Performance Evaluation of a Hybrid TOA/AOA Based IR-UWB Positioning System

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Abstract. In this paper, we evaluate performance of IR-UWB positioning system, which is based on the angle-of-arrival (AOA) and time-of-arrival (TOA) estimation techniques, with different IR-UWB waveforms, such as root raised cosine pulse, 5th order Gaussian mono-pulse, 4th modified Hermite pulse (MHP), and sine-type prolate shperoidal pulse. For ranging performance evaluation, the minimum mean square error (MMSE) technique is employed to resolve the multipath components, and the ranging performance is evaluated with various waveforms. For high precision angle estimation, the multiple signal identification and classification (MUSIC) method is employed. Simulation results show that the MHP pulse outperforms other considered waveforms in a hybrid TOA/AOA based IR-UWB positioning system.

Keywords: TOA, AOA, IR-UWB, MMSE, MUSIC.

1 Introduction

Recently, the high precision ranging techniques become an issue because of its various applications such as enhanced 911, U-health service, context aware service, navigation, high precision robot control and so on. In indoor environment, the time-of-arrival (TOA) and the angle-of-arrival (AOA) techniques are well known schemes for a high precision ranging system. Generally, the TOA based ranging scheme has better accuracy than the AOA based ranging scheme, because the AOA requires line-of-sight (LOS) wireless communication environment. However, the AOA system is more costly effective than the TOA system because the TOA system provides two-dimensional (2-D) positioning information with minimum three base stations (BSs), while the AOA system requires only two BSs. The proposed joint TOA and AOA positioning scheme requires only one BS for 2-D positioning information. By using the proposed hybrid TOA/AOA based IR-UWB positioning scheme, thus, we can precisely estimate the location of target with relatively less costs as compared with the existing methods using minimum three BSs or the estimating cell ID with one MS [1].

The TOA based ranging scheme experiences always multipath problem because of its signal's reflection, extinction, and so on. Once a signal passes multipath channels, a BS receives a combined signal that has many different phases [2]. To estimate more accurate distance, it is required to resolve the multipath channel accurately. In indoor positioning scheme, if ranging guarantees high precision, the performance of a hybrid

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TOA/AOA location scheme is highly trustful. Although the short pulse duration of IR-UWB waveform enables to resolve multipath channels accurately, the performance of ranging system under the condition of different waveforms is not studied enough. Since the IR-UWB waveform influences on the performance of IR-UWB ranging system, the ranging performance is evaluated with various waveforms in this paper. The MMSE are employed to resolve the multipath components for high precision ranging in the considered TOA scheme, while the MUSIC method is employed to measure the angle of target mobile terminal in the considered AOA scheme. The performance of proposed scheme is evaluated through the computer simulation over the channel models produced by IEEE 802.15.4a [3].

2 System Description

A simplified transceiver structure for TOA/AOA based IR-UWB positioning system is shown in Fig.1. The channel impulse response (CIR) can be estimated by applying the inversion or pseudo inversion of the known signal matrix. Then, the estimated channel matrix is applied to the TOA estimation process. Each antenna of antenna array receives an emitted signal with different delays caused distance gap on each antenna and the angle of target is estimated with the AOA scheme.

As mentioned in previous section, a pulse signal experiences multipath channel and a receiver receives an overlapped signal. Fig. 2 shows the comparison of various received signals according to interval of multipath in no noise communication condition. In the figure, we assumed that the pulse width is 2ns and the amplitudes of delayed signals are all the same. As shown in the figure, the multipath components are overlapped except for the Fig. 2-(d). The overlapped signals can cause to increase the error rates in ranging estimation.

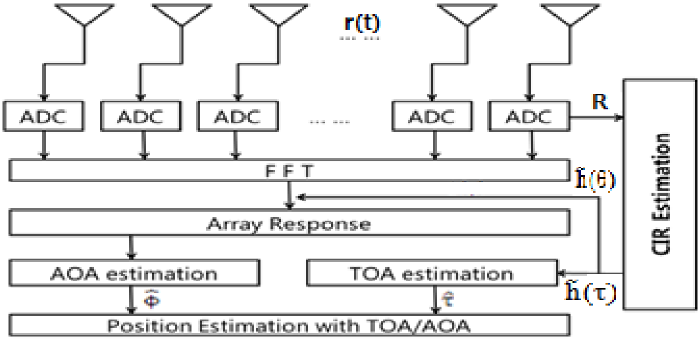

Fig. 1. The hybrid TOA/AOA positioning system design

Fig. 3 shows an example of received signal in a realistic TOA based IR-UWB ranging estimation system. As shown in the figure, the received signal consists of multiple multipath components and it is generally difficult to resolve the multipath components. If the overlapped multipath components can be resolved by using a received signal and already known transmitted signal, however, we can provide a higher precise TOA ranging performance.

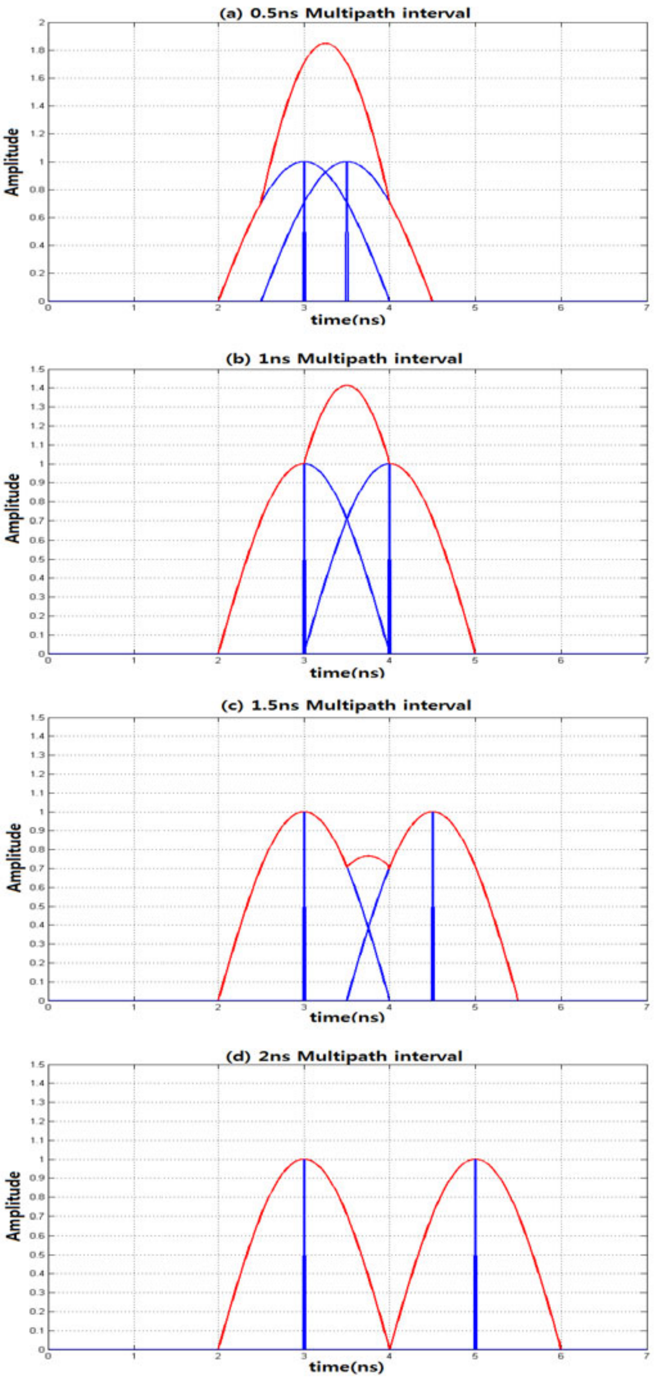

Fig. 2. Comparison of various received signals according to interval of multipath

At the receiver, the received signal over the multipath fading channel can be expressed as follows:

$$r(t) = \sum_{k=0}^{L_p-1} \alpha_k s(t-\tau_k) + w(t), \tag{1}$$

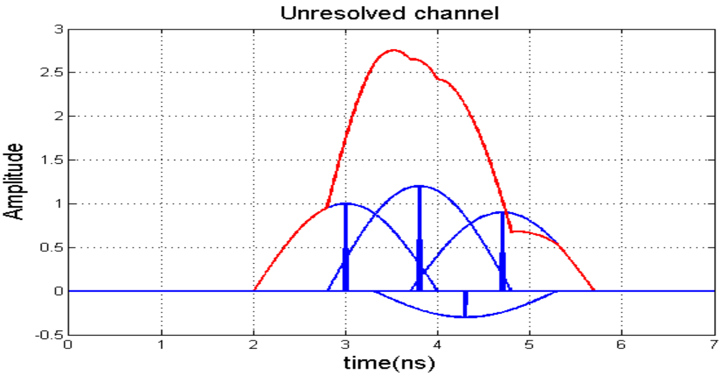

Fig. 3. Example of received signal with multiple multipath components

where L_p is the total number of multipath channels, α_k and τ_k are the amplitude and the propagation delay of the k-th path, respectively. $s(\cdot)$ is the transmitted pulse shape and w(t) is the additive white Gaussian noise with mean zero and variance σ_w^2 . By applying the harmonic signal model, (1) can be represented in frequency domain as follows [4][5]:

$$\begin{aligned} R(f) &= S(f)H(f) + W(f) \\ &= \sum_{k=0}^{Lp-1} \alpha_k S(f) e^{-j2\pi f \tau_k} + W(f), \end{aligned} \tag{2}$$

The discrete measurement data of (2) can be obtained by sampling at L equally spaced frequencies and is given by

$$R(f) = \sum_{k=0}^{L_p-1} \sum_{l=0}^{L\ -1} \alpha_k S(m+l) e^{-j2\pi(f_0+l\Delta f)\,\tau_k} + W(m), \tag{3}$$

where $m = 0, 1, \cdots, M-1$, f_0 is center frequency, and Δf is the sampling interval in frequency domain. Since we use harmonic model in L frequency samples, the N samples are divided into M consecutive segments of length L, where $M = N - L + 1$. Therefore, the transmitted signal S is formed into a $M \times L$ matrix and the sampled signal of (3) can be rewritten as follows:

$$\mathbf{R} = \mathbf{SH} + \mathbf{W} = \mathbf{SVa} + \mathbf{W}, \tag{4}$$

where

$$\mathbf{R} = [R(0) \quad R(1) \quad \cdots \quad R(M-1)]^{\mathrm{T}},$$

$$\mathbf{S} = \begin{bmatrix} S(0) & S(1) & \dots & S(L-1) \\ S(1) & S(2) & \cdots & S(L) \\ \vdots & \vdots & \ddots & \vdots \\ S(M-1) & S(M) & \cdots & S(M+L-2) \end{bmatrix},$$

$$\mathbf{H} = [H(f_0) \quad H(f_1) \quad \cdots \quad H(f_{L-1})]^{\mathrm{T}},$$

$$\mathbf{W} = [W(0) \quad W(1) \quad \cdots \quad W(M-1)]^{\mathrm{T}},$$

$$\mathbf{V} = [\mathbf{v}(\tau_0) \quad \mathbf{v}(\tau_1) \quad \cdots \quad \mathbf{v}(\tau_{L_p-1})],$$

$$\mathbf{v}(\tau_k) = [1 \quad e^{-j2\pi\Delta f\tau_k} \quad \dots \quad e^{-j2\pi(L-1)\Delta f\tau_k}]^{\mathrm{T}},$$

$$\mathbf{a} = \left[\alpha_0 e^{-j2\pi f_0\tau_0} \quad \alpha_1 e^{-j2\pi f_0\tau_1} \quad \cdots \quad \alpha_{L_p-1} e^{-j2\pi f_0\tau_{L_p-1}}\right]^{\mathrm{T}}.$$

3 Channel Models and IR-UWB Pulses

3.1 Channel Models

The CM1 and CM3 of IEEE 802.15.4a UWB channel model are considered. The CM1 represents a LOS environment of less than 4m and the CM3 is for a LOS environment of 4-10m. In this paper, we assumed the direct path is the multipath component having the strongest amplitude because of LOS environment.

3.2 Various IR-UWB Pulses

Various IR-UWB pulses are considered for IR-UWB positioning system. We employed the RRC pulse, the 5th order Gaussian mono-pulse, the 4th MHP pulse [6], and a sine type of PS pulse [7].

4 Channel Impulse Response Estimation

The CIR can be estimated by applying the inversion or pseudo inversion of the known signal matrix. By multiplying both sides of (4) by the inverse of the signal shape matrix $\mathbf{S}^{+}$, where $\mathbf{S}^{+} = \mathbf{S}^{\mathrm{H}}\{\mathbf{S}\cdot\mathbf{S}^{\mathrm{H}} + (\sigma_{\mathrm{w}}^{2})\cdot\mathbf{I}\}^{-1}$is for MMSE, it can be rewritten as follows:

$$\mathbf{S}^{+}\mathbf{R} = \mathbf{S}^{+}\mathbf{SH} + \mathbf{S}^{+}\mathbf{W} \text{ or } \widetilde{\mathbf{H}} = \mathbf{H} + \widetilde{\mathbf{W}}, \tag{5}$$

where I represents an identity matrix. Then, the estimated channel matrix $\widetilde{\mathbf{H}}$ is applied to the TOA estimation process and the frequency response of the estimated noisy CIR from (5) can be written as follows [4]:

$$H(j2\pi l \vartriangle f) = \sum_{k=0}^{L_p-1} \alpha_k z_k^l + W_k \ , \tag{6}$$

where $z_k = e^{-j2\pi\vartriangle f\tau_k}$ with $\vartriangle f = 1/L \cdot\vartriangle t$.

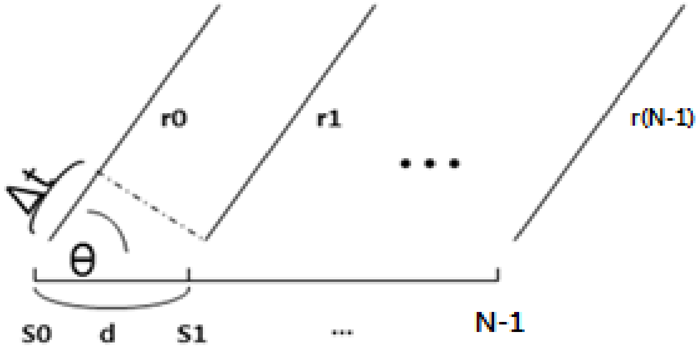

Fig. 4. Difference of detected signal depending on location of antenna in array antennas

5 AOA Estimation Using MUSIC

The direction of propagation of a radio-frequency wave can be estimated by the antenna array. Fig. 4 indicates the difference of detected signals depending on location of an antenna in array antennas. When a transmitted signal arrives to array antennas, each antenna receives the signal with different delays caused from distance gap on each antenna. The received signals between antennas are phase-shifted and they can be defined as follows:

$$\mathrm{e}^{-\mathrm{j}2\pi\mathrm{f}\Delta\mathrm{t}} = \mathrm{e}^{-\mathrm{j}2\pi\mathrm{fdcos}\theta/\mathrm{c}} = \mathrm{e}^{-\mathrm{j}2\pi\mathrm{dcos}\theta/\lambda} = \mathrm{e}^{-\mathrm{jkdcos}\theta} \left(\mathrm{k} = \frac{2\pi}{\lambda}\right), \tag{7}$$

and the relation of detected signals on S0 and S1 is expressed as follows; $\mathrm{S1} = \mathrm{S0e}^{-\mathrm{jkdcos}\theta}$. Thus, the detected signals on the array antenna can be defined as steering vector given by [8]:

$$\mathrm{s}(\theta) = \left[1 \quad \mathrm{e}^{-\mathrm{jkdcos}\theta} \quad \mathrm{e}^{-2\mathrm{jkdcos}\theta} \quad \cdots \quad \mathrm{e}^{-\mathrm{j(N-1)kdcos}\theta}\right]^{\mathrm{T}}, \tag{8}$$

where N is number of antennas in array.

5.1 MUSIC Algorithm

The MUSIC super-resolution techniques are based on eigen-decomposition of the autocorrelation matrix of the received signal vector. The received signal vector can be expressed as follows:

$$\mathrm{R} = \mathrm{SH} + \mathrm{W}, \tag{9}$$

where

$$S= [s(\theta_1)\, s(\theta_2)\ \cdots\ s(\theta_M)],$$
$$H = [\mathrm{H}_1 \mathrm{H}_2 \cdots\ \mathrm{H}_M]^T,$$

and M is number of multipaths. The matrix S is N × M matrix.
The autocorrelation matrix of received signal is expressed as follows:

$$\mathrm{R}_{RR} = \mathrm{E}\{\mathrm{R}R^H\} = \mathrm{VA}V^H + \sigma_w^2 \mathrm{I} = \mathrm{R}_s + \sigma_w^2 \mathrm{I}, \tag{10}$$

where

$$\mathrm{R}_s = \mathrm{VA}V^H$$

$$\mathrm{A} = \begin{bmatrix} E[|H_1|^2] & 0 & \cdots & 0 \\ 0 & E[|H_2|^2] & \cdots & 0 \\ 0 & 0 & \cdots & E[|H_M|^2] \end{bmatrix}$$

The signal covariance matrix, R_s, is clearly a N × N matrix with rank M. Therefore, it has N-M eigenvectors corresponding to the zero eigenvalues. Let q_m be such an eigenvector. Then,

$$\begin{aligned} \mathrm{R}_s\, q_m &= \mathrm{SA}S^H q_m = 0, \\ &\Rightarrow \mathrm{q}_m^H \mathrm{SA}S^H q_m = 0, \\ &\Rightarrow S^H q_m = 0 \end{aligned} \tag{11}$$

The last equation of (11) is valid since the matrix A is clearly positive definite. The equation (11) implies that all the N – M eigenvectors (q_m) of R_s corresponding to the zero eigenvalues are orthogonal to all the M signal steering vectors. Let $Q_n$is the $\mathrm{N} \times (\mathrm{N}-\mathrm{M})$ matrix of these eigenvectors, then the MUSIC plots the pseudo-spectrum as follows:

$$P_{MUSIC(\theta)} = \frac{1}{\sum_{m=1}^{N-M} |S^H(\theta) q_m|^2} = \frac{1}{s^H(\theta) Q_n\, Q_n^H s(\theta)} = \frac{1}{\left|Q_n^H s(\theta)\right|^2}, \tag{12}$$

Since the eigenvectors making up Q_n are orthogonal to the signal steering vectors, the denominator becomes zero when θ is a signal direction. Therefore, the estimated signal directions are the M largest peaks in the pseudo-spectrum.

6 Simulation Results

In this section, we evaluated the performance of proposed hybrid TOA/AOA based IR-UWB positioning system with various waveforms. As channel models, the CM1 and the CM3 of IEEE 802.15.4a standard were employed for computer simulations.

Fig. 5 depicts the position estimation error of hybrid TOA/AOA based IR-UWB system. As shown in the figures, the positioning system with MHP pulse outperforms the system with all other pulses for both CM1 and CM3 in high SNR region. Note that the positioning performance with other pulses is not remarkably enhanced as the SNR increase in CM3 while the positioning performance is enhanced as the SNR increase in CM1.

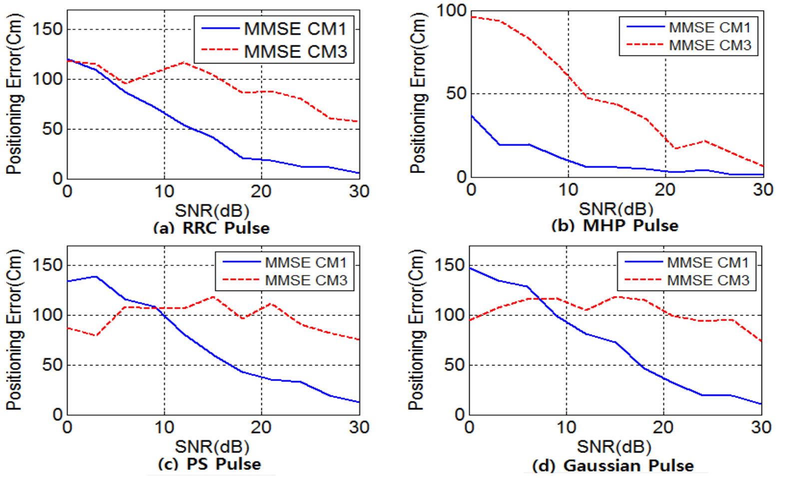

Fig. 5. Positioning estimation error of hybrid scheme with various waveforms

7 Conclusion

In this paper, we evaluated performance of hybrid TOA/AOA based IR-UWB positioning system with various shapes of waveforms. In a hybrid TOA/AOA scheme, it is shown that the MHP pulse outperforms all the pulses for both CM1 and CM3 in high SNR region. Although the accuracy of TOA scheme is better than that of hybrid TOA/AOA scheme, the hybrid TOA/AOA based IR-UWB positioning system requires only one BS, unlike the TOA system does three BSs. If the required accuracy of positioning system is tens of centimeters, the hybrid TOA/AOA based IR-UWB positioning system with MHP pulse can be considered because of its high performance and economic effects.

Acknowledgment

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References

[1] Kim, N.Y.: Research on Computationally Efficient Network-based Wireless Geolocation Systems, doctoral dissertation, Dept. of Information and Communication Engineering, Korea Advanced institute of Science and Technology (2010)
[2] Taylor, J.D.: Introduction to Ultra-Wideband Radar Systems. CRC Press, Boca Raton (1995)

[3] IEEE 802.15 WPAN Low Rate Alternative PHY Task Group 4a, PART 15.4:Wireless MAC and PHY Specifications for LR-WPANs, Draft P802.15.4a/D7 (March 2007)

[4] Manolakis, D., Ingle, V., Kogon, S.: Statistical and Adaptive Signal Processing. McGraw-Hill, New York (2000)

[5] Kim, N.Y., Kim, S., Kim, Y., Kang, J.: A High Precision Ranging Scheme for IEEE802.15.4a Chirp Spread Spectrum System. IEICE Transactions on Communications E92-B(3), 1057–1061 (2009)

[6] Michael, L.B., Ghavami, M., Kohno, R.: Multiple pulse generator for ultra-wideband communication using Hermite polynomial based orthogonal pulses. In: Proc. IEEE Conf. UltraWideband Syst. Technol., pp. 47–51 (May 2002)

[7] Yin, L., Hongbo, Z.: Interference Mitigation in UWB Communications through Pulse Waveform Design. In: Environmental Electromagnetics, the 2006 4th Asia-Pacific Conference, August 1-4, pp. 569–572 (2006)

[8] Gross, F.B.: Smart Antennas for Wireless Communications with Matlab. McGraw-Hill, New York (2005)