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CFAR-Based TOA Estimation and Node Localization Method for UWB Wireless Sensor Networks in Weibull Noise and Dense Multipath

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***Abstract*—In the presence of dense multipath, the threshold-based time of arrival (TOA) estimation methods have attracted interest for node localization in ultra-wideband (UWB) wireless sensor networks (WSNs). Since the first arrival path is not always the strongest one in many actual situations, we propose to determine the real TOA using the constant false alarm rate (CFAR) detector method. Unlike conventional Gaussian or Rayleigh background, we assume the amplitude of the observal noise to be Weibull distributed. Given the probability of false alarm, the threshold of TOA detector is derived based on Weibull distribution function. Using the obtained TOA values, the multilateral localization is employed to compute the positions of nodes. The three-dimensional (3D) Taylor algorithm is given to solve the non-linear equations. The simulations prove that the proposed method has high time-resolution and low computational load in positioning of WSN nodes under Weibull noise and dense multipath.**

Keywords- wireless sensor networks; 3D node localization; TOA estimation; Weibull distribution; CFAR; dense multipath

I. INTRODUCTION

Wireless sensor network (WSN) consists of a large number of intelligent sensor nodes and has become a new wireless network for information acquisition. In recent years, node localization in wireless sensor network has been widely used in intelligent medical, industrial monitoring, traffic control and military fields [1][2]. With high time-resolution of ultra-wideband (UWB) signals, the range-based time of arrival (TOA) method is a main way in node localization of UWB wireless sensor networks [3]. The process of localization is divided into two steps, the TOA estimation and the position estimation.

TOA estimation problem is conventionally studied with a variety of techniques such as correlator methods, super-resolution subspace methods, etc. Recently, for dense multipath environment, the threshold-based TOA estimation methods in UWB systems have attracted significant interest. In these methods, the first arrival path is detected by comparing the received signal or the output of matched filter (MF) [4]or energy detectors (ED) [5] with a threshold. For ED-based IR-UWB systems, a maximum energy selection (MES) method has been developed in [6] by choosing the maximum energy cell as the first arrived path. However, the strongest energy cell does not necessarily correspond to the first arrival path since TOA estimation is affected by multipath components and non-line sight (NLOS) scenarios. Thus, threshold comparison (TC) method has been proposed in [7] by comparing each energy cell with an appropriate threshold. However, the optimal threshold depends on SNR and channel, the method can not accurately determine the TOA signal. In [8], an adaptive threshold based on cell averaging constant false alarm rate (CA-CFAR) detector is developed. However, at low SNR and non-Gaussian noise, its detection performance is not very satisfactory.

In general, the current threshold-based TOA methods only work well under Gaussian noise background, in which the amplitude of observal noise is Rayleigh distributed. However, there is actual noise such as band-limited white noise, whose amplitude is not Rayleigh distributed.

In this paper, we propose a novel CFAR-based TOA estimation and node localization method for UWB wireless sensor networks in Weibull noiseand dense multipath. We compare the absolute values of the sampled received signal with an adaptive CFAR threshold to determine the real TOA. Unlike conventional Gaussian or Rayleigh background, we assume the amplitude of the observal noise to be Weibull distributed [9]. Given the probability of false alarm, the decision threshold of TOA detector is derived based on Weibull distribution function [10]. Using the obtained TOA values, we employ the multilateral localization to compute the positions of nodes, and give a three-dimensional (3D) Taylor algorithm to solve the non-linear equations [11]. The simulations prove that the proposed method has high time-resolution in 3D positioning of WSN nodes under Weibull noise amplitude and dense multipath environment. Also, it is suitable for power-limited WSN sensors.

The remainder of this paper is organized as follows. Section II gives the signal model. Section III describes the proposed CFAR-based TOA estimation method in Weibull noise. In section IV, the node position estimation method using 3D Taylor algorithm is given. In section V, the TOA estimation performance and node localization accuracy are evaluated by computer simulation. Finally, conclusions are given in section VI.

II. SIGNAL MODEL

We consider the situation that the transmitting node and the receiving node are synchronized with each other. In a

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dense multipath environment, an impulse radio (IR) UWB signal is sent from an unknown node, the received signal at an anchor could be represented by

$$r(t)=\sum_{l=1}^{L}\alpha_l p(t-\tau_l)+n(t) \tag{1}$$

where $p(t)$ denotes the transmitted UWB pulse. L is the number of propagation paths, which is large in dense multipath environment. α_l and τ_l denote the channel attenuation coefficient and time delay of the lth path, respectively. Among them, the first path delay τ_1 is the TOA to be estimated. $n(t)$ is assumed to be a band-limited white additive noise.

The received signal is directly sampled, where N denotes the total number of the samples. We define $x(n)$ as the absolute values of the samples, then

$$x(n)=|r(n)|=A(n)+w(n) \tag{2}$$

for $n=1,\cdots,N$, where $A(n)$ is the amplitude of the sampled UWB signal. $w(n)$ is the amplitude of the sampled noise, which could be regarded to obey Weibull distribution with standard variance σ.

III. CFAR-Based TOA Estimation in Weibull Noise

A CFAR detector is originally used in target detection of radar systems to control the false alarm rate P_{fa}. Similar to the CFAR theory in Radar detection [12], given the statistic parameters of Weibull noise, we extend the CFAR detector method into WSN application in dense multipath in order to determinate the TOA according to the given P_{fa}.

By assuming that the noise samples are band-limited complex white additive noise, the amplitude distribution of the noise should obey a Weibull distribution. For a random variable x, the probability density function (PDF) and the cumulative density function (CDF) of the Weibull distribution can be respectively described as

$$f(x)=\frac{\lambda}{\sigma}\left(\frac{x}{\sigma}\right)^{\lambda-1}\exp\left[-\left(\frac{x}{\sigma}\right)^{\lambda}\right];x>0 \tag{3}$$

and

$$F(x)=1-\exp\left[-\left(\frac{x}{\sigma}\right)^{\lambda}\right];x>0 \tag{4}$$

where σ and λ are the two parameters of the Weibull distribution.

The detection problem can be described as

$$\begin{cases} x(n)=w(n) & H_0 \\ x(n)=A(n)+w(n) & H_1 \end{cases} \tag{5}$$

The decision is completed according to

$$Decision=\begin{cases} H_0, & x(n)<\gamma \\ H_1, & x(n)\geq\gamma \end{cases} \tag{6}$$

Under the case of H_0, if a threshold γ is given, then P_{fa} is the probability that the noise sample $x(n)$ is greater than the threshold, i.e.,

$$P_{fa}=\int_{\gamma}^{\infty}f(x)dx=1-\int_{-\infty}^{\gamma}f(x)dx=\exp\left[-\left(\frac{\gamma}{\sigma}\right)^{\lambda}\right] \tag{7}$$

Therefore, given the statistic parameter σ and λ of the Weibull noise and the false alarm rate P_{fa}, we can estimate the TOA according to a decision threshold written as

$$\gamma=\left(-\sigma^{\lambda}\ln(P_{fa})\right)^{\frac{1}{\lambda}} \tag{8}$$

Consider N independent and identically distributed Weibull random variables $x_n=x(n)$, n=1,2,…N, when the parameter λ is fixed, we can calculate the maximum likelihood (ML) estimate of the statistic parameter σ [13].

Since the joint PDF of $x_1,\cdots,x_N$ is

$$f(x_1,\cdots,x_N)=\prod_{n=1}^{N}\left[\frac{\lambda}{\sigma}\left(\frac{x_n}{\sigma}\right)^{\lambda-1}\exp\left[-\left(\frac{x_n}{\sigma}\right)^{\lambda}\right]\right], \tag{9}$$

let the partial derivative of $\ln f(x_1,\cdots,x_N)$ with respect to σ be zero, we have

$$\frac{\partial\ln f(x_1,\cdots,x_N)}{\partial\sigma}=-\frac{1}{\sigma}+\frac{\lambda}{\sigma^{\lambda+1}}\sum_{n=1}^{N}x_n{}^{\lambda}=0 \tag{10}$$

Thus, the ML estimate of the parameter σ could be obtained by

$$\hat{\sigma}=\left(\frac{1}{N}\sum_{n=1}^{N}x_n{}^{\lambda}\right)^{\frac{1}{\lambda}} \tag{11}$$

Therefore, given N noise samples $x(n)$, n=1,2,…N, substituting (11) into (8), the threshold γ used for TOA estimation can be calculated by

$$\gamma=\left(-\frac{1}{N}\ln(P_{fa})\sum_{n=1}^{N}x_n{}^{\lambda}\right)^{\frac{1}{\lambda}} \tag{12}$$

Upon determining the threshold, the TOA can be estimated as

$$\hat{\tau}_{TOA}=\left[\min_{n}\left(n\,|\,\{x(n)>\gamma\}\right)\right]T_s \tag{13}$$

where T_s is the sampling period.

IV. Three-dimensional Node Localization

A. Three-dimensional Taylor Algorithm

The Taylor algorithm [15] starts from calculating an initial coordinate value and solving hyperbolic equations by iteration. Each iteration is compared with a local linear least-squares (LS) solution to promote the accuracy. Here we extend it to the 3-D case. Assume that the coordinates of an unknown node and the m-th anchor node (m=1,2,⋯,M) are (x,y,z) and (X_m,Y_m,Z_m), respectively. The distance between the unknown node and the m-th anchor node is

$$R_m = \sqrt{(x - X_m)^2 + (y - Y_m)^2 + (z - Z_m)^2} \tag{14}$$

and the distance difference between the unknown node to the m-th and the 1st anchor nodes is $R_{m1} = c\Delta t_m$, $m = 2, 3, \cdots, N_a$, where $\Delta t_m = t_m - t_1$ is the time difference of arrival (TDOA), t_m is the TOA parameter with respect to the m-th anchor node, which is obtained by CFAR algorithm. Starting with an initial estimate $(x^{(0)}, y^{(0)}, z^{(0)})$, the 3D Taylor algorithm iteratively calculate the position error $\mathbf{\Delta}$ using weighted LS (WLS) method.

$$\mathbf{\Delta} = \begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \end{bmatrix} = (\mathbf{G}^T \mathbf{Q}^{-1} \mathbf{G})^{-1} \mathbf{G}^T \mathbf{Q}^{-1} \mathbf{h} \tag{15}$$

where $\boldsymbol{Q}$ is the covariance matrix of TDOA,

$$\mathbf{G} = \begin{bmatrix} \frac{(X_0 - x)}{r_0} - \frac{(X_1 - x)}{r_1} & \frac{(Y_0 - y)}{r_0} - \frac{(Y_1 - y)}{r_1} & \frac{(Z_0 - z)}{r_0} - \frac{(Z_1 - z)}{r_1} \\ \frac{(X_0 - x)}{r_0} - \frac{(X_2 - x)}{r_2} & \frac{(Y_0 - y)}{r_0} - \frac{(Y_2 - y)}{r_2} & \frac{(Z_0 - z)}{r_0} - \frac{(Z_2 - z)}{r_2} \\ \vdots & \vdots & \vdots \\ \frac{(Z_0 - z)}{r_0} - \frac{(Z_2 - z)}{r_2} & \frac{(Y_0 - y)}{r_0} - \frac{(Y_{M-1} - y)}{r_{M-1}} & \frac{(Z_0 - z)}{r_0} - \frac{(Z_{M-1} - z)}{r_{M-1}} \end{bmatrix} \tag{16}$$

and

$$\mathbf{h} = \begin{bmatrix} \Delta r_1 - (r_1 - r_0) \\ \Delta r_2 - (r_2 - r_0) \\ \vdots \\ \Delta r_{M-1} - (r_{M-1} - r_0) \end{bmatrix}. \tag{17}$$

Let the initial coordinate value of the unknown node be $(x^{(0)}, y^{(0)}, z^{(0)})$. By substituting $x = x^{(0)}, y = y^{(0)}, z = z^{(0)}$ into the expression of R_m to obtain $(\Delta x, \Delta y, \Delta z)$. The next step is to replace x with $x^{(0)} + \Delta x$, y with $y^{(0)} + \Delta y$ and z with $z^{(0)} + \Delta z$, and repeat the whole process until $\Delta x, \Delta y$ and Δz are small enough. Thus the target coordinate (x, y, z) can be obtained.

B. Multilateral 3D Localization Process

We use multilateral 3D localization method for WSN to calculate the cross points of sphere or hyperbolic based on geometry relationship and available information concerning both TOAs and the positions of anchor nodes. The number of anchor nodes satisfies $M \geq 5$ for multilateral localization, and $\sqrt{(x - X_m)^2 + (y - Y_m)^2 + (z - Z_m)^2} = ct_m$, for $m = 1, 2, \cdots, M$, where c is the speed of light, 3×10^8 m/sec.

V. SIMULATIONS

In the section, we conduct computer simulations using MATLAB to illustrate the performance of the proposed method. At first, We show the estimation performance of the CFAR-based TOA method in Weibull noise and dense multipath. Upon obtaining the TOA and distance from an unknown node to an anchor node, we verify the 3D node localization algorithm in WSN by the simulations.

A. Simulation of TOA estimation

We assume that the transmit signal is a UWB pulse waveform having the second order derivative function of Gaussian function, $p(t) = \frac{A_p e^{-2\pi t^2 / T_p^2}}{1 - 4\pi t^2 / T_p^2}$ with $T_p = 1ns$ and $A_p = 1$. The UWB signal are propagated in dense multipath environment. The amplitude of the first-path signal is 1. The path delays are assumed to be uniform distributed within [0, 40] ns. The sampling frequency f_s is $10GHz$, and the sampling number N is 2000. Here we add a noise amplitude of Weibull distibution with parameter λ =1.5. In TOA detection, we set $P_{fa} = 10^{-5}$.

The received UWB signal under dense multipath and Weibull noise are shown in Fig. 1. SNR=10dB. Fig. 1 includes the first path signal, the multipath signals and background noise. Also, the adaptive CFAR threshold is illustrated in the figure. It is shown that the proposed CFAR-based TOA method can accurately judge the location of the first path, thus the TOA can be effectively estimated.

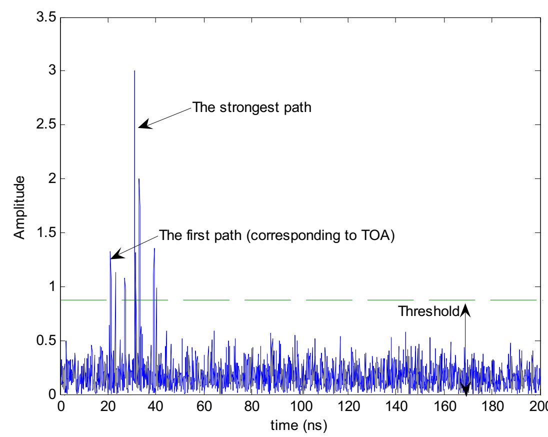

Fig. 1. The received UWB signal under dense multipath and Weibull noise.

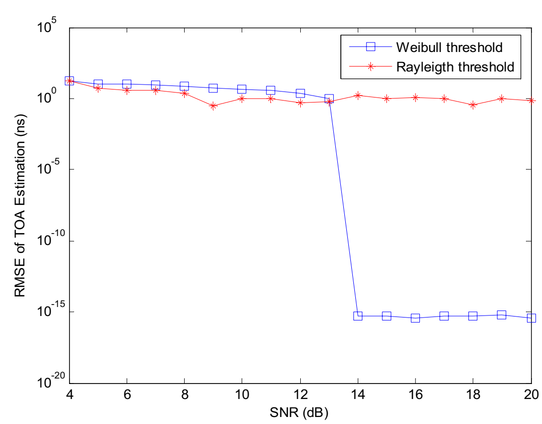

Fig. 2. RMSE v.s. SNR for TOA estimation using two methods

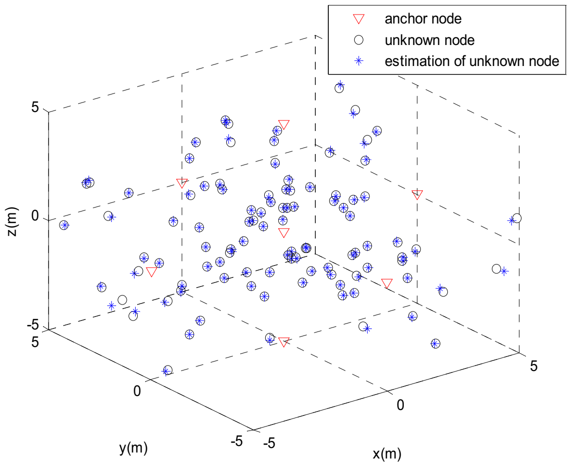

Fig. 3. 3D Node Localization (100 unknown nodes, 7 anchor nodes)

The RMSE (root mean square error) v.s. SNR for TOA estimation under dense multipath and Weibull noise is shown in Fig. 2.

The simulation in Fig.2 shows better performance of the proposed CFAR estimation algorithm compared with the conventional CFAR method using Rayleigh threshold [15].

B. Simulation of node localization using 3D Taylor Algorithm

In fig. 3, 100 unknown nodes randomly are generated in a $5m\times5m\times5m$ space, and 7 anchors are put in fixed locations. The proposed CFAR-based TOA estimation method is used to determine the distance from an unknown node to an anchor, then 3D Taylor algorithm is employed to calculate coordinates of these nodes. SNR=10dB. It shows that the coordinates of 100 nodes can be accurately calculated using 7 anchors. Our method greatly enhances the localization accuracy and reduces the computational complexity.

VI. Conclusion

The first path is not always the strongest one in many actual situations such as NLOS, thus, the biases may be generated in TOA estimation and localization. In this paper, we propose a novel CFAR-based TOA estimation and node localization method for UWB wireless sensor networks in Weibull noise and dense multipath. The simulation results reveal that the proposed methods provide better performance compared with the conventional method. Also, the proposed method is suitable for WSN node localization in 3D space with power-limited sensors.

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