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Performance and Analysis of an Enhanced DOA Estimating Theory in Wireless Sensor Networks

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Abstract: It is well known that wireless sensor network become more and more popular in modern communication systems. The DOA estimating theory is used to renew system topology and routing method of the whole network which is of great important in military communication. In this work, we raised an enhanced DOA (Direction of Arrival) estimating method which is used in wireless military sensor networks with uniform circular array. The array based sensor network is widely used in battlefield communication or emergency communication. Compared with traditional DOA estimating method such as ESPRIT and MUSIC, our new method has better performance but lower calculation consumption. From the simulation results, we can also infer that our method has better performance in Block Error Rate (BER) and lower mean-square error when the SINR of the received signal is poor, which is meaningful for establishing and maintaining a stable and perfect battlefield communication. *Copyright © 2013 IFSA.*

Keywords: DOA, WSN, Wireless communication, Self-organized network, Military sensor network.

1. Introduction

In wireless sensor networks, DOA estimation theory is very common and important for establishing network topology and renews sensor nodes locations of the whole environment. Military sensor network with uniform circular array is usually used in poor transmission conditions and is required high survivability and flexibility [1, 2].

The wireless sensor network recently becomes popular for its convenience in many conditions [3-5]. In water communications, sensors are deployed using plane, the self-organized character will help the establishment of networks [6, 7]. However, there exist a problem that how to find out the exact position of next transmission node to make the transmission more energy efficient. The power supply of sensor network always is limited, so the method to locate transmission node is one main target of the problem.

Estimation of Direction of Arrival (DOA) [8-10] is one possible solution. Other solutions such as GPS (Global Position System), TOA also make sense. But the DOA method is the one that can be adopted easily by only adding some signal processing technique integrated in chips. Of course, TOA has the same advantage but weak in accuracy. So in this work, we only talk about DOA method.

Traditional DOA estimating methods such as ESPRIT and MUSIC [11] are still widely used for their good performance. The gradual unbiased estimation value of these methods will require spectral peak searching for MUSIC [12] and rotating deformation for ESPRIT [13], which will seriously strict the utilize of these method. Of course, recently, some enhanced method such as using sparse signal processing [14, 2, 6] and array signal processing [2]. The estimation based on UCA (Uniform Circular Array) is a special array signal processing method. The distribution of multi antennas help estimate the angle using a phase difference.

In this paper, based on the scenario of wireless military sensor networks, e.g. water sensors, we present an enhanced independent component analysis (ICA) based DOA estimation method used in uniform circular array. From simulation results, we proved that our method has better performance and lower calculation consumption.

This paper is organized as follows. Part 2 gives the description of real scenarios. In Part 3, we formulated the mathematical description of signal model and our method. In Part 4, simulation assumptions and result are given with analysis. Conclusions are given in Part 5.

2. Description of Scenario

In Fig. 1, we illustrated the scenario using a schematic diagram. Sensors are deployed freely around the given area and any adjacent sensors can communicate with each other through the direct way. Of course, the multi-hop is also available in real scenario, but in this work, we do not study the multi-hop scenario.

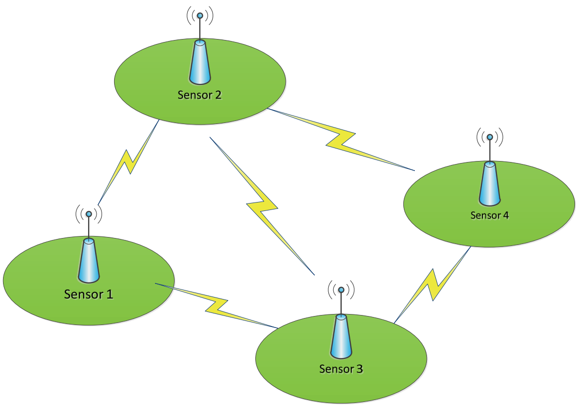

Fig. 1. Scenario of Sensor Network. The deployment of multi transmission node constitutes a network, with multi path and complex transmission power, etc.

Estimation of DOA is used to determine adjacent available nodes that main node can adopt transmission in a high success rate.

The UCA is defined the antenna configured with multi antennas separated with fixed distance to make the difference of phase and received power as is given in Fig. 2.

There are 8 antennas located in a circle using centralized deployment. While considering any antenna with zero phase, the phase of received signal from adjacent antennas can be described using the description such as $Ae^{j\varphi(wd)}$, where A is the power of received signal and d is the distance from zero-phase antenna.

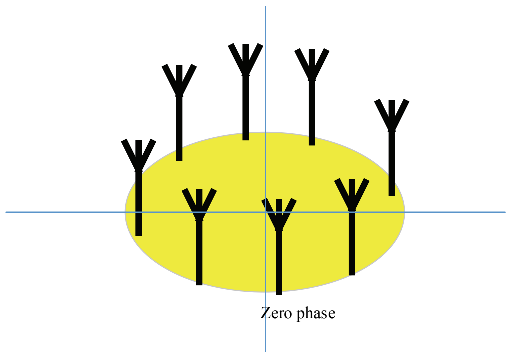

Fig. 2. Description of Uniform Circular Array.

3. Problem Formulation and Optimization

In order to estimate the pattern of target array, we take independent component analysis method. The independent component analysis system is used to maximum the non-Gaussian feature of the separated signal. Fig. 3 is the flow chart of the signal processing process.

The separation matrix W can be easily calculated by Robust ICA described in reference [2, 15, 16].

$$\hat{S} = W^H X \tag{1}$$

When number of signals equals the number of arrays, then $\hat{A} = W^{-1}$; if it is less than number of arrays, $\hat{A}$ is defined generalized inverse of W:

$$\hat{A} = X\hat{S}^H(\hat{S}S^H)^{-1} \tag{2}$$

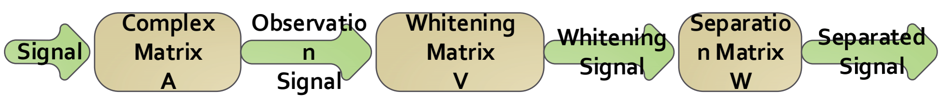

Fig. 3. Flow Chart of Signal Processing Process.

Consider a M -dimension isotropy uniform circular array with r radius circular. θ_k and φ_k are azimuth and pitch angles of the k^{th} signal, $x_l(t)$ is the output of the l^{th} array.

$$x_l(t) = \sum_{k=1}^{D} s_k(t)\exp(-j2\pi\frac{r}{\lambda}\cos(\varphi_k) \times\cos(\frac{2\pi(l-1)}{M}-\theta_k)) + n(t) \quad (3)$$

The steering vector of the k^{th} signal is defined as follows:

$$a(\theta_k,\varphi_k) = [a_1(\theta_k,\varphi_k), a_2(\theta_k,\varphi_k), \cdots a_M(\theta_k,\varphi_k)]^T \quad (4)$$

The estimating value of the steering value $\hat{a}(\theta_k,\varphi_k)$ has only phase difference compared with ideal steering value, that is, for the l^{th} array, we have:

$$2\pi\frac{r}{\lambda}\cos(\varphi_k)\cos(\frac{2\pi(l-1)}{M}-\theta_k) = \text{angle}(\hat{a}_l(\theta_k,\varphi_k)) + 2\pi K_l + \Theta \quad (5)$$

where Θ is the phase difference and K_l is the correction factor for cycle correction, we will give our method to solve the two factors in Section 3.1 and 3.2.

3.1. Cycle Correction Method

Cycle correction is very important for independent component analysis (ICA) where many researchers ignore the influence of non-ideal cycle [16]. Regular value of aperture of the circular array is 0.8~4, from equation (5) we can easy infer that the steering vectors may exceed $[0,2\pi)$. In our method, we found there are three useful properties which may cancel the influence of non-cycle influence. The following is the detailed demonstration of the three properties.

Property 1: Phase summary of steering vectors from same signal equals zero for the uniform circular array is central symmetry [3]. Described in mathematical equation:

$$\sum_{l=1}^{M}(angle(\hat{a}_l(\theta_k,\varphi_k)) + 2\pi K_l) = 0 \quad (6)$$

Property 2: The numeric area of K_l should satisfy:

$$-\frac{r}{\lambda} - \frac{angle(\hat{a}_l(\theta_k,\varphi_k))}{2\pi} < K_l < \frac{r}{\lambda} - \frac{angle(\hat{a}_l(\theta_k,\varphi_k))}{2\pi} \quad (7)$$

for the roundedness of cosine:

$$\cos(\varphi_k)\cos(\frac{2\pi(l-1)}{M}-\theta_k) \in (-1,1) \quad (8)$$

Property 3: Phase difference of adjacent element of steering vectors from same signal will satisfy sinusoidal variation 4. That is:

$$2\pi\frac{r}{\lambda}\cos(\varphi_k)[\cos(\frac{2\pi(l-1)}{M}-\theta_k) - \cos(\frac{2\pi(l-2)}{M}-\theta_k)] = 2\pi\frac{r}{\lambda}\cos(\varphi_k)[-2\sin(\frac{\pi}{M})\sin(\frac{\pi(2l-3)}{M})] \quad (9)$$

Property 1~3 finish the cycle correction operation, so we can calculate and after cancelling the influence shown in equation (5).

3.2. Cancel Phase Difference Θ

Consider a normalize operation with estimation value of steering vector $\hat{a}(\theta_k,\varphi_k)$. It is easy to know that corresponding rows of ideal steering vector and estimated value are equal:

$$2\pi\frac{r}{\lambda}\cos\varphi_k[\cos(\frac{2\pi(l-1)}{M}-\theta_k) - \cos(-\theta_k)] = \overline{angle}(\hat{a}_l(\theta_k,\varphi_k)) - \overline{angle}(\hat{a}_1(\theta_k,\varphi_k)) \quad (10)$$

where $\overline{angle}$ is the phase after correction of cycle taken in part 3.1. We will have equations totally and each two of them can get value of θ_k . The analytic solution of the angle is:

$$\hat{\theta}_{kl} = \arctan(\frac{m_1^2 - m_2^2 q}{m_1 n_1 - m_2 n_2 q}) \quad (11)$$

$$m_1 = \sin(\frac{2(l-1)\pi}{M}), n_1 = \cos(\frac{2(l-1)\pi}{M}) \quad (12)$$

$$m_2 = \sin(\frac{\pi}{M}), n_2 = \cos(\frac{\pi}{M}) \quad (13)$$

$$q = \frac{\overline{\text{angle}}(\hat{a}_l(\theta_k,\varphi_k)) - \overline{\text{angle}}(\hat{a}_1(\theta_k,\varphi_k))}{\overline{\text{angle}}(\hat{a}_2(\theta_k,\varphi_k)) - \overline{\text{angle}}(\hat{a}_1(\theta_k,\varphi_k))} \quad (14)$$

3.3. Our Enhanced Algorithm

From the discussion above, we have finished the mathematical analysis of DOA in uniform circular array. In this part, we will give our process of the enhanced algorithm [17].

Our algorithm is described as follows:

1) Determine the number of received signals;

2) Separate the signal using ICA and get

3) Calculating array pattern using equation (2)

4) Do cycle correction using the method discussed in part 3.1

5) Do phase correction using the method discussed in part 3.2

6) When the DOA of received signal is near, correct the received signal using:

$$(\theta,\varphi)=\arg\max\left|\hat{a}(\theta,\varphi)^{\mathrm{H}}a(\theta,\varphi)\right|^2 \quad (15)$$

Note that step 6 is used when DOA of received signal is less than $\Delta\theta$. $\Delta\theta$ will decrease when number of arrays increase. The searching method described in equation (15) will help improve performance when DOA of received signal is near.

4. Simulation and Analysis

In this part, we present three different simulations to evaluate our method. We randomly generated 4 sensor nodes and SCME as the fading channel environment. We are to check whether our method works well. If not strictly declared, our result is done through 1000 times Monte Carlo simulations.

4.1. The Method of Calculating SINR of Required Sensor Node

The wideband system is used widely in recent sensor networks, so in our simulation, we use the parameter and scenario used in 3GPP LTE Self Organized Networks with wideband and multi transmission stream.

In spatial domain, multi antenna help increase degree of freedom, so multi stream transmission is adopted. Different from traditional single antenna method, the estimation based on UCA cannot be done when number of received antenna is smaller than transmit antenna.

Thus, we use the SCME channel to simulate the real channel environment which is also widely used in 3GPP related work. The SCME channel model describes the correlation of time, spatial and frequency domain in a statistical model. This part has been proved in our previous work listed in reference [18].

In any sample period t , channel information of the u^{th} received antenna and the s^{th} transmit antenna can be drawn from SCME model using the equation (16):

$$h_{u,s,n}(t)=\sqrt{\frac{P_n\sigma_{SF}}{M}}\sum_{m=1}^{M}\begin{pmatrix}\sqrt{G_{tx}\left(\theta_{n,m,AoD}\right)}\exp\left(j\left[kd_s\sin\left(\theta_{n,m,AoD}\right)+\Phi_{n,m}\right]\right)\times\\ \sqrt{G_{rx}\left(\theta_{n,m,AoA}\right)}\exp\left(jkd_u\sin\left(\theta_{n,m,AoA}\right)\right)\times\\ \exp\left(jk\left\|\mathbf{v}\right\|\cos\left(\theta_{n,m,AoA}-\theta_v\right)t\right)\end{pmatrix} \quad (16)$$

where K is the racian factor, σ_{SF} is the variance of shadowing, d_s and d_u are the distance of antenna array of transmit node and receive node.

If line of sight (LOS) scenario applied in the scenario, equation (16) must be written in equation (17).

Define $H_j(n)$ is the channel matrix between transmission node i and the interference transmission nodes j , $P_{tx}(j)$ is the transmit power of the j^{th} node, and P_j^{loss} is the pathloss from the node.

$$h_{s,u,n}(t)=\sqrt{\frac{1}{K+1}}h_{s,u,1}(t)+$$

$$\sigma_{SF}\sqrt{\frac{K}{K+1}}\begin{pmatrix}\underbrace{\begin{bmatrix}\chi_{BS}^{(v)}(\theta_{n,m,AoD})\\ \chi_{BS}^{(h)}(\theta_{n,m,AoD})\end{bmatrix}^T}_{part1}\underbrace{\begin{bmatrix}\exp\left(j\Phi_{n,m}^{(v,v)}\right) & \sqrt{r_{n1}}\exp\left(j\Phi_{n,m}^{(v,h)}\right)\\ \sqrt{r_{n2}}\exp\left(j\Phi_{n,m}^{(h,v)}\right) & \exp\left(j\Phi_{n,m}^{(h,h)}\right)\end{bmatrix}}_{part2}\underbrace{\begin{bmatrix}\chi_{MS}^{(v)}(\theta_{n,m,AoA})\\ \chi_{MS}^{(h)}(\theta_{n,m,AoA})\end{bmatrix}}_{part3}\\ \times\underbrace{\exp\left(jkd_s\sin(\theta_{BS})\right)\times\exp\left(jkd_u\sin(\theta_{MS})\right)}_{part4}\times\underbrace{\exp\left(jk\|v\|\cos(\theta_{MS}-\theta_v)t\right)}_{part5}\end{pmatrix}+\sqrt{\frac{P_n\sigma_{SF}}{M}\frac{1}{K+1}}\sum_{n\neq1,m=1}^{M}\begin{pmatrix}\underbrace{\begin{bmatrix}\chi_{BS}^{(v)}(\theta_{n,m,AoD})\\ \chi_{BS}^{(h)}(\theta_{n,m,AoD})\end{bmatrix}^T}_{part1}\times\\ \underbrace{\begin{bmatrix}\exp\left(j\Phi_{n,m}^{(v,v)}\right) & \sqrt{r_{n1}}\exp\left(j\Phi_{n,m}^{(v,h)}\right)\\ \sqrt{r_{n2}}\exp\left(j\Phi_{n,m}^{(h,v)}\right) & \exp\left(j\Phi_{n,m}^{(h,h)}\right)\end{bmatrix}}_{part2}\times\\ \underbrace{\begin{bmatrix}\chi_{MS}^{(v)}(\theta_{n,m,AoA})\\ \chi_{MS}^{(h)}(\theta_{n,m,AoA})\end{bmatrix}}_{part3}\times\underbrace{\exp\left(jkd_s\sin(\theta_{n,m,AoD})\right)}_{part4}\\ \times\exp\left(jkd_u\sin(\theta_{n,m,AoA})\right)\\ \times\underbrace{\exp\left(jk\|\mathbf{v}\|\cos(\theta_{n,m,AoA}-\theta_v)t\right)}_{part5}\end{pmatrix} \quad (17)$$

$W(n)$ denotes the detector , n is the substream indicator), we can easily get the expression of detector of the i^{th} node:

$$W(n) = (P_{tx}^j P_{loss}^j H^j(n) H^j(n)^* + \sigma_0^2 I)^{-1} \times \sqrt{P_{tx}^j P_{loss}^j} H^j(n) \quad (18)$$

$D(n)$ is the required signal for target node, which is drawn from:

$$D(n) = diag(W^*(n)\sqrt{P_{tx}^j P_{loss}^j} H^j(n)) \quad (19)$$

I is the interference between sub streams with definition:

$$I = W^*(n)\sqrt{P_{tx}^j P_{loss}^j} H^j(n) - D(n) \quad (20)$$

The received signal power of the target user is significantly the square of the absolute value of $D(n)$, where the interference and noise can be defined using the same method.

$$P_{signal} = diag(\sigma_0^2 D(n) D^*(n))_{kk} \quad (21)$$

$$P_{noise} = diag(\sigma^2 W^*(n) W(n) + \sigma_0^2 II^*)_{kk} \quad (22)$$

$$P_{\text{int}erference} = diag(\sum_{j=1}^{N_i} P_{tx}^j P_{loss}^j \sigma_j^2 W^*(n) H^j(n) H^j(n)^* W(n))_{kk} \quad (23)$$

$$SINR_k^{(j)}(n) = \frac{P_{signal}}{P_{noise} + P_{\text{int}erference}} \quad (24)$$

While beamforming adopted, the result has some different in forms. For example, define V^j the beamforming vector, then received signal from the r^{th} antenna and the n^{th} subcarrier can be described using the following equation:

$$Y_r^{(0)}(n) = \sqrt{P_{tx} P_{loss}} H_r^{(0)}(n) V^{(0)} X^{(0)}(n) + \sum_{j=1}^{N_I} \sqrt{P^{(j)}{}_{tx} P^{(j)}{}_{loss}} H_r^{(j)}(n) V^{(j)} X^{(j)}(n) + W \quad (25)$$

After the combination of maximum rate, the predicted received signal could be defined using the MMSE detector, which is proved to be the optimal method of linear detector (if non-linear method is allowed, DPC method proved to be a better one).

$$\hat{X}^{(0)}(n) = \sum_r \sqrt{P_{tx} P_{loss}} V^{(0)^*} (H_r^{(0)}(n)^* H_r^{(0)}(n) V^{(0)} X^{(0)}(n)) + \sum_r \sum_{j=1}^{N_I} \sqrt{P^{(j)}{}_{tx} P^{(j)}{}_{loss}} V^{(0)^*} (H_r^{(0)}(n)^* H_r^{(j)}(n) V^{(j)} X^{(j)}(n)) + \sum_r V^{(0)^*} (H_r^{(0)}(n)^* W) \quad (26)$$

By separating the required signal and interference, the SINR of target node can be described using the equation below. The single layer with beamforming transmission can be solved in a relatively simple way.

$$P_{signal} = P_{tx} P_{loss} (\sum_{r=0}^{N_R - 1} | H_r^{(0)}(n) V^{(0)} |^2)^2 \quad (27)$$

$$P_{intference} = \sum_{j=1}^{N_I} P^{(j)}{}_{tx} P^{(j)}{}_{loss} | \sum_{r=0}^{N_R - 1} V^{(0)*} (H_r^{(0)}(n))^* H_r^{(j)}(n) V^{(j)} |^2 \quad (28)$$

$$P_{noise} = (\sum_{r=0}^{N_R - 1} | H_r^{(0)}(n) V^{(0)} |^2) \sigma^2 \quad (29)$$

If multi-layer beamforming transmission be used between sensors, the solution also has some difference.

The dimension of V^j has changed to $N_T \times N_{layer}$, compared with only number of antennas below. The SINR of the k^{th} layer and the n^{th} subcarrier can be written using:

$$SINR_k^{(0)}(n) = \frac{diag[P_s]_{kk}}{diag[P_N + P_I]_{kk}} \quad (30)$$

The signal part is a matrix that only the diagonal contain the power of the received signal, which can be written by:

$$P_s = P_{tx} P_{loss} diag[(W(n))^* H^{(0)}(n) V^{(0)}] \times diag[V^{(0)*} (H^{(0)}(n))^* W(n)] \quad (31)$$

$$P_I = \sum_{j \neq 0} P^{(j)}{}_{tx} P^{(j)}{}_{loss} (W(n))^* H^{(j)}(n) V^{(j)} V^{(j)*} H^{(j)}(n) W \quad (32)$$

$$P_N = | (W(n))^* |^2 \sigma^2 \quad (33)$$

So far, we have fully analyzed the condition that multi antenna and multi stream scenario are applied. In real sensor worlds, MIMO OFDM has been adopted with the development of personal wireless communications.

4.2. Comparison of MSE

First we test the veracity of our method. Define there are two non-coherent signal, the DOA of them are (55.1, 23.2)/degree and (86.4, 37.1)/degree for sensor 2 and sensor 3. The compared algorithms are UCA-ESPRIT and High-Resolution MUSIC.

In Fig. 4, the SINR distribution provided by section 4.1 is given. From this figure, we can infer that by applying pathloss and shadow fading, the performance of deploying sensors will not only affect by distance, but also influenced by shadowing. The shadowing will also influence the accuracy of estimation method.

Fig. 5 and 6 shows the Mean Square Error (MSE) of pitch angle estimation and azimuth estimation using the three methods. The x label indicates the received SNR, y label indicates the MSE.

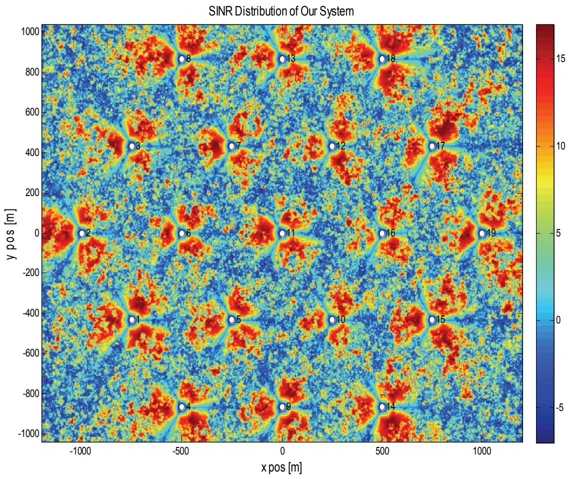

Fig. 4. Compare of Pitch Angle Estimation.

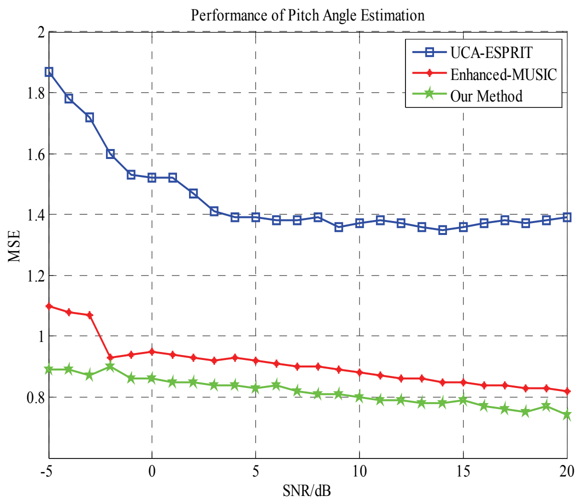

Fig. 5. Compare of Pitch Angle Estimation.

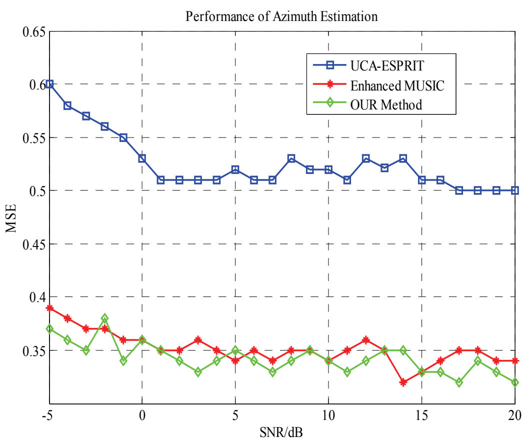

Fig. 6. Compare of Azimuth Estimation.

From these figure, we can infer that:

1) When the SNR is low, our method performs better than other two commonly used method, compared with enhanced MUSIC, the performance is near, but when applying the independent analysis, the incensement is about 5 %;

2) When SNR increases, our method works stable.

4.3. Simulation Result when DOA is Close

It is mentioned in equation (13) that our method may perform better when the coming DOA is very close, so define the DOA of sensor 2 as (20,20) and the DOA of sensor 3 gradually changes from 20.1 to 23/degree.

Here we define the success of estimation as:

1) When the intervals of DOA is less than 1 degree, the difference between estimated DOA and real DOA is less than half of the interval;

2) When the interval of DOA is more than 1 degree, the difference is less than 0.5 degree.

From the simulation result, we can see that when the coming DOA is very near, our method has higher probability to make the correct evaluation.

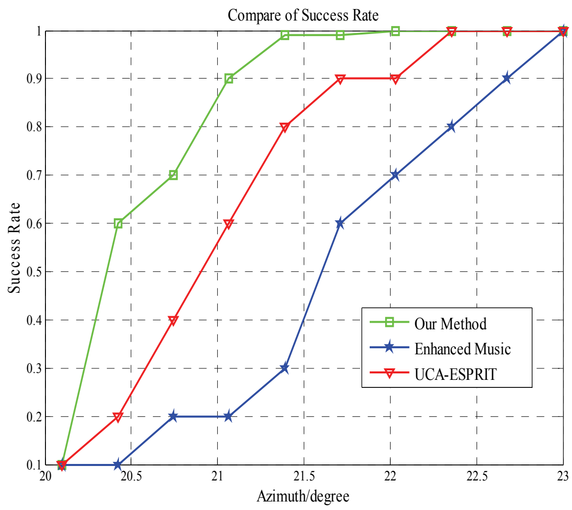

Fig. 7. Compare of Success Rate.

4.4. Comparison of Time Consumption

Compared with other two methods, we use profile tool to make a direct evaluation provided by Matlab software. Simulation environment is the same in part 4.2.

From Fig. 8, we can see the time consumption of these three methods. Our method cost less for our method will not need searching spectral peak; this is meaningful if we take our method into real sensor network.

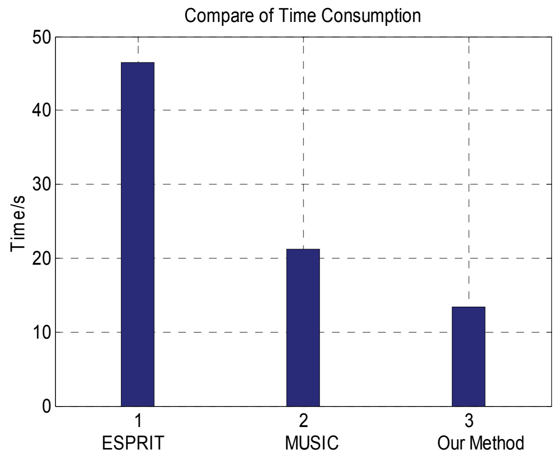

Fig. 8. Compare of Time Consumption.

5. Conclusions

In this paper, we present an enhanced DOA estimating method that is suitable for military self-organized wireless sensor networks. The uniform circular array (UCA) is a widely used in military sensor networks, the ICA method is proved effective than traditional E-MUSIC and E-ESPRIT. Simulation result proves that our method has better performance and lower time consumption compared with widely used E-MUSIC and UCA-ESPRIT, especially when the SNR is low, our method still have good performance. This is meaningful for military use.

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