. Deconcolution : Deconvolution of the time domain waveforms can be used to determine impulse response of Linear Time Invariant (LTI) systems. Deconvolution methods are essentially inverse filters [10]. The received signal r(t) can be represented as a convolution of the transmitted signal and channel impulse response (CIR).

$$r(t) = s(t) * h(t) + n(t) \qquad (4)$$

where n(t) is the additive white Gaussian noise. In the frequency domain convolution transforms into multiplication. So the above equation (4) becomes

$$R(f) = S(f)\, H(f) + N(f) \qquad (5)$$

In the above equation R(f),S(f), H(f) and N(f) are Fourier transforms of r(t), s(t), h(t), n(t) respectively. In ideal conditions we divide R(f) by S(f) to obtain the channel response and estimate the TOA of the first path. The vector form representation of the above equation (5) is R = SH + N

Where $R = [R(1) \ldots\ldots R(N)] \in C^{N}$

$S = dia[S(1) \ldots\ldots S(N)] \in C^{NxN}$

$N = [N(1) \ldots\ldots N(N)] \in C^{N}$

$H = [H(1) \ldots\ldots H(N)] \in C^{N}$

Let Y = $S^{-1}R$ then we have Y = H + W, where W = $S^{-1}N$. One of the adverse effects of inverse filtering is noise enhancement. The following constrained inverse filter provides a better performance against noise

$$H = \frac{1}{1+(\frac{\lambda}{|S|^2})}\frac{R}{S} \qquad (6)$$

where λ *is taken as 50 [11]*

B. ML Estimation: If Gaussian noise is added then ML criterion is equivalent to the minimum mean squared error (MMSE) criterion. Given an observation vector r of the received signal

$$r = S(\tau)\alpha + n \qquad (7)$$

Where $n \in C^{M}$ *with elements* $n_i = n(iT_S)$ *for* $i = 1, 2, \ldots, N$

$r \in C^{M}$ *with elements* $r_i = r(iT_S)$ *for* $i = 1, 2, \ldots, N$

$S(\tau) = \left[S^{(D_1)} \ldots\ldots S^{(D_L)}\right] \in C^{NxL}$

$S^{(D_l)} = \left[0_{D_l} \quad p \quad 0_{N-Z-D_l}\right]^T \in C^{N}$ *for* $l = 1, 2, \ldots\ldots$

$0_{D_l} = [0, \ldots \ldots, 0] \in C^{D_l}$

$0_{N-Z-D_l} = [0, \ldots \ldots, 0] \in C^{N-Z-D_l}$ *where* $p \in C^{Z}$ *with elements* $p_i = p(iT_S)$, *for* $i = 1, 2, \ldots, Z$.

p(t) is the transmitted pulse, Z is the number of sample of the pulse shaper, D_l is the discretized version of time delay τ_l, such that $\tau_l = D_l T_S$, T_S is the sampling time and Nis the number of samples of the received signal.

The ML estimate of the delay vector τ is the value that minimize the following mean squared error

$$M(\tau) = \frac{1}{N}\sum_{i=1}^{N}|r_i - \hat{r}_i|^2 \text{ where } \hat{r}_i = \hat{r}(iT_S) = \sum_{l=1}^{L}\alpha_l S(iT_S - \tau_l)$$

The ML estimate of τ in the continuous-time domain, reformulated in the discrete-time domain, is given by [12]

$$\hat{\tau} = arg_\tau \max \left\{\chi^T(\tau)R_p^{-1}(\tau)\,\chi(\tau)\right\} \qquad (8)$$

Where $\chi(\tau) = S^T(\tau)r$ is the correlation between the received signal and different delayed versions of S(τ) and $R_p = S^T(\tau)\,S(\tau)$ is the auto correlation matrix of S(τ). Hence Eq. (8) can be written as

$$\hat{\tau} = arg_\tau \max \{(S^T(\tau)r)^T(S^T(\tau)\,S(\tau))^{-1}S^T(\tau)r\} \qquad (9)$$

C. MUSIC Pseudo Spectrum Algorithm: The MUSIC algorithm is a typical sub spaced based method. The sub spaced based methods are better than parametric methods like ML algorithm. The MUSIC algorithm is based on Eigen vector decomposition (EVD) of the covariance matrix of received signal. The vector form of the signal in frequency domain is written as

$$R = SH + N \qquad (10)$$

Where R, S, H, N are vector representation of frequency domain of received signal, transmitted signal, channel and noise respectively. From vector form (10) of received signal, if we assume that the auto correlation matrix of the received signal can be obtained as

$$R_{yy} = E[RR^T] \qquad (11)$$

$= SE[HH^T]S^T + \sigma^2 I = SPS^T + \sigma^2 I$, *where P = E[HH] and P is symmetric and positive definite with rank L. Let the number of samples N be larger than the number of paths L, and rank of* SPS^T *will be L. Then from the formulation of received signals and additive noise, we obtain*

$$SPS^T = \sum_{i=1}^{N} \mu_i V_i V_i^T \tag{12}$$

$$\text{and}\ R_{yy} e_i = SPS^T e_i + \sigma^2 e_i \tag{13}$$

where e_i is the eigenvector and associated with corresponding Eigen value λ_i. The Eigen decomposition of auto correlation matrix gives two orthogonal sub spaces known as signal and noise subspace. The principle largest L Eigen values span the signal subspace and the rest span the noise subspace. The Eigen values of the noise sub space $\{\lambda_{L+1}, \ldots\ldots, \lambda_N\}$ are equal to the variance of the noise σ_x^2. Let U_N and U_S be the noise and signal sub spaces respectively, then $U_S = [\{e_1 \ldots e_L\}]$, $U_N = [\{e_{L+1} \ldots e_N\}]$. The MUSIC pseuedospectrum is given by [13]

$$F_{mu}(\tau) = \frac{1}{E(\tau)^H U_N U_N^H E(\tau)} \tag{14}$$

Where $E(\tau) = \begin{bmatrix} 1 & e^{jw_0\tau} \ldots\ldots & e^{jw_0(N-1)\tau} \end{bmatrix}$, $w_0 = \frac{2\pi}{N}$.

The Toa of the first arriving path can be estimated by finding the delay at which pseuedospectrum MUSIC achieve the maximum value.

D. Two Stage Estimation: In two stage estimation first stage is a simple coarse estimation that provides the time reference for the symbol synchronization and estimates the threshold used in Toa estimation algorithm [14]. The two stages estimation process is performed in frequency domain. It is assumed that an all zero training sequence is used for the estimation. The coarse estimation consists of an energy estimator and a simple search algorithm that identifies the beginning of the symbol by applying a minimum distance criterion. In coarse estimation an acquisition time of length equal to the duration of $K_S + 1$ is considered. Minimum acquisition window shall be equivalent to two symbol duration in order to perform the fine estimation over a single symbol $K_S = 1$. The fine TOA estimation $\hat{\tau}_0^c$ and a high resolution time delay $\tilde{\tau}$ estimates of the first arriving path with respect to the time reference obtained in the coarse estimation stage. The TOA estimation resulting from the fine estimation is given by

$$\hat{\tau_0} = \hat{\tau}_0^c + \tilde{\tau} \tag{15}$$

The fine TOA estimator consists of finding the first delay $\tilde{\tau}$ that exceeds the given threshold P_{th} in the power delay profile summed overall direction [15]. P_{th} is assumed based on coarse estimation

$$\tilde{\tau} = \min\arg_{\tau}\left(P(\tau) > P_{th}\right) \tag{16}$$

Where $P(\tau) = E_\tau^H R_{yy} E_r \quad (17)$

The signature vector is represented as $E_r = \begin{bmatrix} 1 & e^{-jw_0\tau} \ldots\ldots & e^{-jw_0(N-1)\tau} \end{bmatrix}$, *where* $w_0 = \frac{2\pi}{N}$.

For more robust estimation R_{yy} *is averaged over* K_S *symbols.*

E. Numerical Results: For numerical evaluation of the above algorithms we consider the channel models developed within the framework of the IEEE 802.15.4a. In particular it is used the CM1 Residential LOS channel model.The pulse p(t) is Gaussian second order derivative with a 3dB bandwidth of 1.3 GHz and a centre frequency f_0 = 4:5GHz according to the European ECC. The pulse repetition period is $T_f = T_{sym}/N_f$ = 128ns.All simulations are given for 100 independent channel realizations.

Simulation Parameters

Parameter	Value
Pulse duration P(t), T_p	0.77 ns
Band Width BW	1.3GHz
Number of frames per symbol, N_f	31
Number of symbols in the acquisition interval, K_S	47 symbols
Symbol duration, T_{sym}	3974.4 ns
Sampling rate, $1/T_S$	3GHz

The remaining parameters are chosen according to the algorithm in consideration.

Fig.3. depicts the normalized root mean square error (RMSE) of the estimated TOA in nanoseconds (ns) of various algorithms against varying snr

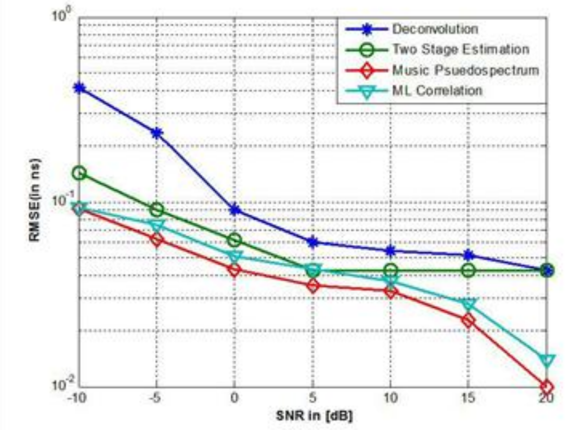

Fig. 3. Error performance of various algorithms as a function of Eb/No in LOS environment.

F. Conclusion: Various TOA estimation techniques for UWB system complaint with 802.15.4a have been presented. It is observed that music psuedospectrum has higher performance due to separating into signal and noise subspaces, the effect of noise is reduced but also this method has high complexity due to matrix Eigen decompositionmaking this algorithm quite difficult to be used in practical applications. Another drawback of this method is that the number of paths L should be known as priori information of channel. ML has the second best performance against noise; no prior information is needed forthe implementation of ML estimation method, but it has high complexity due high sampling rate. Two Stage Estimation has a good performance and also low complexity but is asymptotic at higher SNR in nature due blind resolution. De-convolution is poor against lower SNR another drawback associated with the De-convolution methods is their increased complexity and memory requirements (mainly due to matrix inversions), which increase the implementation cost of this method in a real system. So we can observe a trade-off between complexitiesandaccuracy so far two stage estimation has the best trade-off between accuracy and complexity.

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