Joint TOA/AOA Estimation of IR-UWB Signals in the Presence of Multiuser Interference

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***Abstract*—We present a joint estimator of the time-of-arrival (TOA) and angle-of-arrival (AOA) for impulse radio ultra-wideband (IR-UWB) localization systems in which an antenna array is employed at the receiver and multiuser (MUI) interference exists. The proposed method includes 3 steps: (1) time-alignment and averaging to reduce the power level of the MUI and background noise; (2) preliminary TOA estimation based on energy detection followed by quadratic averaging; (3) joint TOA and AOA estimation using a recently proposed log likelihood function, but further extended to consider the effect of MUI. The validity of the proposed method is demonstrated by numerical simulations over a realistic space-time channel model.**

***Index Terms*—impulse radio ultra wideband, angle of arrival, time of arrival, multiuser interference.**

I. Introduction

Impulse-radio ultra-wideband (IR-UWB) is an attractive technology for the implementation of wireless indoor positioning systems due to its high temporal resolution, low cost architecture and low power requirements. The first IR-UWB positioning/tracking systems performed localization of a single user by triangulation, using estimates of the time of arrival (TOA) of the transmitted signal at multiple single-antenna receivers.When the receivers are equipped with antenna arrays, localization can benefit from spatial information in the form of angles of arrival (AOA). For that reason, hybrid approaches that jointly estimate the TOA and AOA have been attracting much attention recently, e.g., [1], [2], [3].

All of the above approaches have been designed specifically for a single user. However, in practical applications of positioning systems, multiple emitters operate simultaneously in the same radio environment. Consequently, the resulting multiuser interference (MUI) can severely degrade TOA/AOA estimation unless special measures are taken to suppress it. In IR-UWB systems this can be achieved by exploiting the known time-hopping (TH) code or direct sequence (DS) spreading patterns of the desired user. For example, in [4], the authors develop a TOA estimation method that performs non-linear filtering on the received signal energy to mitigate MUI. In [5], TOA estimators based on the maximum-likelihood (ML) criterion with interference cancellation are proposed, although they are mainly based on a single-path model. In [6], a MUI-resistant TOA estimator in weak non-line-of-sight (NLOS) environments is proposed based on the expectation maximization (EM) and pseudo-quadratic ML algorithms. In [7], a multiuser AOA estimation technique is proposed using a digital channelization receiver.

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To the best of our knowledge, joint TOA/AOA estimation of IR-UWB signals in the presence of MUI has not been previously considered. In this paper, we propose a simple, yet highly accurate joint TOA/AOA estimator of a desired user's signal corrupted by MUI. The proposed method consists of three steps: (1) the received signal at each antenna is time-aligned according to the TH code and training sequence of the desired user and averaged over multiple data symbols; (2) a preliminary TOA estimate for the direct path is obtained through energy detection at each antenna followed by non-linear averaging; (3) the coarse TOA estimate is used to initiate a fine search for the TOA and AOA of the desired user. This last step is performed by maximizing a log-likelihood function (LLF) in which the onset of the secondary paths is characterized by a special gating mechanism. This LLF is obtained by extending our recent work in [8] for single user TOA/AOA estimation, to the more general MUI scenario.

The rest of this paper is organized as follows. Section II introduces the system model and formulates the problem in mathematical terms. Section III presents and justifies the individual steps of the proposed method. Section IV demonstrates the performance of the method using numerical experiments. Finally, Section V concludes the paper.

II. System Model and Problem Formulation

We consider a multiuser localization system as depicted in Fig. 1, with K active users (tags) each equipped with a single antenna transmitter, and a receiver (tag reader) equipped with a uniform linear array (ULA) of $Q \geq 1$ identical antenna elements. We are interested in the localization of a single user of interest, say user 0, in the presence of MUI.

The IR-UWB signal $s_k(t)$ transmitted by user $k \in \{0, \ldots, K-1\}$ is composed of N_{s} consecutive symbols of duration T_{s}, each of which consists of N_f frames of duration T_f. Each frame is further divided into N_c chips of length T_c (i.e., $T_f = N_c T_c$) where each chip consists of N_p pulse periods of duration T_p ($T_c = N_p T_p$). Within the jth frame of the ith symbol, a single unit-energy pulse $w(t)$ of length

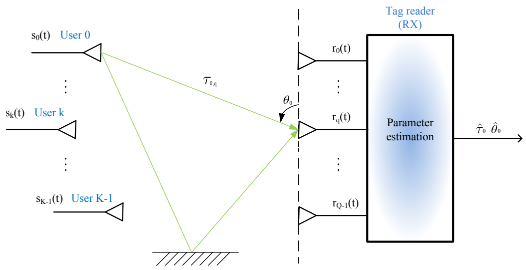

Fig. 1. Multiuser localization system.

T_p is transmitted in the chip identified by the unique TH code[1] $c_k(j) \in \{0, \ldots, N_c - 1\}$ assigned to user k. The pulse position is further modulated by a known training sequence $a_k(i) \in \{0, \ldots, N_p - 1\}$, adopted by user k for the purpose of ranging. Hence, over the observation interval of length $T_o = N_s T_s$, the signal $s_k(t)$ is described by

$$s_k(t) = \sum_{i=0}^{N_s-1} \sum_{j=0}^{N_f-1} \sqrt{E_k}\, w(t - iT_s - jT_f - c_k(j)T_c - a_k(i)T_p) \tag{1}$$

where E_k is the transmitted energy per pulse of the kth user.

After multipath propagation, the transmitted signals are acquired at the tag reader. Under the far field assumption, the TOA at the qth antenna of user 0's signal through the primary path, i.e., the first path in a line-of-sight (LOS) environment, can be written as

$$\tau_{0,q} = \tau_0 + (q - \frac{Q-1}{2})\Delta\tau_0, \quad q \in \{0, \ldots, Q-1\} \tag{2}$$

where τ_0 denotes the TOA at the antenna array geometric center and $\Delta\tau_0$ is the time difference of arrival (TDOA) between adjacent antennas. For a 2-dimensional (2D) geometry, the TDOA is related to the AOA, θ_0, by $\Delta\tau_0 = \frac{d}{c}\cos\theta_0$ with d denoting the inter-antenna spacing and c the speed of light.

The multipath channel between the kth user and qth antenna element is represented by $\mathcal{H}_{k,q}\{\cdot\}$, with $k \in \{0, ..., K-1\}$ and $q \in \{0, ..., Q-1\}$. The response to the emitted pulse $w(t)$ of the channel between user 0 and the qth receive antenna, is modelled as the superposition

$$\mathcal{H}_{0,q}\{w(t)\} = \eta_0(t - \tau_{0,q}) + \zeta_{0,q}(t) \tag{3}$$

where $\eta_0(t)$ denotes the pulse image arriving along the primary path while $\zeta_{0,q}(t)$ represents the total contribution of the images received along secondary paths, i.e., excluding the primary one. We model the primary pulse image $\eta_0(t)$ as a deterministic signal and the secondary pulse images $\{\zeta_{0,q}(t)\}_q$ as independent Gaussian random processes with zero mean and cross-correlation function

$$E[\zeta_{0,q}(t)\zeta_{0,q'}(u)] = g(t - \tau_{0,q})P(t)\delta_c(t-u)\delta_{q,q'}. \tag{4}$$

In (4), $P(t)$ is the average power delay profile (APDP) of the wireless channel, $\delta_c(t)$ is the Dirac delta function, $\delta_{qq'}$ is the Kronecker delta function, and $g(t)$ is a gating function used to characterize the onset of the secondary images (after the primary one) [8]. In this work, for simplicity of implementation, we set $g(t) = u(t - T_p)$, where $u(t)$ denotes the standard unit step function.

[1] In practice, the maximum value of $c_k(j)$ is less than $N_c - 1$ to allow for a guard interval between successive frames.

The response to $w(t)$ of the channel between an interfering user k and the qth receive antenna, is denoted as

$$\mathcal{H}_{k,q}\{w(t)\} = \zeta_{k,q}(t), \quad k \in \{1, ..., K-1\} \tag{5}$$

where $\zeta_{k,q}(t)$ represents the total contribution of the pulse images received along all paths, i.e., including the primary one. We model $\{\zeta_{k,q}(t)\}_q$ as independent Gaussian random processes with zero mean and cross-correlation function

$$E[\zeta_{k,q}(t)\zeta_{k,q'}(u)] = P(t)\delta_c(t-u)\delta_{q,q'}. \tag{6}$$

Image components $\zeta_{k,q}(t)$ corresponding to different users (including $k = 0$) are assumed to be statistically independent.

The noisy IR-UWB signal received at the qth antenna output, can be expressed as

$$r_q(t) = \sum_{k=0}^{K-1} \mathcal{H}_{k,q}\{s_k(t)\} + n_q(t), \quad 0 \le t \le T_o \tag{7}$$

where $n_q(t)$ is an additive noise term modelled as a spatially and temporally white Gaussian process with zero mean and known power spectral density level σ_n^2. The noise terms $n_q(t)$ are assumed to be statistically independent from $\zeta_{k,q'}(t)$.

The problem addressed in this paper can be stated as follows. Given the observation of the received antenna signals at the reader, $\{r_q(t) : 0 \le t \le T_o, q = 0, \ldots, Q-1\}$, we seek to jointly estimate the TOA and AOA parameters of the primary path, respectively τ_0 and θ_0 for user 0, in the presence of interference from the other users $k \in \{1, \ldots, K-1\}$.

III. PROPOSED METHOD

The proposed method for joint parameter estimation consists of three main steps: (1) symbol and frame alignment followed by averaging to reduce MUI and white noise; (2) preliminary TOA estimation to narrow down the search range; (3) joint fine estimation of TOA and AOA based on an ML criterion.

A. Frame Alignment and Averaging

First, the received signals $r_q(t)$ at each antenna $q \in \{0, \ldots, Q-1\}$ are time-aligned and averaged according to the TH code and training sequence of user 0, which are known at the receiver side, resulting into

$$\begin{aligned} x_q(t) &= \frac{1}{N_s N_f} \sum_{i=0}^{N_s-1} \sum_{j=0}^{N_f-1} r_q(t + iT_s + jT_s + c_0(j)T_c + a_0(i)T_p) \\ &= \sqrt{E_0}[\eta_0(t - \tau_{0,q}) + \zeta_{0,q}(t)] + \bar{n}_q(t) + z_q(t), \\ &\quad 0 \le t \le T_f \end{aligned} \tag{8}$$

where the MUI term $z_q(t)$ is given by

$$z_q(t) = \frac{1}{N_s N_f} \sum_{k=1}^{K-1} \sum_{i=0}^{N_s-1} \sum_{j=0}^{N_f-1} \sqrt{E_k}\zeta_{k,q}(t - \tau_{i,j,k}) \tag{9}$$

with

$$\tau_{i,j,k} = (c_k(j) - c_0(j))T_c + (a_k(i) - a_0(i))T_p \in \{-N_cT_c + T_p, -N_cT_c + 2T_p, \ldots, N_cT_c - T_p\} \tag{10}$$

and $\bar{n}_q(t)$ is zero-mean white Gaussian noise with power spectral density level $\bar{\sigma}_n^2 = \frac{1}{N_s N_f}\sigma_n^2$. In this paper, for simplicity, we model the summation of all the interference terms from other users $k \in \{1, \ldots, K-1\}$ in (9) as a Gaussian distributed random process with zero mean, but independent from the noise and desired signal.

As explained in Section II, each user k is assigned a unique TH identification code $c_k(j)$ and training sequence $a_k(i)$ that shift the transmitted pulses from user k at a specific location within each frame of each symbol. When we time-align the received signals within each frame of each symbol according to the TH code and training sequence of user 0, $c_0(j)$ and $a_0(i)$, pulses from the interfering users $k \in \{1, \ldots, K-1\}$ will fall at random locations within the different frames. Then, by averaging all time-aligned received data frames, the effects of the MUI as well as the additive noise can be reduced.

B. Preliminary TOA Estimation

After obtaining the time-aligned array output signals $\{x_q(t)\}$, a preliminary TOA estimation is carried out for each antenna q. This step is proposed to alleviate the computational cost of the fine 2D search for joint TOA/AOA estimation in the final step. In this work, we use a threshold crossing (TC) method because of its simplicity and robustness. Our experiments have shown that more sophisticated methods, e.g., the ones in [9], do not necessarily lead to noticeable performance improvements in this preliminary estimation step.

In the TC method, the TOA estimate at the qth antenna is obtained as the smallest value of the time t, for which the instantaneous power of the time-aligned signal at the qth antenna output, $x_{0,q}^2(t)$, exceeds a given threshold $\lambda > 0$, i.e.,

$$\hat{\tau}_{0,q} = \min\{t : x_q^2(t) > \lambda, 0 < t < T_u\} \tag{11}$$

where T_u is the initial search range (i.e., uncertainty region) for the unknown TOA. The value of the threshold λ in (11) can be selected by considering the trade-off between the probabilities of false alarm and missed detection [10]. In this regard, we note that the noise variance now has to be adjusted to account for the presence of MUI.

Next, the preliminary TOA estimates $\hat{\tau}_{0,q}$ are averaged to obtain a single coarse estimate of the TOA at the array geometric center, i.e., τ_0 in (2). After comparing different approaches for the calculation of a mean TOA value, we found that the quadratic mean, given by

$$\hat{\tau}_0 = \frac{1}{Q}\Big(\sum_{q=0}^{Q-1} \hat{\tau}_{0,q}^2\Big)^{1/2}. \tag{12}$$

achieved better performance than other approaches. This can be explained by the fact that outlier estimates resulting from the application of (11) tend to be smaller than the true delay, and the quadratic mean gives a lesser weight to these smaller values.

C. Refined Joint ML-based Estimation

In this third and final step, the preliminary TOA estimate (12) is used to initiate a fine search for the TOA and AOA of user 0. This is achieved by maximizing a LLF based on the work in [8], but extended to take into account the presence of MUI in the scenario considered here. The derivation of this extended LLF calls for the characterization of the random processes $\{x_q(t)\}$.

According to the Gaussian assumption for the combined pulse images $\{\zeta_{k,q}(t)\}$, the MUI interference $z_q(t)$ and the noise $\bar{n}(t)$, as well as their assumed mutual independence, it follows from (8), (9) that $x_q(t)$ is also a Gaussian process with non-zero mean

$$\mu_q(t) = E[x_q(t)] = \sqrt{E_0}\,\eta_0(t - \tau_{0,q}) \tag{13}$$

and covariance function

$$\begin{aligned} R_q(t,u) =& E[(x_q(t) - \mu_q(t))(x_q(u) - \mu_q(u))] \\ =& E_0 P(t) g(t - \tau_{0,q})\delta_c(t-u) + \bar{\sigma}_n^2 \delta_c(t-u) \\ &+ E[z_q(t) z_q(u)]. \end{aligned} \tag{14}$$

According to (9), $z_q(t)$ is a sum of multipath contributions $\zeta_{k,q}(t)$ from the $K-1$ interfering users at the qth antenna, shifted by all possible values of the delays $\tau_{i,j,k}$ in (10), i.e., after proper alignment for desired user 0. Therefore,

$$\begin{aligned} &E(z_q(t) z_q(u)) = \\ &\frac{1}{(N_s N_f)^2}\sum_{k=1}^{K-1}\Big(\sum_{i=0}^{N_s-1}\sum_{j=0}^{N_f-1} E_k P(t-\tau_{i,j,k})\delta_c(t-u) + \\ &\sum_{k=1}^{K-1}\sum_{\substack{i,i',j,j' \\ (i,j)\neq(i',j')}} E_k P(t-\tau_{i,j,k})\delta_c(t-u-\tau_{i,j,k}+\tau_{i',j',k})\Big). \end{aligned} \tag{15}$$

It can be shown that the delta functions $\delta_c(t - u - \tau_{i,j,k} + \tau_{i',j',k})$ in the second term of (15) contribute small extraneous peaks in the LLF (to be developed later) at a distance of $|\tau_{i,j,k} - \tau_{i',j',k}|$ or more from the desired peak within the vicinity of $\hat{\tau}_0$ in (12). Assuming that the delays $\tau_{i,j,k}$ are different for each pair of indices due to the random nature of the TH code, the difference $|\tau_{i,j,k} - \tau_{i',j',k}|$ is such that most of these peaks fall outside the search range for the delay parameter. Accordingly, the second term in (15) can be neglected and we can approximate $R_q(t,u)$ as

$$R_q(t,u) \simeq \big(E_0 P(t) g(t - \tau_{0,q}) + \sigma_z^2(t) + \bar{\sigma}_n^2\big)\delta_c(t-u) \tag{16}$$

where $\sigma_z^2(t)$ is the instantaneous power level of the MUI given by

$$\sigma_z^2(t) = \frac{1}{(N_s N_f)^2}\sum_{k=1}^{K-1}\sum_{i=0}^{N_s-1}\sum_{j=0}^{N_f-1} E_k P(t - \tau_{i,j,k}). \tag{17}$$

The time delay variables $\tau_{i,j,k}$ in (17) account for the asynchronism between the different users, frames and symbols. Due to the random nature of the TH codes $c_k(j)$ and training sequences $a_k(i)$, it is reasonable to model the time delays $\tau_{i,j,k}$ as independent realizations of a random variable υ

with probability density function (PDF) $f(\upsilon)$. Hence, since the value of the product $N_{\rm s}N_f$ is typically large under the proposed scenario in this work, the law of large numbers can be invoked to obtain the following approximation

$$\frac{1}{N_{\rm s}N_f}\sum_{i=0}^{N_{\rm s}-1}\sum_{j=0}^{N_f-1}P(t-\tau_{i,j,k})\simeq$$
$$E[P(t-\upsilon)]=\int_{-N_cT_c+T_p}^{N_cT_c-T_p}P(t-\upsilon)f(\upsilon)d\upsilon. \quad (18)$$

Using (18) in (17) we finally obtain

$$\sigma_z^2(t)=\frac{\bar{P}(t)}{N_{\rm s}N_f}\sum_{k=1}^{K-1}E_k \quad (19)$$

where we define $\bar{P}(t)=\int_{(-N_c+1)T_c}^{(N_c-1)T_c}P(t-\upsilon)f(\upsilon)d\upsilon$.

Let $\mathbf{x}=\{x_q(t): t\in[0,T_f],\, q\in\{0,\ldots,Q-1\}\}$ represent the complete set of observed data, after time-alignment for user 0 and frame averaging, and define $\boldsymbol{\phi}=[\tau_0,\theta_0]$ as the vector of unknown parameters being estimated. By proceeding as in [8], a closed form expression for the LLF of $\mathbf{x}$, given the value of the unknown parameter vector $\boldsymbol{\phi}$, can be derived. This involves passing to discrete-time by uniformly sampling the signals $x_q(t)$ at the Nyquist rate F_s, making use of the multi-dimensional Gaussian PDF expression for the resulting vector of time samples, inverting the associated data covariance matrix, and finally converting back to continuous-time. After these operations, the desired LLF is obtained as

$$\ln\Lambda(\mathbf{x},\boldsymbol{\phi})=-\frac{1}{2}\sum_{q=0}^{Q-1}\big(l_{1,q}(\mathbf{x};\boldsymbol{\phi})+l_2(\boldsymbol{\phi})\big) \quad (20)$$

where the data-dependent terms $l_{1,q}(\mathbf{x};\boldsymbol{\phi})$ are given by

$$l_{1,q}(\mathbf{x};\boldsymbol{\phi})=\int_0^{T_f}\frac{\big(x_q(t)-\mu_q(t)\big)^2}{E_0P(t)g(t-\tau_{0,q})+\sigma_z^2(t)+\bar{\sigma}_n^2}dt \quad (21)$$

with $\tau_{0,q}$ as defined in (2) in terms of the TOA τ_0 and AOA θ_0. During the calculation of $l_2(\boldsymbol{\phi})$, we found that its final value is almost constant for different choices of τ_0 and θ_0, as long as the channel delay spread is smaller than T_f. Accordingly, in our final implementation of the proposed algorithm the term $l_2(\phi)$ will be omitted.

The evaluation of (21) requires the knowledge of $\mu_q(t)$ in (13), which in turn depends on $\eta_0(t)$, i.e., the received pulse image from user 0 along the primary path. In practice, the pulse shape $\eta_0(t)$ is unknown and must be estimated along with the desired parameters. Here, we proceed as in [8] and estimate $\mu_q(t)$ simply as a time-shifted version of $x_0(t)$ over an interval of duration T_p. That is, for each candidate value of the unknown TOA $\tau_{0,q}$, we replace $\mu_q(t)$ in (21) by $x_0(t+\tau_{0,q})$ when $0\le t\le T_p$ and by 0 otherwise.

Finally, the joint ML estimator is obtained by maximizing the LLF using a two-dimensional fine search, as in:

$$\hat{\boldsymbol{\phi}}_{\rm ML}=\arg\min_{\boldsymbol{\phi}\in\mathcal{P}}\big(\sum_{q=0}^{Q-1}l_{1,q}(\mathbf{x};\boldsymbol{\phi})\big) \quad (22)$$

where $\mathcal{P}$ denotes the parameter space over which the search is performed. In practice, the search range for τ_0 is limited to a few chip intervals around the preliminary estimate $\hat{\tau}_0$ in (12), while the search for θ_0 is limited by the antenna distance d and the sampling resolution of the available discrete-time signals.

IV. NUMERICAL EXPERIMENTS

In this section we investigate through computer simulations the performance of the proposed method under realistic operating conditions. We consider a $K=4$ user system with timing system parameters chosen as follows: $N_{\rm s}=32$, $T_{\rm s}=512$ns, $N_f=4$, $T_f=128$ns, $T_c=4$ns and $T_p=0.5$ns. An optimal TH code set from [11] is used, specifically: for the desired user $c_0(j)=[3,2,3,6]$, and for the interfering users $c_1(j)=[7,9,1,7]$, $c_2(j)=[2,0,4,2]$ and $c_3(j)=[9,5,7,1]$, where j runs from 0 to 3. The training sequences $a_k(i)$ are generated as independent and identically distributed equiprobable random variables from the discrete set $\{0,\ldots,7\}$. The pulse $w(t)$ is a Gaussian doublet with effective bandwidth $B=4$GHz.

The UWB radio channels are generated using the CM1 channel model in the IEEE 802.15.4a standard with a delay spread of 80ns. Spatial dependence is incorporated into the propagation model according to the approach in [12]. That is, the AOA of each path follows a Laplacian distribution with a cluster mean value uniformly distributed over $[45^o,135^o]$ and a standard deviation of 5° for each cluster. The receiver is equipped with a ULA of $Q=3$ identical antenna elements with inter-element spacing $d=50$cm, whose outputs are sampled at the rate $F_s=16$GHz.

In the second step, the initial search range is set to $T_u=48$ns and the preliminary estimate $\hat{\tau}_0$ in (12) is rounded to the nearest available time sample, i.e., multiple of $F_s^{-1}=0.0625$ns. The search range for the fine estimation (22), which is limited by the sampling period F_s^{-1}, consists of a regular grid of 17×55 points in the $(\tau_0,\Delta\tau_0)$ plane centered at $(\hat{\tau}_0,0)$. The estimation performance is measured using the root-mean-square error (RMSE), evaluated by averaging over 500 runs using independent channels and noise realizations.

Fig. 2 shows the performance of the preliminary TOA estimation with respect to the number of symbols $N_{\rm s}$, with the SNR $=N_fE_0/\sigma_n^2$ of the desired user fixed at 15dB. Here, the RMSE is also compared for different numbers of interfering users, with same power as the desired one, i.e., $E_k=E_0$. We note that the estimation performance becomes stable when $N_{\rm s}$ reaches a value of 16, beyond which only marginal improvements are obtained.

Results of the fine TOA estimation using the proposed joint estimator are presented in Fig. 3 as a function of SNR. In this case, $N_{\rm s}=32$, $K=4$, and the results are compared for different values of the interference power, i.e., $E_k=\rho E_0$ where $\rho\in\{0,0.5,1,1.5\}$. The case $\rho=0$ corresponds to the single-user case which represents a lower bound on the estimation accuracy in the presence of MUI. It is clear that the fine TOA estimation from the joint ML estimation step achieves fairly high accuracy (mostly less than 0.1 ns). In particular, comparing with Fig. 2, we find that the RMSE of the TOA estimation drops from 0.12ns following the preliminary

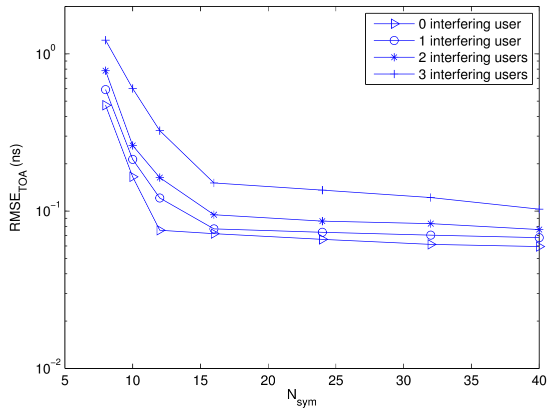

Fig. 2. RMSE of preliminary TOA estimates versus N_s ($E_k = E_0$, SNR= 15dB).

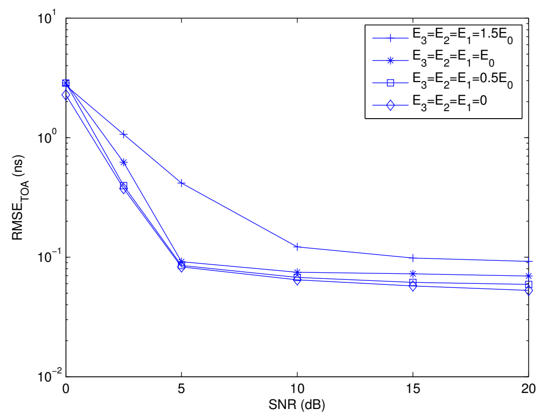

Fig. 3. RMSE of TOA estimates versus SNR for different MUI power (N_s = 32, $K = 4$).

estimation, to about 0.08ns after the fine search, for a net additional gain of about 3.5dB.

Fig. 4 compares the AOA estimation performance of the proposed method with different power level of MUI. As in Fig. 3, the energies of the interfering users are set to values larger, equal or smaller than the energy of the desired user. It can be seen that the AOA estimation accuracy improves as the interference degrades. At SNR of 10 dB, the attainable RMSE value is under 2° for all the cases. When the interference user energy is 1.5 times that of the desired user, the performance of the AOA estimation slightly degrades. This is reasonable because the total energy level of the additive MUI amounts for 4.5 times (13dB) that of the desired user in this scenario.

V. Conclusion

In this paper, we proposed a new three-step method for the joint TOA/AOA estimation of a desired IR-UWB signal with an antenna array receiver, in the presence of multiuser interference. In the first step, the received signals which consist of the linear superposition of all the user transmissions, are time-aligned according to the unique TH code and training sequence of the desired user, and averaged, which greatly reduces the power of unwanted MUI and additive noise. In the second step, a preliminary TOA estimate is obtained via energy detection followed by non-linear averaging. In the third step, the final joint TOA/AOA estimation is achieved by maximization of a LLF through a fine 2D search over a smaller region around the preliminary TOA. This LLF was obtained by extending the LLF derived in [8] to incorporate the effect of MUI. Simulation experiments were carried out where the (near-far) effect of the MUI power on the parameter estimation accuracy for the desired user was considered. The results show that the proposed method can efficiently minimize the impact of MUI on AOA/TOA estimation and attain accuracy levels very close to the corresponding single-user bound.

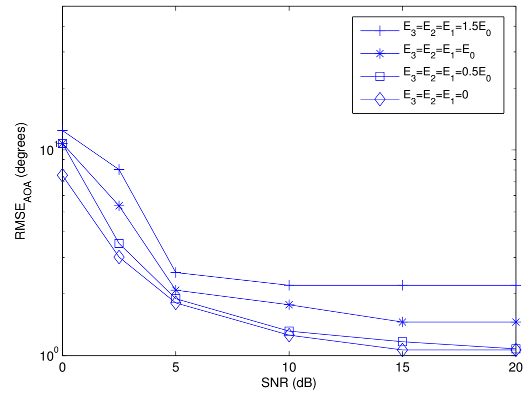

Fig. 4. RMSE of AOA estimates versus SNR for different MUI power (N_s = 32, $K = 4$).

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