

# An Improved Method for TOA Estimation in TH-UWB System considering Multipath Effects and Interference

Mahdieh Ghasemlou\*

Department of Telecommunications Engineering, Islamic Azad University Tehran South branch, Tehran, Iran  
mahdieh\_ghasemlou@yahoo.com

Saeid Nader-Esfahani

School of Electrical and Computer Engineering, University of Tehran, Tehran, Iran  
nader@ut.ac.ir

Vahid Tabataba-Vakili

School of Electrical Engineering, Iran University of Science & Technology, Tehran, Iran  
vakily@iust.ac.ir

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## Abstract

UWB ranging is usually based on the time-of-arrival (TOA) estimation of the first path. There are two major challenges in TOA estimation. One challenge is to deal with multipath channel, especially in indoor environments. The other challenge is the existence of interference from other sources. In this paper, we propose a new method of TOA estimation, which is very robust against the interference. In this method, during the phase of TOA estimation, the transmitter sends its pulses in random positions within the frame. This makes the position of the interference relative to the main pulse to be random. Consequently, the energy of interference would be distributed, almost uniformly, along the frame. In energy detection methods, a constant interference along the frame does not affect the detection of arrival time and only needs the adjustment of the threshold. Simulation results in IEEE.802.15.4a channels show that, even in presence of very strong interference, TOA estimation error of less than 3 nanoseconds is feasible with the proposed method.

**Keywords:** Threshold, Interference, TOA, Ranging.

## 1. Introduction

Owing to its high time resolution, impulse radio-ultra wideband (IR-UWB) technology is an excellent signaling for accurate wireless localization used in many security, medical, search and rescue, and military applications [1]. Ranging with the use of UWB systems is usually done from the time-of-arrival (TOA) of the first path of the received signal; in these systems, the distance between the receiver and transmitter is measured based on the estimation of the signal propagation delay, which can be challenging in the presence of multipath and interference [2-3].

When channel parameters are unknown like in the case of multipath environment, the estimation of the TOA is dependent upon the channel estimation [4-5]; in this case, channel coefficients and delays are estimated using, for example, the maximum likelihood method. However, the very high complicity of this method due to the high number of paths in a real multi-path channel makes its implementation limited. Coherent methods like matched filtering [6] are also costly to be implemented, due to their need for high rate sampling. To reduce complexity of UWB systems, non-coherent methods such as energy detector owing to their sub-Nyquist sampling, and consequently their low implication cost, are in spotlight of attention [7-8]. Algorithms based on energy detector are generally divided into two categories including

i) maximum energy selection (MES), and ii) threshold crossing (TC) algorithms.

MES-based TOA algorithms depend on the selection of the maximum amount of energy, and hence, have limited application in real multipath channels in which the first path is not usually the strongest one [2]. In TC-based TOA algorithms, receiver samples are compared with a threshold, and the TOA is estimated as the first sample crossing the threshold. The main feature of threshold-based algorithms is their analog implementation, which has attracted substantial attention in some applications like wireless sensor networks needing low-consumption devices [6].

The choice of the threshold strongly influences the performance of the TOA estimation. There are different methods for setting the threshold; it can be selected on the basis of noise level, regardless of channel properties and the energy of the received signal [9-10]; the threshold can also be defined on the basis of a constant normalized value between the lowest and highest amounts of energy samples [8]. Better approaches have been proposed for determining the normalized threshold on the basis of the received signal statistics such as its kurtosis [11], and the comparison between kurtosis and skewness results in the fact that skewness is more appropriate for accurate TOA estimation [12], and in [13] also the four statistical parameters including kurtosis skewness, maximum slope and standard deviation are compared. Since the maximum

\* Corresponding Author

slope and skewness are more sensitive to SNR changes, the common criterion for determining the thresholds has been calculated using skewness and maximum slope.

In [14], a new method has been proposed to improve the estimation accuracy based on the received signal characteristics, that is based on determine 2 thresholds. Threshold in the first step is calculated based on the Gaussian distribution of noise samples, and the second one is based on the times energy samples in different threshold frames are more than the threshold in the first step. In [15], the first step threshold is calculated based on the chi-square distribution. Although it is expected that the chi-square distribution is more convenient for the noise samples, but the results show that since the threshold in the first step is not appropriate, so there is not much difference between the Gaussian and chi square distributions. So, as it was mentioned in [14] the first step requires a more appropriate threshold.

A new method has been proposed based on a rank test, which suffers from high complexity, especially when the number of frames increases [16]. Another thresholding method has also been introduced on the basis of the channel impulse response and real environment measurements [17].

Ranging through non-coherent receivers in the presence of interference is difficult, as the system may estimate the moment at which the interference is received as the real TOA. Many methods have been so far proposed for reducing interference; for example, nonlinear filters have been suggested to be used for lowering interference effects [18-19]; however, these method result in substantial errors in the presence of strong interferences.

In a recent conference paper [20], we have put forward a new method for estimating the TOA in a multipath channel and in the presence of interference. In this method, the transmitter sends its pulse not in a constant but a random position within the frame; therefore, the position of the interference relative to the main pulse is always changing, making the interference energy evenly distributed in different distances from the main pulse; such an interference will not have any effect in detecting the moment the pulse is entered, TOA, and it is just needed to increase the threshold to the level of this interference. To overcome the multipath problem of the channel, we have made use of serial backward search for multiple cluster (SBSMC) algorithm [19].

In [20] we introduced an approximate formula for the threshold, using a simple model. The present work is an extension of [20], in that a more accurate threshold is introduced by using an exponential profile for the channel model, according to IEEE 802.15.4a. This threshold can be adjusted for different environments by using the cluster decay factors of that environment.

The rest of the paper has been organized as follows; in section 2, the model of the UWB system with time hopping (TH) and the structure of the receiver have been discussed; section 3 has been devoted to the ED-based

algorithms for the TOA estimation as well as our proposed method for threshold determination. The performance of the present method has been compared with other methods in section 4, followed by a conclusion in section 5.

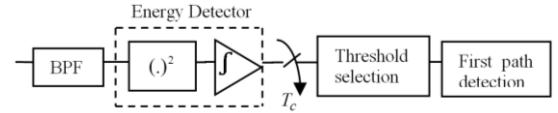


Fig. 1 Threshold-based TOA estimator with ED scheme

## 2. System Model and Receiver Structure

### 2.1 The Shape of the Signal Wave and the Structure of the Receiver

IEEE 802.15.4a [21] is an international standard modeling UWB channels with the use of Saleh-Valenzuela model. In TH-IR signaling, each symbol within a period of  $T_{sym}$  is divided into  $N_f$  number of time intervals of  $T_f$  the so-called frames. Each frame is also divided into  $N_c$  intervals of  $T_c$  called chips. The TH codes are randomly denoted by  $c_j \in \{1, 2, \dots, N_h\}$  where  $N_h$  represents maximum hopping within a frame, and generally,  $N_h \leq N_c$ ; here, we have considered  $N_h = N_c$ .

Fig. 1 shows a design of the ED-based TOA estimator [11]. To remove the out-of-band noise, the received signal first passes through a band-pass filter (BPF) with the bandwidth  $B$  and center frequency  $f_0$ . If we consider the first user as the desired user, the output of the BPF in the presence of interference can be written as [22]:

$$r(t) = s(t) + i(t) + n(t) \quad (1)$$

$$s(t) = \sum_{n=1}^{N_{sym}} \sum_{k=1}^{N_f} w^{(1)}(t - c_k^{(1)}T_c - (k-1)T_f - (n-1)T_{sym}) \quad (2)$$

$$s(t) = \sum_{n=1}^{N_{sym}} \sum_{k=1}^{N_f} w^{(1)}(t - c_k^{(1)}T_c - (k-1)T_f - (n-1)T_{sym}) \quad (2)$$

and

$$w^{(u)}(t) = \sqrt{\frac{E_s^{(u)}}{N_f}} \sum_{l=1}^L \alpha_l^{(u)} P(t - \tau_l^{(u)}) \quad (3)$$

where  $L$  is the number of the multipath components for the  $u$ th user;  $\alpha_l^{(u)}$  and  $\tau_l^{(u)}$  are respectively amplitudes and delays of the  $l$ th multipath component of the  $u$ th user, and  $\tau_1^{(1)}$  is estimated as the TOA. Without loss of generality,

the normalization  $\sum_{l=1}^L E\{\alpha_l^{(u)}\}^2 = 1$  can be considered

for all users.  $N_{sym}$  is the number of the symbols, and  $E_s^{(u)}$  represent average received energy per symbol. Component  $i(t)$  is the interference, and  $n(t)$  is the additive white Gaussian noise (AWGN) with zero mean and the two-sided power spectral density  $\frac{N_0}{2}$ . No modulation is considered for the ranging process.

When  $U$  users exist, so that each user transmits  $N_{sym}$  symbols at each time,  $i(t)$  can be expressed as:

$$i(t) = \sum_{u=2}^U \sum_{n=1}^{N_{sym}} \sum_{k=1}^{N_f} w^{(u)}(t - c_k^{(u)} T_c - (k-1)T_f - (n-1)T_{sym}) \quad (4)$$

After passing the filter, the received signal is entered the ED which is usually composed of a non-linear squaring element and an integrator. A sample is taken from the output of the integrator along the received signal after each  $T_c$  seconds. Therefore, energy samples of  $z[k]$  are obtained as follows:

$$z[k] = \int_{(k-1)T_c}^{kT_c} |r(t)|^2 dt \quad k = 1, \dots, N_b \quad (5)$$

where  $N_b = N_{sym} \cdot n_b$  and  $n_b = N_f \cdot N_c$ .

## 2.2 Energy Matrix of TH-IR

In TH-IR, the energy samples of  $z[k]$  are regulated according to the transmitted TH code, making the energy matrix of the dimensions of  $(N_f \cdot N_{sym} \times N_c)$  as follows [23]:

$$z[k(j), n] = z[n + (k-1)N_f \cdot N_c + (j-1)N_c + c_j^{(1)}] \quad (6)$$

Where  $k(j) = N_f \cdot (k-1) + j$ ,  $j \in \{1, 2, \dots, N_f\}$ ,  $1 \leq k \leq N_{sym}$  and  $1 \leq n \leq N_c$ .

## 2.3 Nonlinear filtering

To reduce the interference, many methods have been proposed to be applied to the energy matrix [19,21]. Therefore, before the TOA estimator, a filtering can be applied to the samples. The most common approach is to use an averaging filter obtaining the average of the samples in each column; therefore,

$$z[j, n] = \frac{1}{N_{sym}} \sum_{k=1}^{N_{sym}} z[k(j), n] \quad (7)$$

We particularly use a median filter, and thus have [23]:

$$z[j, n] = \text{median}\{z[j, n], z[j+1, n], \dots, z[j+w-1, n]\} \quad (8)$$

Where  $\in \{1, 2, \dots, N_f\}$ ,  $1 \leq n \leq N_c$  and  $w$  is the length of the filter.

Since the nonlinear filtering performance is strongly reduced in the presence of the interference [19], in our proposed method, the averaging filter is first applied to each column of the matrix, and then, the error in the TOA estimation is removed through choosing a new threshold. At the next stage, the energy samples of the transmitted pulses within different frames are summed together. Therefore:

$$z[n] = \sum_{j=1}^{N_f} z[j, n] \quad (9)$$

## 3. ED-based TOA Estimation Algorithms

There are many ED-based algorithms for the TOA estimation used for detecting the first path; the simplest algorithm is the MES choosing the first maximum energy:

$$\hat{t}_{MES} = [\arg \max\{z[n]\} + 0.5]T_c = (n_{\max} + 0.5)T_c \quad (10)$$

$$1 \leq n \leq N_c$$

where the TOA is considered as the center of the integral interval. It is possible that the maximum value of the energy is not the first, giving rise to errors even in the high signal-to-noise ratio (SNR) [8]. Therefore, the estimation of the TOA is done on the basis of the TC, and the received values are compared with a suitable threshold  $\xi$ ; in this case, the TOA is estimated as follows:

$$\hat{t}_{TC} = [\min\{n | z[n] > \xi\} + 0.5]T_c \quad (11)$$

Table 1: Comparison of the cluster decay factors for different environments [21]

Environment	Residential		Office		Outdoor	
	LOS	NLOS	LOS	NLOS	LOS	NLOS
Channel Model	CM1	CM2	CM3	CM4	CM5	CM6
$\Gamma$ (ns)	22.61	26.27	14.6	19.8	31.7	104.7

### 3.1 The Proposed Method

In the common method, the transmission position of the main pulse is fixed within the frame. If the interference along different symbols is also occurred at a constant position of the frame, the TOA will be strongly affected after averaging over different frames; and if the interference pulse starts before the main pulse, it will be estimated as the main entrance time, leading to large errors. The main idea of the present work is to get a constant interference energy along the frame after averaging; a constant interference along the frame does not cause any error in detecting the starting time of the pulse, and it is sufficient to take the effect of this constant interference just in the chosen threshold; to this end, it is needed to consider the TH code of the users along different symbols to be pseudo-random, and to use  $N_h = N_c$ ; then, owing to the point that the interference position with respect to the main pulse is always changing in different symbols, the interference energy after averaging over the symbols will be evenly distributed at different distances from the main pulse, and thus, will be approximately constant. The assumption of  $N_h = N_c$  results in interference between the frames, which should be taken into account in determining the threshold.

### 3.2 The Proposed Threshold Determination

Determining an appropriate threshold is of vital significance, and strongly influences the estimation of the TOA. None of the threshold determination methods proposed so far [6,8,9,11] can provide us with an appropriate threshold in the presence of the interference, as the system considers the arrival time of the interference received before the main pulse as the TOA. However, in

our proposed method, if the number of the symbols  $N_{sym}$  is large enough, the sum of the interference and noise along the frame will be approximately constant, and thus, can be considered as the threshold. Our simulations indicate that about 1000 symbols suffice to have the summation of the interference and noise energies constant; this constant value is indeed the expectation value of the sum of the energies of the noise, and the inter frame interference (IFI) and multi user interferences (MUIs):

$$\xi = \mu_N + \mu_{IFI} + \mu_{MUI} \quad (12)$$

where  $\mu_N$ ,  $\mu_{IFI}$ , and  $\mu_{MUI}$  are respectively the expectation values of the energies of the noise, IFI, and MUI within each chip. It can be proven that [24]:

$$\mu_N = N_f \cdot B \cdot N_0 \cdot T_c \quad (13)$$

$$\mu_{IFI} = \left(3 + \frac{1}{e^{\Gamma} - 1}\right) \frac{E_s}{N_c^2} \quad (14)$$

$$\mu_{MUI} = \sum_{u=2}^U \frac{E_s^{(u)}}{N_c} \quad (15)$$

where  $\Gamma$  is the exponential decay constant of the clusters in the IEEE 802.15.4a model. This coefficient has been tabulated in Table 1 for different environments [21].  $N_0$  is the noise density. The coefficient  $N_f$  in  $\mu_N$  is because of the summation done over  $N_f$  energy samples of the noise within the frames of a symbol.  $\sum_{u=2}^U E_s^{(u)}$  is the sum of the energies of the interfering users in each symbol, and  $E_s^{(1)}$  is the energy of the desired user, which for the sake of simplicity is indicated as  $E_s^{(1)} = E_s$ .

### 3.3 SBSMC Algorithm

The multipath components received in UWB channels enter the receiver in many clusters, and the cluster of the first path may not be the strongest. To detect the arrival time of the first cluster, we have made use of the SBSMC algorithm [19] which is on the basis of detecting the largest sample and backward element-by-element search within a window of the length of  $w_{sb}$ ; in this algorithm, the number of K samples, which are the noise and interference samples, before the detected sample should be smaller than the threshold.  $w_{sb}$  is calculated on the basis of the time delay at which the largest path is received after the arrival of the first path, which is typically 60 ns [18]. Hence, the TOA is estimated as follows [19]:

$$\begin{aligned} i &= [\max \arg \in \{n_{\max}, \dots, n_{\max} - w_{sb}\} | z[n] > \xi \text{ and} \\ &\max \{z[n-1], \dots, z[\max(n-K, n_{\max} - w_{sb})] < \xi + 0.5\}] T_c \end{aligned} \quad (16)$$

## 4. Simulation Results

The parameters of the TH-IR system considered here are as follows: the shape of the received pulses is the second derivative of the Gaussian pulse. Two models of indoor residential channels in LOS conditions, the CM1 model, and

the indoor office environment in LOS conditions, the CM3 model, have been used. The channel realizations are sampled at 10 GHz, and 100 different realizations are produced; each realization has one TOA. The criterion for making comparison between our method and other methods is the mean absolute error (MAE). The variance of the noise is assumed to be 1, and  $E_s$  is calculated for obtaining different  $\frac{E_s}{N_0}$  ratios. To model the MUI, one interfering user is considered; that is  $U=2$ . The simulations were done for five situations:  $\frac{E_s^{(2)}}{N_0} = 0, 10, 20, 30 dB$ , and the situation in which there is no interfering user.

The other parameters of the simulations are  $T_c = 4 ns$ ,  $T_f = 128 ns$ ,  $T_{sym} = 512 ns$ ,  $B = 500 MHz$ ,  $w_{sb} = 15$  (according to 60 ns). The number of the averaged symbols is  $N_{sym} = 1000$ . Three methods compared with each other are i) the old method with the use of  $N_h = N_c/2$  and a constant TH code among different symbols (random within different frames), and the threshold given in Ref. [9], ii) the method i and using averaging nonlinear filtering [18], and iii) the new method with  $N_h = N_c$ , based on random TH code among different symbols, and the threshold obtained by our proposed method. The simulation results of channel CM1 shown in Figs. 2-6, and of channel CM3 shown in Figs. 7-11 indicate that the ranging error of the present method is less than that of the other methods, particularly in the presence of strong interferences and high values of  $\frac{E_s}{N_0}$ .

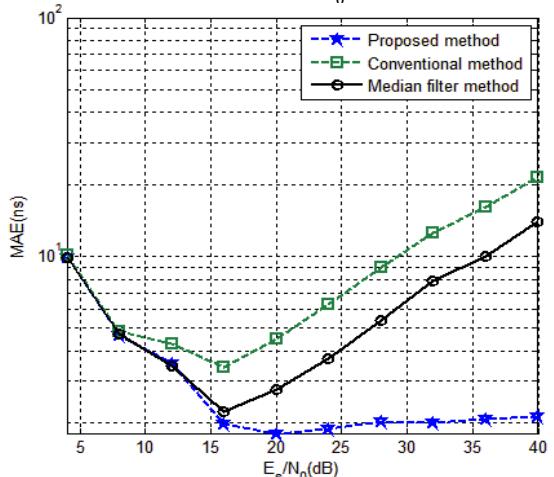


Fig. 2 MAE with no interference in CM1

In the presence of interference at levels of  $\frac{E_s^{(2)}}{N_0} = 0, 10, 20 dB$  the proposed method can achieve the error below 4 ns that is equivalent to a chip at high  $\frac{E_s}{N_0}$  (12 dB or higher). Even when the interference is high, like at  $\frac{E_s^{(2)}}{N_0} = 30 dB$ , our method can reduce the estimation error at higher  $\frac{E_s}{N_0}$ , whereas in other compared methods not exist this decreased error.

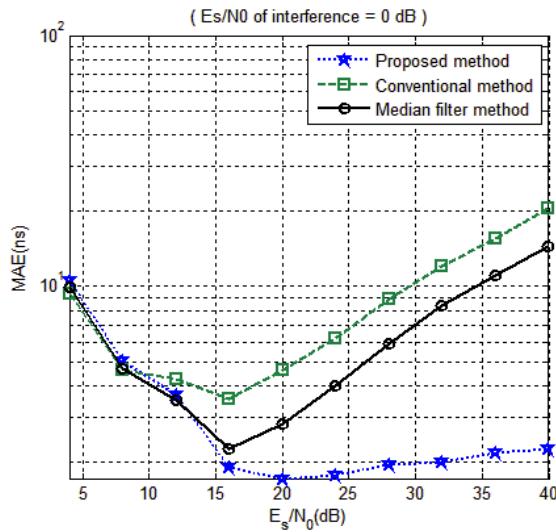
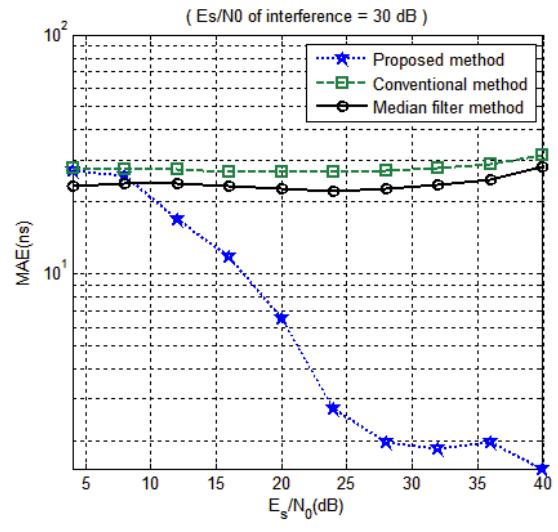
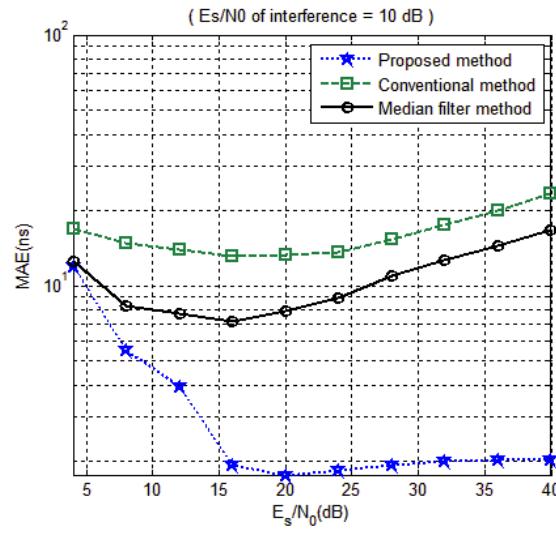
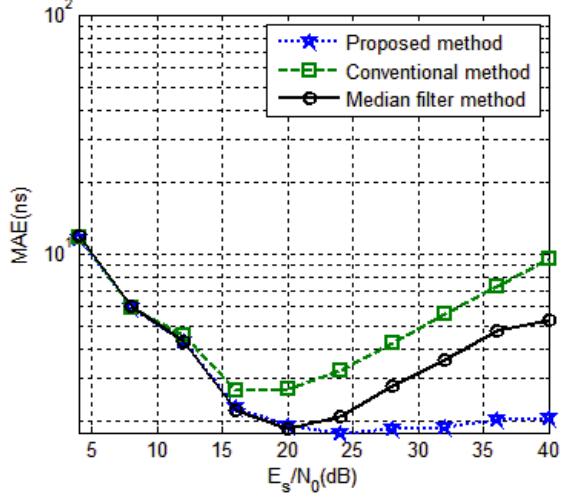
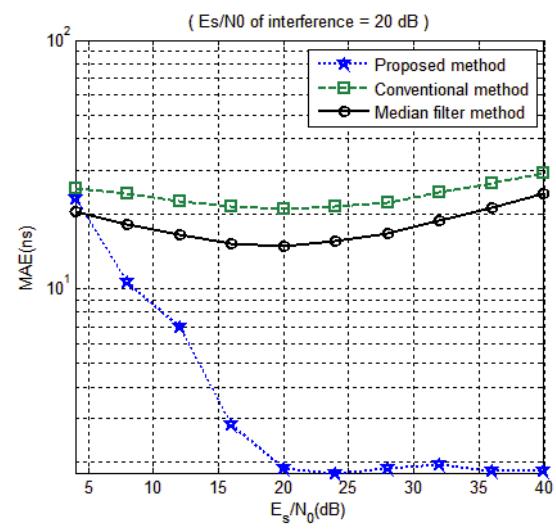
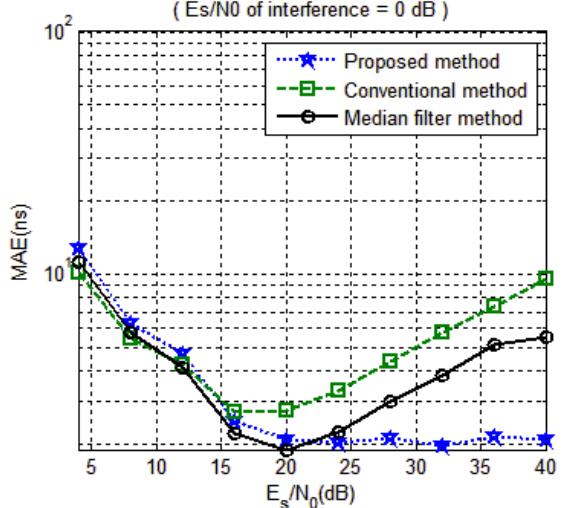
Fig. 3 MAE with interference user  $\square s \frac{E_s}{N_0} = 0 \text{ dB}$  in CM1Fig. 6 MAE with interference user  $\square s \frac{E_s}{N_0} = 30 \text{ dB}$  in CM1Fig. 4 MAE with interference user  $\square s \frac{E_s}{N_0} = 10 \text{ dB}$  in CM1

Fig. 7 MAE with no interference in CM3

Fig. 5 MAE with interference user  $\square s \frac{E_s}{N_0} = 20 \text{ dB}$  in CM1Fig. 8 MAE with interference user  $\square s \frac{E_s}{N_0} = 0 \text{ dB}$  in CM3

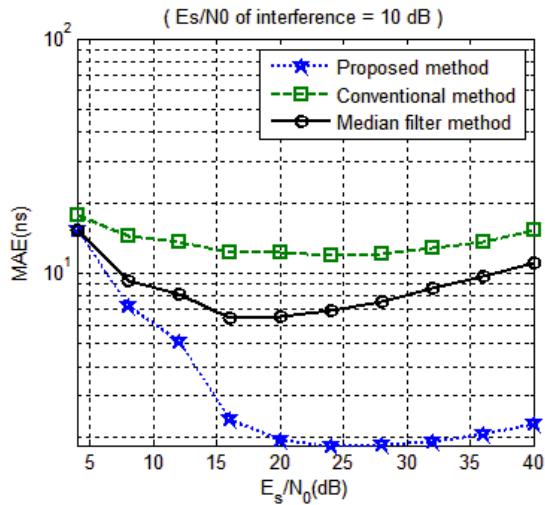


Fig. 9 MAE with interference user  $\frac{E_s}{N_0} = 10 \text{ dB}$  in CM3

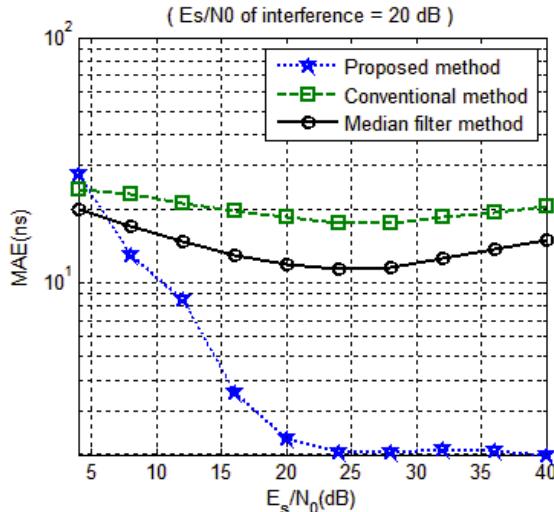


Fig. 10 MAE with interference user  $\frac{E_s}{N_0} = 20 \text{ dB}$  in CM3

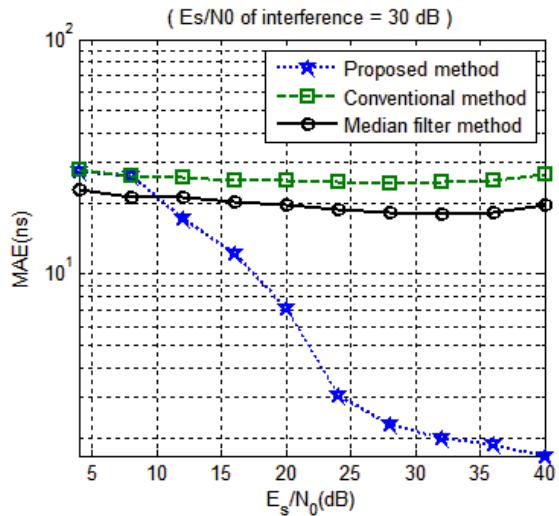


Fig. 11 MAE with interference user  $\frac{E_s}{N_0} = 30 \text{ dB}$  in CM3

## 5. Conclusions

A new method based on the ED has been put forward for improving the estimation of the TOA in UWB systems with multi-path channels and in the presence of interference. The problem of the multi-path channels has been tackled with the use of the SBSMC algorithm. Moreover, a new approach, which can be called interference smoothing, has been suggested for lowering the destructive effect of the interference on the TOA estimation. This method can increase the accuracy of the distance measurements, particularly in the presence of strong interferences; indeed, it can remove the problem of the earlier-than-the-first-path detection which usually occurs due to the presence of interference. The capability of the present method has also been proven through some simulations.

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**Mahdieh Ghasemlou** received the B.S. degree in Electrical engineering from Guilan University, Rasht, Iran, in 2008, and the M.Sc. degree in telecommunication engineering from Islamic Azad University Tehran South branch, Tehran, Iran, in 2013. Her research interests include the area of wireless communication systems, with emphasis on ultra wideband (UWB) communications, Ranging and localization techniques.

**Saeid Nader-Esfahani** received the B.S. degree in electrical engineering from University of Tehran, Tehran, Iran, in 1970, and the M.Sc. degree and the PHD degree in telecommunication engineering, University of Essex, England, in 1975 and 1978, respectively. He has done research in the areas of approximation and synthesis of filters, equalizations, adaptive filters, applications of cyclostationarity in signal processing, applications of HOS in signal processing, wireless communication systems. His current research interests include Blind Equalizations, OFDM systems, Ultra Wideband systems, compressive sensing, and cognitive radio. He is a Professor of Telecommunications of the University of Tehran. He has published more than 80 international journals, conference papers.

**Vahid Tabataba-Vakili** received the B.S. degree in electrical engineering from Sharif University of Technology, Tehran, Iran, in 1970, and the M.Sc. degree and the PHD degree in communication systems engineering, Bradford University, England, in 1974 and 1978, respectively. His research interests include multi-user detection, space-time processing & coding, Bandwidth efficient digital modulation & coding, mobile radio cell planning, mobile cellular systems with emphasis on resource and mobility management, physical layer of wireless systems with emphasis on source/channel coding, MIMO and multi-access systems. He is a Professor of Telecommunications of Iran University of Science & Technology. He has published more than 110 international journals, conference papers.