Adaptive CA-CFAR Threshold for Non-Coherent IR-UWB Energy Detector Receivers

Abdelmadjid Maali, Ammar Mesloub, Mustapha Djeddou, Hassane Mimoun, Geneviève Baudoin, and Abdelaziz Ouldali

Abstract—In the present letter, a new adaptive threshold comparison approach for time-of-arrival (TOA) estimation in ultra wideband (UWB) signals is proposed. This approach can be used with non-coherent energy detector receivers in UWB systems. It exploits the idea of cell averaging constant false alarm rate (CA-CFAR) used in radar systems, where the threshold changes every energy block. The performance of several approaches are compared via Monte Carlo simulations using the CM1 channel model of the standard IEEE 802.15.4a. Both simulation results and comparisons are provided highlighting the effectiveness of the proposed approach.

Index Terms—Time-of-arrival (TOA), ultra wideband (UWB), cell averaging constant false alarm rate (CA-CFAR).

I. INTRODUCTION

ULTRA-WIDEBAND (UWB) is a promising technology that offers many advantages. It is used in numerous applications and especially in wireless sensor networks. The most interesting advantage this method provides for localization problems is the high time resolution [1]. One of the problems for UWB receivers is to find the first arrived path. This is called time-of-arrival (TOA) estimation problem.

The most commonly used UWB receivers are matched filter (MF) receivers and energy detection (ED) receivers. MF receivers operate at high sampling frequency and use complex algorithms, which make them inadequate for some applications. ED receivers work at sub Nyquist sampling frequency and use low complex algorithms that make them low cost and good candidates for many applications [2]. With ED receivers, the TOA estimation problem consists of detecting the first energy block containing the received signal energy. A simple way to deal with this problem is to choose the maximum energy block as a leading edge. This method is called maximum energy selection (MES) [2][3]. A second way compares each energy block to an appropriate threshold. This approach is called threshold comparison (TC) [2][3]. A third way called maximum energy selection with search back (MESSB) [2], which is, combines the previous two algorithms.

In the present letter, a new adaptive threshold algorithm is derived for TOA estimation. It is an application of cell averaging constant false alarm rate (CA-CFAR) radar in non-coherent UWB energy detector receivers.

II. SIGNAL MODEL

In impulse radio UWB systems, the received signal can be expressed as

\[ r(t) = \sum_{i=-\infty}^{+\infty} b_i w_{rs}(t - iT_s) + n(t), \]  

where \( b_i \) is the bit information, \( i \) is the symbol index and \( T_s \) is the symbol duration. \( n(t) \) is an additive white Gaussian noise with variance \( \sigma^2 \). \( w_{rs}(t) \) is the received symbol waveform given by

\[ w_{rs}(t) = \sum_{j=0}^{N_f-1} w_r(t - jT_f - c_jT_c), \]

where \( N_f \) is the number of frames per symbol, \( T_f \) and \( T_c \) are the frame and chip durations respectively, \( \{c_j\} \) are the time hopping codes used to avoid catastrophic collision between multiple users. \( c_j \in \{0, ..., N_c - 1\} \), with \( N_c \) being the number of chips per frame. Finally, \( w_r(t) \) is the received pulse waveform, which is expressed as

\[ w_r(t) = \sum_{\tau_l}^{L} \alpha_l w(t - \tau_l), \]

where \( \{\alpha_l, \tau_l\} \) are the attenuation and delay of \( l^{th} \) path respectively, \( w(t) \) is the emitted pulse waveform. \( \tau_{TOA} = \tau_l \) is the delay of the first arrived path and \( L \) is the number of multipath components.

The signal at the receiver antenna is amplified by a low noise amplifier (LNA), passes through a band-pass filter (BPF), is processed with a square law device, and feeds an integrator before sampling as indicated in Fig. 1.

The integrator output samples provide energy blocks denoted \( z(n) \) and expressed as [2][4]:

\[ z(n) = \sum_{j=0}^{N_f-1} \int_{jT_f + (c_j+n-1)T_b}^{(j+1)T_f + (c_j+n)T_b} |r(t)|^2 dt, \]

where \( n \in \{1, 2, ..., N_b\} \) stands for the block index, \( T_b \) is the integration and sampling period, \( N_b \) is the number of blocks contained in the time frame \( T_f \) and half of the next frame,
illustrated in Fig. 3. Then the estimated TOA is given by

\[
\text{TOA} = \frac{\text{sum of energy blocks from both sides}}{\text{channel mean delay}},
\]

where \( N_b \) is the sum of energy blocks from both sides, excluding guard blocks. Generally, the guard blocks duration is chosen larger or equal to the channel mean delay \( \tau_c \).

III. PROPOSED APPROACH: CA-CFAR THRESHOLD

The proposed approach is summarized in Fig. 2. The main idea is to apply the CA-CFAR technique used for threshold computation in radar systems [6]. Each energy block or block under test (BUT) \( z(n) \) is compared to an adaptive threshold, which is formed by the sum of other blocks subsequently multiplied by a threshold multiplier \( T \). The first block exceeding this adaptive threshold is considered a leading edge block as illustrated in Fig. 3. Then the estimated TOA is given by

\[
\tau_{CA-CFAR} = \min_n \{z(n) > T U\} - 0.5T_b,
\]

where \( U = \sum_i z(i) \) is the sum of energy blocks from both sides, excluding guard blocks. Generally, the guard blocks duration is chosen larger or equal to the channel mean delay [6].

A. Relation between thresholds and false detection probability

This section gives the relationship between false detection probability \( P_f \) and threshold multiplier \( T \). In addition, it shows how \( P_f \) changes when \( T \) either increases or decreases. The development is presented for two cases: fixed and CA-CFAR threshold.

1) Fixed threshold: In [5], \( z(n) \) assumed a centralized chi-square distribution for noise blocks only and a non-centralized chi-square distribution for noise plus signal blocks, i.e.,

\[
z_n(n) \sim \chi^2(M, \sigma^2), \quad (7)
\]

\[
z_s(n) \sim \chi^2(M, \sigma^2, E_n), \quad (8)
\]

where \( z_n(n) \) and \( z_s(n) \) are the noise energy blocks and the noise plus signal energy blocks respectively. \( M \) is the degree of freedom, which is approximated via \( M \approx 2BT_b \) [5], where \( B \) is the signal bandwidth. \( E_n \) is the signal energy contained in \( z_s(n) \).

The relationship between the false detection probability \( P_f \) and a fixed threshold \( \xi \) can be expressed as

\[
P_f = P(z(n) > \xi) = \exp\left(-\frac{\xi}{2\sigma^2}\right) \sum_{k=0}^{m-1} \frac{1}{k!}\left(\frac{\xi}{2\sigma^2}\right)^k,
\]

where \( m = \frac{2}{\sigma^2} \approx BT_b \).

2) CA-CFAR threshold: In our approach, the threshold changes every BUT \( z(n) \). The used threshold is \( \xi = T U \) with \( U = \sum_i z(i) \).

If the \( z(i) \) are chi-square distributed so is their sum[7]. For each BUT \( z(n) \), reference energy blocks are taken as noise blocks and they are chi-square distributed with \( M \) degrees of freedom. The sum of the \( z(i) \) denoted \( U \) is chi-square distributed with \( N_b \times M \) degrees of freedom. The false detection probability \( P_f \) can be expressed as

\[
P_f = P(z(n) > T U) = \int_0^{+\infty} \exp(-\xi/T) f_U(u)\,du.
\]

After development, \( P_f \) can be expressed as follows [6]:

\[
P_f = \frac{1}{(1 + T)N_bm} \sum_{k=0}^{m-1} \frac{1}{k!} \left(\frac{N_bm}{N_bm + k}\right)^{N_bm + k} \left(\frac{T}{1 + T}\right)^k.
\]

As for CA-CFAR radar, the false detection probability \( P_f \) only depends on \( T, N_b \) and \( M \).

IV. SIMULATION, RESULTS AND DISCUSSION

In the subsequent simulations, the mean absolute error (MAE) for various approaches is analyzed. The CM1 (residential LOS) channel model of IEEE802.15.4a has been considered [8]. Channel realizations are sampled at 8GHz; one thousand distinct realizations are generated, each of which has a TOA uniformly distributed within \( [0, T_T] \). The other parameters are \( T_T = 200 \times 10^{-6}, N_s = 1 \times 10^6, T_c = 1 \times 10^{-3}, B = 4 \times 10^6 \) and the guard blocks duration is equal to 20\( \times 10^{-6} \).

A. Properties of the threshold multiplier \( T \) in CM1 channel model

Different values of the threshold multiplier \( T \) are investigated in CM1 channel, and the results are depicted in Figs. 4 and 5. For low \( \frac{N_b}{N_s} \), noise blocks are comparable to signal plus noise blocks then \( U \) takes large values. In order to detect the first signal plus noise block, \( T \) must take smaller values.
order to avoid false detections which increase M\textsuperscript{AE}. For high \( \frac{E_b}{N_0} \) values, noise blocks are lower than signal plus noise blocks which makes \( U \) smaller. \( T \) should take larger values in order to avoid false detections which decrease \( P_{fa} \) and \( M\text{AE} \).

**B. Performances of various TOA estimation algorithms**

The performances of various algorithms are assessed in IEEE802.15.4a CM1. Results are summarized in Figs. 6 and 7. \( \xi_n = 0.4 \) and \( w_z = 30 \) ns are the normalized threshold and the searched back window respectively [2]. \( T = 0.015 \) for \( T_b = 1 \) ns and \( T = 0.05 \) for \( T_b = 4 \) ns. We notice that there are two regions a low \( \frac{E_b}{N_0} \) region, where the MES, MESSB and CA-CFAR algorithms give better results than the TC algorithm, and a high \( \frac{E_b}{N_0} \) region, where the proposed approach gives the best results. In the low \( \frac{E_b}{N_0} \) region, there is a problem of false detections made by the noise energy blocks which are important and exceed different thresholds. In the high \( \frac{E_b}{N_0} \) region, noise blocks are not important. Therefore CA-CFAR and TC give the best results. Our approach gives better results thanks to its adaptive threshold, which avoids false detections and gives a more accurate TOA estimation.

**V. CONCLUSION**

In the present letter, a new algorithm for TOA estimation in UWB systems is proposed. This algorithm consists of using an adaptive CA-CFAR threshold, which is formed by the sum of energy blocks and a multiplication by a threshold multiplier and cause several false detections which increase \( M\text{AE} \). For high \( \frac{E_b}{N_0} \) values, noise blocks are lower than signal plus noise blocks which makes \( U \) smaller. \( T \) should take larger values in order to avoid false detections which decrease \( P_{fa} \) and \( M\text{AE} \).

**REFERENCES**