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Channel-based Optimization of Transmit-Receive Parameters for Accurate Ranging in UWB Sensor Networks

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ABSTRACT

Accurate positioning can be achieved by using ultra-wideband (UWB) wireless sensor network technology. For this purpose, several parameters should be optimized in the transceivers to achieve accurate estimation of the time-of-arrival (TOA) of the first multipath component. Optimum parameters depend on the environment where the positioning is held on. This paper presents a rigorous simulation-based method for simultaneous optimization of parameters, affecting the accuracy of the TOA estimation, in several standard UWB channel types. Optimum values of parameters are computed through rigorous simulation-based ranging trials, for the standard channels.
KEYWORDS- *UWB; channel; TOA; Ranging; optimization; IEEE 802.15.4a*

1. INTRODUCTION

Localization capability is essential in most of the wireless sensor network applications. However, the precise location information may be unavailable due to the constraint in energy, computation, or terrain. Ultra-wideband (UWB) is a promising solution to this problem, which became popular after the Federal-Communications-Commission (FCC) in the USA allowed the unlicensed use of UWB devices in February 2002, subject to emission constraints. Due to its unlicensed operation and low-power transmission, UWB can coexist with other wireless devices, and its low-cost, low-power transceiver circuitry makes it a good candidate for short- to medium-range wireless systems such as WSNs and wireless personal area networks (WPANs).

Ranging is one of the most important phases of positioning and several issues make this phase challenging. The transmitted signal will usually arrive at the receiver via several paths, referred to as multipath, where the signal encounters various propagation mechanisms such as reflection, scattering, and/or diffraction. In a typical UWB channel, the first path may be considerably weaker than the strongest component, and it may arrive several tens of nanoseconds earlier than the strongest [1].

Methods have been suggested to correct the errors caused by this discrepancy. Jump-back-search-forward (JBSF) [2] is a popular technique for correcting the estimated time-of-arrival (TOA). In this method, the algorithm jumps backwards from the peak index to the beginning of the search back window. Then, it searches for the leading edge in the forward direction, and picks the first threshold-exceeding sample as the leading edge. Therefore, the choice of the window length and threshold can affect the accuracy. Different threshold selection methods are suggested in [3, 4]. The use of a normalized value between the minimum and maximum energy samples, and the minimization of the mean-absolute-error (MAE) of the TOA estimate is considered in [2, 3].

This paper presents a rigorous method for *simultaneous* optimization of parameters, affecting the accuracy of TOA estimation, in standard UWB channels. The factors which mutually affect each other are: the channel, order of the Gaussian monocycle, threshold, and the JBSF window length. To the best knowledge of the authors, no previous papers have dealt with simultaneous optimization of the above parameters, to enhance the ranging accuracy. In addition, the distance between the unknown transmit-receive point affects optimum values of the above parameters. As the distance is unknown, it is desirable to minimize its mutual effects with other optimization parameters. This paper suggests optimum parameter values for several standard channel types, including, residential, outdoor, office, and industrial, while the effect of the distance, on the ranging error, is minimized. In fact, the dependence of the distance on the ranging error is evaluated, in such a way that it is considered as an optimization parameter. For further enhancing of the ranging accuracy, some *bias* values as a correction parameter are suggested, for each standard channel type. The parameter values given in this paper are obtained based on intensive simulation-based trials.

In the remainder of the paper, basics of ranging, in UWB sensor networks, are explained. Next, the previous and new methodologies are presented. Finally, the results, discussions, and conclusions are made.

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2. Fundamentals of Ranging

2.1. Receiver Model

Due to the extremely large bandwidths of IR-UWB systems, satisfying the Nyquist sampling rate condition is practically unrealizable; therefore, the leading edge detection may have to be achieved at lower-rate samples. This can be realized using energy blocks and processing the signal with a square-law device before sampling it. The signal arriving at the receiver antenna is first passed through a band-pass filter of bandwidth B, processed with a square-law device, and finally fed to an integrator and dump device with a sampling duration of t_s. In order to improve the ranging accuracy the resulting samples are further averaged over N_l symbols, thanks to the long preambles dedicated for accurate ranging. The schematic of an ED receiver is illustrated in Fig. 1 [4].
The integrator output samples can be expressed as

$$z[n] = \frac{1}{N_l}\sum_{j=1}^{N_t}\int_{(j-1)T_f+(n-1)l_s}^{(j-1)T_f+nl_s} |r(t)|^2 dt \qquad (1)$$

Once the received signal is sampled, the leading edge sample can be searched back starting from the strongest sample. In [2], a search-back scheme is discussed for finding the leading edge. The algorithm jumps backward to a prior sample, and starts searching for the leading edge in the forward direction. The parameters, such as the search-back window length w, threshold, etc., for this approach can be optimized based on the statistics of a particular channel model.

2.2. The Transmit Signal and Receiver Parameters

There are two important matters that should be considered while designing the transmit signal: i) the compliance to the FCC limit, while maximizing the power, to achieve the highest possible SNR, ii) maximizing the zero correlation zone, prior to the leading edge, to minimize the self-interference. Typically a Gaussian monocycle of the following form is used:

$$p(t) = \frac{A}{\sqrt{2\pi\tau^2}} e^{(-t^2/2\tau^2)} \quad (2)$$

where, A and τ are the amplitude and spread of the pulse, respectively. To better comply with the FCC spectrum regulations, it is usually preferred to use the time-derivatives of the Gaussian monocycle. In the n^{th} derivative of the monocycle, $p_n(t)=dp(t)/dt$, the unit of A is chosen properly so that $\int p_n^2(t)dt$ is expressed in Joules. It is desirable to increase A and decrease τ to reach the highest SNR and the shortest pulse duration. But, this can cause the power spectrum exceed the FCC-defined limits. Designing the transmission formats is also important to prevent inter-pulse and inter-symbol interferences. In [4], four different signaling waveforms (DS-IR, TR-IR, MTOK-IR, TH-IR) are presented, and their characteristics and trade-offs are discussed. The MTOK sequences of length 31 have optimal correlation characteristics, when they are processed with a bi-polar template at the receiver.

In a JBSF algorithm, there is a trade-off between the window length and the threshold. If the window length and threshold are selected, respectively, too short and too high, the probability of the first ray detection decreases. Also, if the window length and threshold are selected, respectively, too long and too low, the probability of the false alarm increases. Maximization of the probability of detection of the leading edge does not necessarily yield the best ranging accuracy. It is suggested that the optimum threshold is the value which minimizes the MAE of the TOA estimate [3]. This is expressed as:

$$\xi_{opt} = \underset{\xi}{\operatorname{argmin}}\{e^{(\mathrm{MAE})}(n_{le} \mid \xi, D_{le}, E_\lambda, \sigma_n^2)\} \qquad (3)$$

where ξ_{opt} is the optimum threshold value, n_{le} is the index of the first arriving path, D_{le} is the delay vector, which shows the number of noise-only samples prior to the leading one, E_λ is a vector of waveform energies falling within different samples, λ indicates the channel realization number, and σ_n^2 is the variance of the noise, typically assumed to be an additive white Gaussian noise (AWGN).

3. THE PROPOSED METHODOLOGY

The idea is to minimize the mean absolute error of the range estimation, by optimally selecting the order of the Gaussian monocycle, threshold, and window length. This is expressed as:

$$\{\xi_{opt}, n_{opt}, w_{opt}\} = \underset{\xi,n,w}{\operatorname{argmin}}\{e^{(\mathrm{MAE})}(n_{le}|\xi, n, w, D_{le}, E_\lambda, \sigma_n^2)\} \qquad (4)$$

where, ξ_{opt} , n_{opt} , w_{opt} are the optimum values for the threshold, the order of the monocycle, and the window length, respectively. Other parameters were defined in the previous section. Amongst all possible transmission formats, mentioned previously, the MTOK is selected, as it provides suitable correlation characteristics. For each n, order of a Gaussian monocycle, parameters A and τ are selected so that the generated MTOK signal maximally fits and utilizes the available power and bandwidth, specified by the FCC mask. As the mask is different for indoor and outdoor environments, different sets of parameters will be presented.

The numerical optimization approach can be explained as follows. For a given standard channel, the UWB channel parameters are taken from the IEEE 802.5.4a models [1]. Then, realistic received signals, containing multipath components, are generated, accordingly. The arrival time of the received signal and amplitude fading is implemented with respect to an arbitrarily selected distance between a pair of transmit-receive points. Finally, noise is added, and the overall simulated signal is applied to a receiver block. At the receiver, a JBSF-based TOA estimation algorithm is implemented. Simulations are performed for several distance values. Optimum window length, threshold, and the order of the Gaussian monocycle are found by carefully studying the mean and standard deviation of the distance-estimation error values. The procedure will be explained shortly.

Two cumulative distribution functions (CDFs) are defined and used, as follows. i) The CDF for the “peak to lead duration”, denoted as CDF_{PLD}. ii) The CDF for the “peak to lead energy ratio”, denoted as CDF_{PLR}. The CDF_{PLD} is used to select the search back window length. If the PLD which corresponds to the CDF_{PLD} =1 is set for the window length, the first sample will be located in the search back window. But, this will increase the probability of false alarm. Instead, the PLD corresponding to the CDF_{PLD} values less than one, may decrease the TOA estimation error. The CDF_{PLR} is used to set the threshold. If the square of the inverse of the PLR which corresponds to the CDF_{PLR} =1 is used as the threshold, the sample which contains the lead will be detected. However, this will increase the probability of the noise detection. Instead, the square of the inverse of a PLR value, which corresponds to a CDF_{PLR} value less than one, can decrease the TOA estimation error.

4. NUMERICAL RESULTS AND DISCUSSIONS

For a selected derivative of the Gaussian monocycle, $p_n(t)$, the values of A and τ are selected so that the power spectrum of the MTOK sequence fits the FCC mask. This is done, both for indoor and outdoor masks. The results are shown in Table I. The power spectral density of an MTOK transmit signal, using the 4th order Gaussian monocycle, n=4, along with the FCC indoor mask, is shown in Fig. 2.

The cumulative distribution functions, CDF_{PLD} and CDF_{PLR}, for some channel models are shown in Figs. 3 and 4, respectively. Each CDF is obtained base on 1000 times generation of each channel. The CDF_{PLD} of CM6 is not plotted in Fig. 3, because its time axis is not within the area of other channels. Also, the CDF_{PLA} of CM2 and CM6 is not plotted in the Fig. 4, as their amplitude ratio is not within the area of the other channels.

The window length, w, has been chosen as numbers corresponding to CDF_{PLD} = 0.9, 0.95, 0.99. It is observed that the w corresponding to CDF_{PLD}=0.95 results in smaller errors in ranging, compared to other values corresponding to CDF_{PLD} =0.90 and 0.99. The w values found using this procedure, for CM1 to CM8 standard channels, are presented in Table II. Similarly, suitable thresholds are estimated as the square of the inverse of the PLR, corresponding to a CDF_{PLR} =0.9, 0.95, 0.99 for each standard channel. These values are presented in Table III.

To generate realistic received signals, with all multipath components, standard UWB channel parameters are used. For each given distance, the delay, corresponding to the direct path is computed and applied to the simulated received signal. Noise is also added, and the overall simulated signal is applied to a receiver block, where a JBSF-based TOA estimation algorithm is examined. The MTOK transmit signal is generated, and passed through a filter whose impulse response is a simulated channel impulse response. Then, an AWGN noise with zero mean and variance σ_n^2 is added to the signal,

$$\sigma_n^2 = kTB \qquad (5)$$

where, k is the Boltzmann constant, 1.38×10^{-23}J/K, T is the absolute temperature, chosen to be 290K, and B is the 10dB bandwidth of the received signal. While the suitable order of Gaussian monocycle is estimated in the noiseless channel, the spectrum of the received signal and its bandwidth is calculated. The 10dB bandwidth of the received signal for standard channels is presented in Table IV.

In order to estimate the distance between a pair of transmit-receive points, a packet of 1024 symbols, as preamble, is used [5]. To calculate the mean and variance of the TOA estimation error, each packet is transmitted 100 times. For each channel model, simulations are performed for distance values of 1, 10 and 30 meters, as the IEEE 802.15.4a models consider ranges up to 30 meters. Suitable threshold and order of the Gaussian monocycle is found based on the error of the distance measurement between a pair of transmit-receive points. Mean of errors for the residential environment are shown in Table V.

Simulation results show that the standard deviation of the errors for 100 transmission events is much smaller than their mean. This is an interesting observation, meaning that the average ranging error, for a given channel type, with specific parameter values, can be treated as a *bias*, or *correction parameter*. The bias, positive or negative, is subtracted from the estimated distance, to correct the estimated range. Therefore, the threshold and the order of Gaussian monocycle which result in similar average errors, for all ranges, should be chosen. For the CM1 (residential LOS) and CM5 (office LOS), ranges up to 10m are considered to be more important, as it is assumed that the LOS ranges more than 10m are less probable to occur.

A positive bias occurs in NLOS regions when the first block, exceeding the chosen threshold, does not include the first ray. Also, it can occur when the first block, which includes the first ray, is detected, while the first ray arrives with a delay, due to NLOS effects. In contrast, a negative bias occurs when a noise-only block prior to the first ray is mistaken for the first ray. The channel and selected parameters affect this phenomenon and the value of the bias. Table VI shows the values of the bias for CM1-CM8 standard channels, where suitable values for parameters n and ξ are also suggested.

As observed in Table V, for CM1 model, considering distance values of 1m to 10m only, the smallest mean absolute difference of errors for various distances (1m and 10m) is obtained for n=3 and ξ=0.99. As the best results are found with n=3 for CM1, optimum parameter values for CM2, is selected from the column with n=3. It is observed that the minimum variance is obtained by selecting the threshold value of 0.9. Similar procedure is performed for other channels. The resulting suitable parameters are suggested in Table VI.

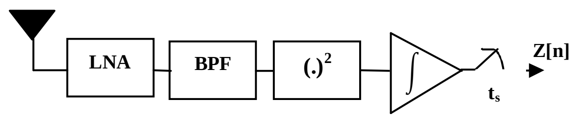

Fig. 1. Sampling the received waveform

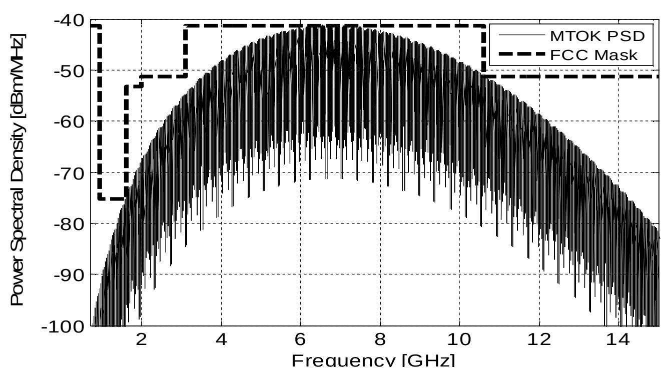

Fig. 2. Power spectral density of an MTOK transmit signal, using the fourth order Gaussian monocycle, with respect to the FCC indoor mask.

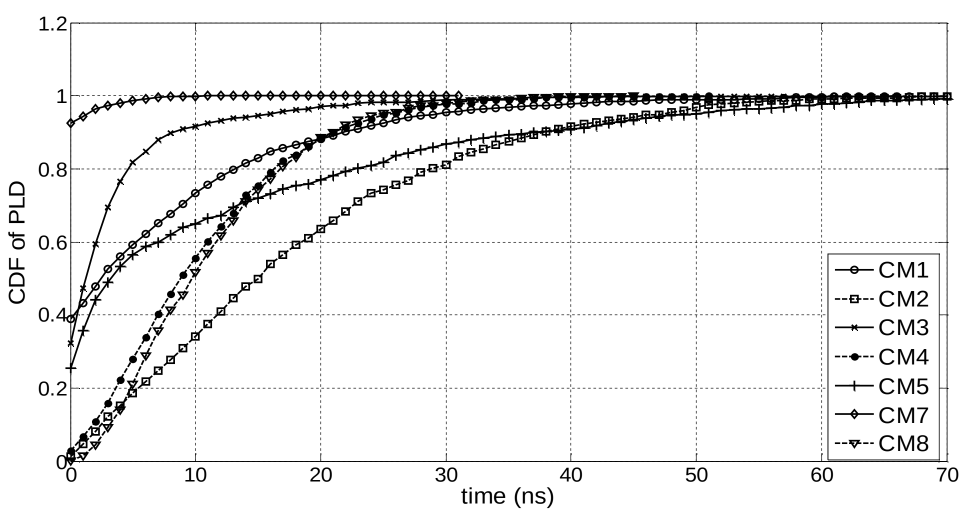

Fig. 3: CDF_{PLD} of channel models

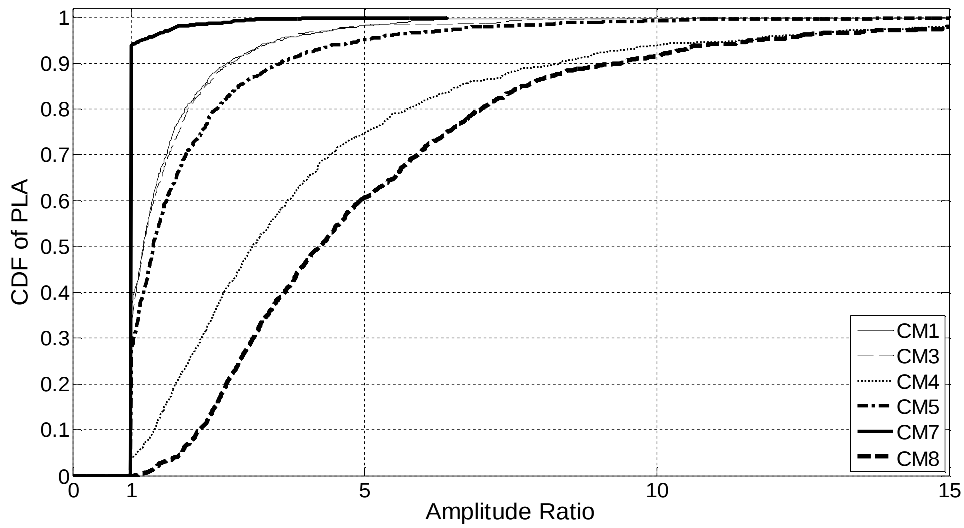

Fig. 4: CDF_{PLA} of channel models

Table I. Parameter values for different orders of the Gaussian monocycle

Order, *n*	***n*=2**		***n*=3**		***n*=4**		***n*=5**		***n*=6**		***n*=7**	
Parameters	*A* $[W.s^{-3}]$	*τ [s]*	*A* $[W.s^{-4}]$	*τ [s]*	*A* $[W.s^{-5}]$	*τ [s]*	*A* $[W.s^{-6}]$	*τ [s]*	*A* $[W.s^{-7}]$	*τ [s]*	*A* $[W.s^{-8}]$	*τ [s]*
Indoor	8.5e-36	2.3e-11	7e-46	3.6e-11	8.5e-56	4.7e-11	9.5e-66	6.5e-11	6.3e-76	7.5e-11	4.4e-86	8.5e-11
Outdoor	8.5e-36	2.3e-11	7e-46	3.6e-11	4e-56	4.3e-11	2e-66	5e-11	1.1e-76	5.8e-11	0.8e-86	6.8e-11

Table II. Search back window length corresponding to CDF_{PLD}=0.95

Channel	**CM1**	**CM2**	**CM3**	**CM4**	**CM5**	**CM6**	**CM7**	**CM8**
***w* [ns]**	30	48	16	26	50	214	2	25

Table III. Threshold values for standard channels

	Threshold, *ξ*							
CDF_{PLR}	CM1	CM2	CM3	CM4	CM5	CM6	CM7	CM8
0.9	0.1435	0.513e-6	0.1351	0.0143	0.0789	0.163e-33	0.9025	0.0115
0.95	0.0816	0.164e-6	0.0797	0.0074	0.0414	0.813e-34	0.7062	0.0074
0.99	0.0309	0.371e-7	0.0185	0.0035	0.0275	0.250e-34	0.1468	0.0030

Table IV. 10dB bandwidths of the received signal for standard channels

Channel	**CM1**	**CM2**	**CM3**	**CM4**	**CM5**	**CM6**	**CM7**	**CM8**
***B* [GHz]**	2-13.4	1.8-13.8	1.8-13	1.8-15	1-21.8	1.9-22	1.4-20.7	1.3-17.5

Table V. Mean error in CM1 and CM2 for different orders and threshold, corresponding to CDF_{PLR} values

CDF_{PLR}	**Distance [m]**	***n*=2**		***n*=3**		***n*=4**		***n*=5**		***n*=6**		***n*=7**	
		CM1	CM2	CM1	CM2	CM1	CM2	CM1	CM2	CM1	CM2	CM1	CM2
0.9	1	0.56	0.44	0.59	0.19	0.60	0.06	0.51	-0.08	0.52	-0.09	0.49	-0.10
	10	0.55	0.43	0.55	0.18	0.56	0.06	0.49	-0.20	0.51	-0.34	0.46	-0.45
	30	0.42	0.17	0.46	0.03	0.44	-0.16	0.30	-0.40	0.29	-0.52	0.28	-0.67
0.95	1	0.45	0.39	0.47	0.14	0.48	-0.03	0.31	-0.13	0.31	-0.14	0.30	-0.14
	10	0.44	0.38	0.45	0.14	0.46	-0.04	0.20	-0.30	0.30	-0.45	0.26	-0.59
	30	0.35	0.09	0.25	-0.01	0.26	-0.23	0.16	-0.49	0.07	-0.64	0.09	-0.79
0.99	1	0.36	0.37	0.28	0.12	0.38	-0.11	0.16	-0.17	0.03	-0.17	0.07	-0.17
	10	0.35	0.34	0.28	0.10	0.35	-0.12	0.15	-0.39	0.02	-0.55	0.07	-0.70
	30	0.31	0.04	0.09	-0.05	0.10	-0.28	0.05	-0.58	-0.16	-0.75	-0.16	-0.91

Table VI. Suitable parameters for all environments

		Parameters		
Environment	Channel	*n*	ξ	Bias
Residential	CM1	3	0.99	0.28
	CM2		0.90	0.12
Outdoor	CM3	3	0.90	0.19
	CM4		0.90	-0.12
Office	CM5	2	0.90	0.63
	CM6		0.90	0.3
Industrial	CM7	2	0.99	0.25
	CM8		0.90	0.40

5. **Conclusions**

In this paper, a rigorous method for simultaneous optimization of essential parameters in the transceivers of an UWB positioning system is presented. It is found that the receiver window length, and threshold, as well as the order of the Gaussian monocycle, at the transmitters, can be optimized, simultaneously, for the best ranging accuracy. Optimum values of parameters, for several standard UWB channels, including residential, outdoor, office, and industrial, are obtained based on rigorous simulation-based ranging trials. The mean value of the ranging error is also observed to be consistently a positive or negative value, with small standard deviation. As a result, the mean error can be subtracted from the estimated distance, as a bias. Numerical values of the bias, associated with other optimum parameter values are presented for each standard channel.

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