SPSA-Based Tracking Method for Single-Channel-Receiver Array

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Abstract. *A novel tracking method in the phased antenna array with a single-channel receiver for the moving signal source is presented in this paper. And the problems of the direction-of-arrival track and beamforming in the array system are converted to the power maximization of received signal in the free-interference conditions, which is different from the existing algorithms that maximize the signal to interference and noise ratio. The proposed tracking method reaches the global optimum rather than local by injecting the extra noise terms into the gradient estimation. The antenna beam can be steered to coincide with the direction of the moving source fast and accurately by perturbing the output of the phase shifters during motion, due to the high efficiency and easy implementation of the proposed beamforming algorithm based on the simultaneous perturbation stochastic approximation (SPSA). Computer simulations verify that the proposed tracking scheme is robust and effective.*

Keywords

Phased array antenna, tracking, single-channel receiver, simultaneous perturbations stochastic approximation (SPSA).

1. Introduction

Phased array antennas have been widely used for the wireless mobile communication service [1-3]. The Direction-of-Arrival (DOA) estimation of the signal sources and beamforming algorithm are of great interest in the phased array antenna systems. In recent years, phased-array antenna systems have been developed to effectively suppress undesired signals from other directions by forming a beam pattern to improve the signal to interference plus noise ratio (*SINR*) [3], [4].

However, the dominating limitation is not the interferences restrain but the imprecise DOA estimation of the moving sources in some situations. For example, interferences and multipath components from undesired direction are easy to be spatially filtered due to the high gain and low side-lobe levels in the phased-array antenna for the mobile satellite receiver [1], [2], [5]. Accordingly the primary task of the beam control system is changed to estimate the DOA of the satellite signal precisely during vehicles' motion [1]. In the direct-sequence code-division multiple-access (DS/CDMA) system, the desired signal power is considered to be much stronger than that of the multiple access interference (MAI) after dispreading, and then the goal is to estimate the desired signal DOA accurately during the motion of signal sources [4], [6]. In this case, the ordinary Eigen structure methods for DOA estimation such as Capon, ESPRIT and Music are not suitable because they provide reduced resolution due to the spreading of the array spatial spectrum caused by the motion [1], [4]. As a result, how to track the DOA and steer the beam to coincide with the direction of the moving source fast and accurately is the primary problem for the communication systems that use the phased antenna array in the interference free conditions.

Generally, the requirements for DOA estimation of moving signal sources include fast acquisition, low computational complexity leading to fast track and fast response in dynamic situations, and satisfactory accuracy in all specified conditions [6]. Several approaches have been developed to deal with this problem, such as the delay lock loop (DLL) and the direction lock loop (DiLL) for code tracking in DS/CDMA systems [4], [6], [7], and zero-knowledge beamforming for the land mobile satellite communications [1]. However, the computational complexity of these DOA tracking algorithms increases with the number of antenna elements [1], [4]. And it is apt to lose the moving target in the high dynamic motion, due to the long time of the algorithm execution.

In this paper, a novel tracking scheme for the array with a single-channel receiver is developed to estimate the DOA of fast moving signal sources. It perturbs the output of the phase shifters to form the fit beam and tracks the moving source by injecting the extra noise into the gradient estimation. The computational complexity of the proposed algorithm is very low and furthermore it does not correlate with the number of antenna elements.

The remainder of the paper is organized as follows: In Sec. 2, the problem formulation is given. Our novel DOA tracking scheme is developed and discussed in Sec. 3. In Section 4, the numerical simulations are given to verify the performance. Finally, the paper is concluded in Section 5.

2. Problem Formulation

What we expect in the receiving terminal is the high signal to interference and noise ratio (*SINR*) for the superior quality of service in the communication system [3]. This goal could be achieved by maximizing the power of the received signal in certain conditions. The output of the phased-array antenna is given by

$$y(k)=\boldsymbol{w}^H\boldsymbol{x}(k) \tag{1}$$

where k is the time index, $\boldsymbol{w}=[w_1,w_2,\cdots w_N]^T$ is the complex beamforming weight vector, N is the number of array elements, and $(\cdot)^T$, $(\cdot)^H$ stand for the transpose and Hermitian transpose operators, respectively. The received array vector is $\boldsymbol{x}(k)=[x_1(k),\cdots x_N(k)]^T=\boldsymbol{s}(k)+\boldsymbol{n}(k)$, where $\mathbf{s}(k)=s(k)\boldsymbol{a}(\theta)$, $\boldsymbol{n}(k)$ are the desired signal, and noise components, respectively. In the desired signal term, $s(k)$ is the desired signal waveform, and $\boldsymbol{a}(\theta)$ is the desired steering vector.

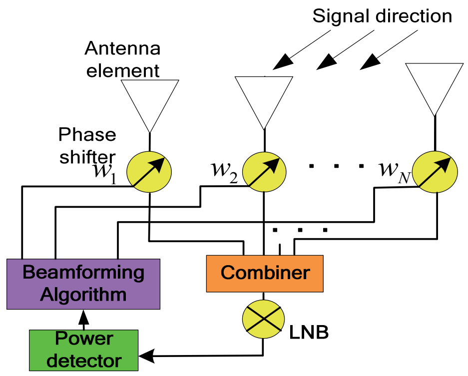

Fig. 1. Block-diagram of the antenna array with a single-channel receiver.

The array with a single-channel receiver is used to reduce the cost and complexity of the system [1], [2], [4], as shown in Fig. 1. The received signals are combined by a power combiner and then down-converted into an intermediate frequency by a low-noise block module. Therefore, the received power by the array is given by

$$\begin{aligned} P &= \boldsymbol{w}^H\mathbf{R}\boldsymbol{w} \\ &= \boldsymbol{w}^H\mathbf{R}_s\boldsymbol{w}+\boldsymbol{w}^H\mathbf{R}_n\boldsymbol{w} \end{aligned} \tag{2}$$

where $\mathbf{R}$, $\mathbf{R}_s$ and $\mathbf{R}_n$ are the correlation (covariance) matrix of the received signal, the desired signal and noise, respectively. And the signal to noise ratio (*SNR*) is given by

$$\rho=\frac{\boldsymbol{w}^H\mathbf{R}_s\boldsymbol{w}}{\boldsymbol{w}^H\mathbf{R}_n\boldsymbol{w}}\,. \tag{3}$$

The noise power is assumed to vary slowly and can be deemed to be invariable at the short sample interval [4], [8]. In this instance, if $\boldsymbol{w}^H\boldsymbol{w}=1$, the power maximization of the received signal is equivalent to the *SNR* maximization according to (2) and (3). So the goal of the beamforming algorithm in this system is given by

$$\max_{w} P=\boldsymbol{w}^H\mathbf{R}\boldsymbol{w}, \quad s.t. \quad \boldsymbol{w}^H\boldsymbol{w}=1\,. \tag{4}$$

However, the power of the received signal is usually contaminated by numerous noises and its accurate gradient is difficult to obtain. Maximizing the power of the received signal for the communication system that uses the high-gain antenna is ordinarily implemented by aligning the beam direction and the desired signal source in the interference free condition. And the beam direction of the phased-array antenna is usually adjusted by the set of phase shifters that are the phases of the weight vector $\boldsymbol{w}$ in (4). Hence, the problem (4) is converted to

$$\max_{\theta} P(\theta)=\boldsymbol{w}^H(\theta)\mathbf{R}\boldsymbol{w}(\theta)\,. \tag{5}$$

The beam direction of the array antenna θ is adjusted by

$$\boldsymbol{w}(\theta)=\left[e^{-j\frac{2\pi f}{c}d_1\sin\theta},\cdots,e^{-j\frac{2\pi f}{c}d_N\sin\theta}\right]^T \tag{6}$$

where c is the speed of wave propagation, f is the carrier frequency, and d_i is the location of the i th array element.

If $\theta=\theta_{\mathrm{signal}}$, where θ_{signal} is the direction of the desired signal, the problem (5) could obtain an optimal solution. In this case, to maximize the power of the received signal is to estimate the DOA of the moving source accurately and duly. However, it is a challenge to track the DOA due to the random motion of the signal source and noises.

3. The Proposed Tracking Method

The single-channel receiver limits the applications of many DOA algorithms, such as Capon, ESPRIT and Music, which require accurate microwave devices for the multi-channel receivers [9-12]. Besides, due to the mobility of the signal source, the received power has a spread spectrum and accordingly fluctuations in the time domain, which may cause the estimated covariance matrix inaccurate and sometimes even ill-conditioned in above DOA algorithms [8]. So, several other algorithms are developed. A single-channel adaptive beamforming structure based on the optimum perturbation technique is presented in [13], which is similar to the sequence perturbation algorithm (named finite difference stochastic approximation, FDSA) in [14]. The zero-knowledge beamforming algorithm in [1], [2] perturbs all phase shifters sequentially or simultaneously to estimate the power gradient of the received signal and updates the control set to form the fit beam, which is also the sequence perturbation algorithm. However, the sequential perturbation is time-consuming and the algorithm convergence may need long time with the increasing number of phase shifters as described in [14], [15].

To solve this problem, a simultaneous perturbation method of the phase shifters is developed in [1], whose conclusions show simultaneous perturbation method results in the faster convergence. And the efficiency of this algorithm does not vary with the change of array dimension. However, the simultaneous perturbation in [1] is fully isotropic, which may require more iterations to converge and cause the algorithm to diverge occasionally.

In fact, the values of the phase shifters are proportioned to the element location and beam pointing. From (6), we can obtain

$$\begin{aligned} \boldsymbol{w}(\theta) &= \left[e^{-j\frac{2\pi f}{c} d_1 \sin\theta}, \cdots, e^{-j\frac{2\pi f}{c} d_N \sin\theta} \right]^T \\ &= [p_1, p_2 \cdots p_N]^T \end{aligned} \tag{7}$$

where p_i is the value of ith phase shifter given by $p_i = 2\pi f d_i \sin\theta / c$. Assumed the beam direction changes from θ_0 at the instant t_0 to θ at the instant t, the adjusting value of the i^{th} phase shifter is given by

$$\Delta p_i = \frac{2\pi f}{c} d_i (\sin\theta - \sin\theta_0)\,. \tag{8}$$

Considering the change of the beam direction is small at a short period, then $\sin\theta \approx \theta$. Hence,

$$\Delta p_i = \frac{2\pi f}{c} d_i \Delta\theta \tag{9}$$

where $\Delta\theta = \theta - \theta_0$. For different phase shifters, the adjusting values are proportioned to their locations d_i and $\Delta\theta$, which should not be adjusted isotropically in the simultaneous perturbation method.

According to the above analysis, a novel tracking scheme based on simultaneous perturbations stochastic approximation (SPSA) algorithm is developed, considering the requirements for the DOA estimation of the moving sources in dynamic situation. It uses an efficient simultaneous perturbation to estimate the gradient using only two noisy measurements of the received signal power in the single-channel reception system. Different from the existing tracking algorithms, the execution time of the proposed algorithm is irrelevant to the number of the phase shifter and its convergence is much fast.

3.1 The Novel Tracking Scheme Based on SPSA

Conventionally, the tracking can be divided into two modes, i.e. initial searching mode and DOA tracking mode [1], [4]. The former mode is to direct the antenna beam to acquire the desired signal while the latter mode is to track the moving target accurately. The initial searching mode can also be foreseen for the cases when the desired signal is lost for a period of time, due to other unexpected factors, such as the blockage and shadow.

After the startup of the system, the beam is steered to scan all the directions where the desired signal may come. A threshold is set to terminate the searching when the received power is enough great and then the DOA tracking mode would be performed. Hence, the DOA tracking mode is more important than the searching mode for the performance of the tracking scheme.

The next course is to track the desired source accurately during motion after acquiring it approximately by the initial searching mode. The weight vector $\boldsymbol{w}(\theta)$ is adjusted in the following form

$$\boldsymbol{w}_{k+1} = \boldsymbol{w}_k - a_k \hat{g}_k(\boldsymbol{w}_k) \tag{10}$$

where $a_k = a/(A+k)^\beta$ is the step size, and $\hat{g}_k(\boldsymbol{w}_k)$ is the estimation of the gradient $\partial P(\boldsymbol{w})/\partial \boldsymbol{w}$ at the k^{th} iteration, which is given by

$$\begin{aligned} \hat{g}_k(\boldsymbol{w}_k) = &\frac{P(\boldsymbol{w}_k + b_k \boldsymbol{d}\Delta\theta\xi_k + c_k\Delta_k) - P(\boldsymbol{w}_k - b_k\boldsymbol{d}\Delta\theta\xi_k - c_k\Delta_k)}{2} \times \\ &(b_k\boldsymbol{d}\Delta\theta\xi_k + c_k\Delta_k)^{-1} \end{aligned} \tag{11}$$

where $\boldsymbol{d}=[d_1,d_2,\ldots,d_N]$ is the elements location, ξ_k and Δ_k are the random perturbation scalar and vector, respectively, both of whom are from a Bernoulli ± 1 distribution with probability of 1/2 for each ± 1 outcome. And $b_k = b/(k+1)^\gamma$, $c_k = c/(k+1)^\gamma$ are small perturbation value at the k th iteration. If $b = 0$, the proposed method is the criteria SPSA, which is the same as the method in [1].

Due to the blind beamforming, the inaccurate element location $\boldsymbol{d}$ and the angle speed of the beam direction $\Delta\theta$ in (11) are available. And their errors could be compensated by the DOA tracking algorithm. The following step-by-step summary shows how the proposed DOA tracking scheme works.

Step 1: Initialize $\theta = 0$ or $\boldsymbol{w} = [1,1,\ldots,1]^T$. In this case, the beam will be perpendicular to the array surface. Steer the beam to scan all the directions that the desired signal may come until the received signal power is greater than the threshold. The threshold ensures that parts of the desired signal are received but not just noise.

Step 2: Start up the tracking scheme. Set $k = 0$ and pick coefficients a, b, c, A, β and γ.

Step 3: Generate a random SPSA perturbation scalar ξ_k and a vector Δ_k. Update the perturbation value b_k, c_k. Two measurements of the received signal power $P(\boldsymbol{w}^+)$ and $P(\boldsymbol{w}^-)$ can be obtained by the weight vectors $\boldsymbol{w}^+ = \boldsymbol{w}_k + b_k\boldsymbol{d}\Delta\theta\xi_k + c_k\Delta_k$ and $\boldsymbol{w}^- = \boldsymbol{w}_k - b_k\boldsymbol{d}\Delta\theta\xi_k - c_k\Delta_k$.

Step 4: Estimate the gradient using (11) and update the antenna beam direction by $\boldsymbol{w}_{k+1}$ produced from (10).

Step 5: Judgment. First, terminate the algorithm if the received signal power decreases much suddenly due to the blockage or shadow, such as buildings, bridges or other objects. And then return to *Step 1* until the signal is reacquired; Second, terminate the algorithm if the received signal power increase little and then return to *Step 2*; or else return to *Step 3* with k+1 replacing k.

Fig. 2 shows the flowchart of the tracking scheme. The parameters a, b, c, A, β, γ in *step 2* determine the speed and accuracy of the algorithm convergence. So the choice of the coefficients is crucial for the performance of the DOA tracking scheme. The values of these coefficients are selected according to the guides from [15], [16]. The change of beam direction is assumed invariable at a short period and consequently $\Delta\theta$ varies less. In this case, there is no contribution on the phase proportion of the phase shifters by $\Delta\theta$. Then, the simultaneous perturbation $\boldsymbol{w}^+$, $\boldsymbol{w}^-$ can be replaced by $\boldsymbol{w}^+=\boldsymbol{w}_k+b_k\boldsymbol{d}\xi_k+c_k\Delta_k$ and $\boldsymbol{w}^-=\boldsymbol{w}_k-b_k\boldsymbol{d}\xi_k-c_k\Delta_k$.

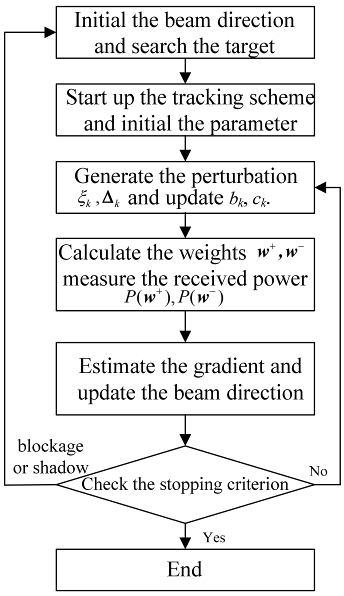

Fig. 2. The flow of the tracking scheme based on SPSA.

3.2 Algorithm Improvement

The faster beamforming algorithm converges, the smaller the direction of the moving source changes during the algorithm execution. So, using the faster beamforming algorithm to track the source becomes easier. The proposed method needs just two measured data every update and converges after a few iterations, which implies that little time is spent for the DOA tracking scheme.

The final error of the DOA tracking scheme is cumulated by the tracking error in every execution. If the outputs of Q executions are averaged, the final tracking error is given by

$$\begin{aligned}\Delta\theta_{\text{err}} &= \sum\nolimits_{i=1}^{Q}(\theta+\delta_i)\Big/Q-\theta \\ &= \sum\nolimits_{i=1}^{Q}\delta_i\Big/Q\end{aligned} \tag{12}$$

where θ is the real direction of the source and θ+δ_i is the output of the scheme at the i th execution. If the tracking error δ_i obeys a probability distribution whose average value is μ, then the value of the final tracking error $\Delta\theta_{\text{err}}$ would be reduced to μ/Q. In this case, the capability of the fast convergence would be transformed to the great tracking accuracy.

There are two major sources of the delay T in any gradient estimation algorithms: 1) time delay due to updating the phase shifters and 2) time delay due to reading the RF detector and low pass filtering [2]. The convergence time of the SPSA can be found

$$T_{\text{conv}} = N_{\text{iter}} \times T \ . \tag{13}$$

The convergence time of FDSA is given by

$$T_{\text{conv}} = N_{\text{iter}} \cdot N \cdot T \tag{14}$$

where N_{iter} denotes the number of required iterations that the algorithm must be executed to converge. And N represents the number of the phase shifters.

From the results in [14], FDSA needs less iterations to converge while every iteration needs more time. In contrast, SPSA needs more iteration to converge while every iteration needs less time. However, FDSA-based tracking method needs more time to converge than SPSA, which means that SPSA-based and the proposed tracking method may apply in more dynamic motions. The convergence speeds of the methods are compared in Section 4.

4. Numerical Analysis and Discussion

A variety of simulations are performed using the Matlab software package to verify the proposed DOA tracking scheme. We assume a uniform linear array antenna with N = 16 isotropic elements spaced half a wavelength apart as shown in Fig. 1. Several existing DOA tracking algorithms are chosen as the comparison objects to expatiate the merits of the proposed tracking scheme, due to their better performances.

To make the system general, assume that the antenna gain loss from boresight is given by [17], [18]

$$G = 12\left(\frac{\Delta\rho}{\rho_{3dB}}\right)^2 dB \tag{15}$$

where the angle $\rho_{3\text{dB}}$ is the half power beamwidth (HPWB) of the antenna, $\Delta\rho$ is the antenna beam deviation from boresight, which is less than $\rho_{3\text{dB}}$. Both of the angels are measured in degree.

4.1 Tracking Performance

The convergence of the proposed tracking algorithm is analyzed in this section. A white noise is introduced to the signal power measurement by different *SNR*s. The target direction deviated from the antenna normal is 10° and the initial direction of the antenna beam is 8° after the initial searching mode. The proposed method parameters are set as a = 0.6, b = 0.02, c = 0.01, A = 0.1, β = 0.602, and γ = 0.101.

It is obvious that the algorithm converges faster along with the higher SNRs as shown in Fig. 3. When

$SNR < 0$ dB, the tracking scheme would diverge. So, the observed performance degradation can only be compared to the results at $SNR \geq 0$ dB.

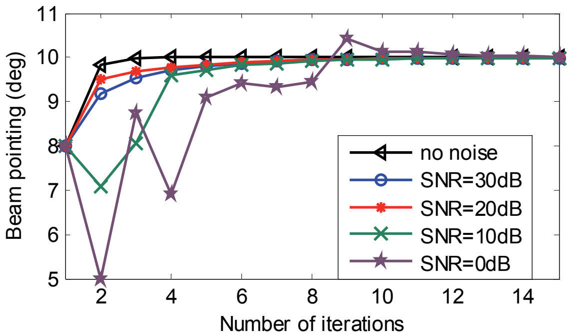

Fig. 3. The convergence of the proposed tracking scheme for different *SNR*s. The target direction deviated from the antenna normal is 10° and the initial direction of the antenna beam is 8° after the initial searching mode.

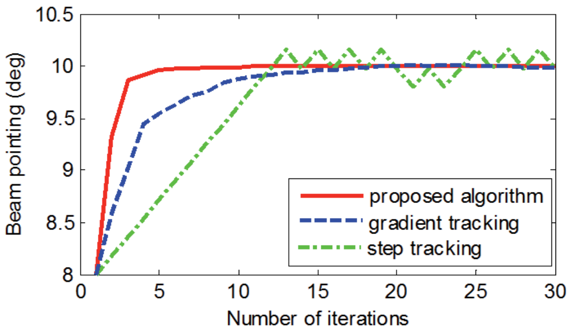

Fig. 4. The convergence of different tracking methods: the proposed algorithm, and the traditional tracking approaches: step tracking and gradient tracking. The target direction deviated from the antenna normal is 10° and the initial direction of the antenna beam is 8° after the initial searching mode.

The traditional tracking approaches: step tracking and gradient tracking are usually applied in the single-channel receiver. Fig. 4 shows the convergence comparisons of the proposed algorithm, the traditional step tracking method [17], and gradient tracking method [18]. The step size of the former method is $\rho_{3\mathrm{dB}}/16$ according to [17], while the proportional coefficient μ in the gradient tracking method is 0.1.

According to the results, both the traditional tracking methods: step tracking and gradient tracking, need more iterations to converge than the proposed algorithm. Moreover, the step tracking accuracy is lower than the other.

The convergence of the proposed tracking algorithm is compared with SPSA which has been proven to converge faster than FDSA-based tracking method in [1]. The SPSA parameters are set as $a = 6$, $c = 0.6$, $A = 2$, $\beta = 0.602$, and $\gamma = 0.101$ while the FDSA parameters are set as $\delta = 0.1$ and $\mu \equiv \boldsymbol{d}$. For each scenario in the simulation, 100 Monte Carlo runs are performed.

The SPSA-based tracking method needs $4{\times}2T$ or 4 iterations to converge while FDSA needs $16T$ or 1iteration as shown in Fig. 5. And the proposed method needs only $2{\times}2T$ or 2 iterations to converge.

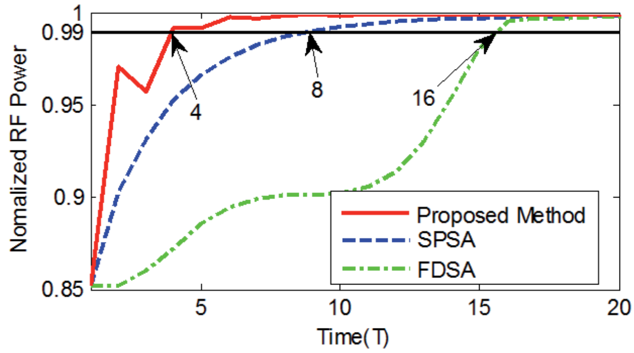

Fig. 5. The convergence of the different methods. The maximum available power is normalized into 1. When the received signal power reaches to 99% of the maximum available power, the antenna beam is assumed to aim at the target accurately.

Considering the stochastic perturbation, the SPSA-based and proposed methods are possible to diverge. In 100 time runs, there are averagely 10 times run not to converge for SPSA, but 0 times run for the proposed method. In practice, the gradient of the satellite tracking is not isotropic. If the value of phase shifters changes in proportion to the element locations, the beam direction varies continually. Otherwise, the beam direction varies dramatically, even small changes of the phase shifter. In this instance, the stochastic perturbation is likely to diverge while the proposed method not.

4.2 Performance Improvement

The performance of the tracking scheme is studied in this section. The direction of the moving signal source varies at the relative angular velocity of $\dot{\theta} = 40\sin(2\pi/5t)^{\circ}/s$, which models an accelerating fast maneuver during a short time. The *SNR* of the measured data is set to 10 dB.

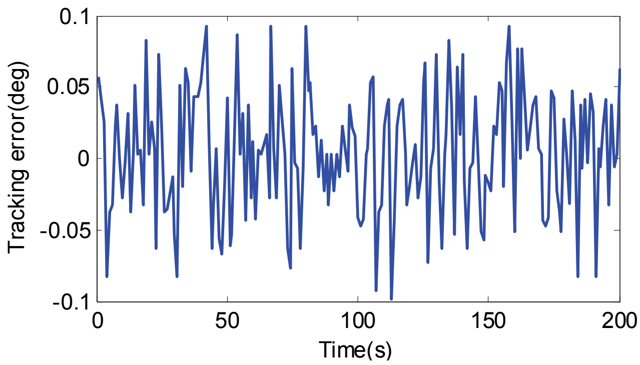

Fig. 6. The tracking errors by the proposed tracking scheme whose execution time is 10 ms in one iteration.

First, the execution time of the proposed tracking scheme is assumed to be 10 ms in one iteration, which is also the update period of the moving signal source direction. The tracking error of the proposed method is less than 0.1° as shown in Fig. 6.

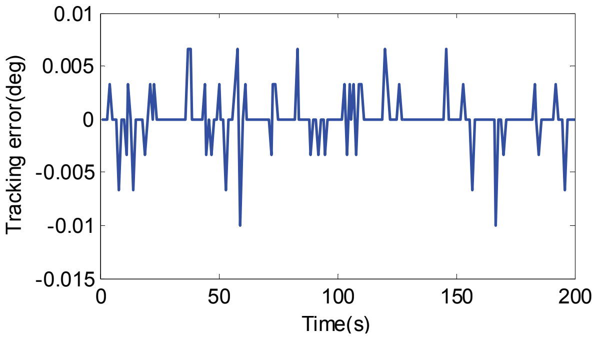

Fig. 7. The tracking errors by the proposed tracking scheme. The execution time of one iteration is 1 ms and every 10 outputs are averaged.

Second, the execution time is assumed to be 1 ms while the outputs of the tracking at an interval of 10 ms are averaged. As shown in Fig. 7, the tracking error is less than 0.01°, which is better than the result in Fig. 5 in the same processor and hardware conditions.

From previous discussions, it emerges that the proposed algorithm requires less measurements to maximize the received signal, and it can provide faster speed and robuster converge for the DOA tracking scheme of the moving signal source. The simulation results also verify the analysis in Section 3.

Compared with the recent methods [11], [12], the proposed algorithm disturbs the set of phase shifters simultaneously rather than the beam pointing. In this case, the parameters changes of phase shifters and various system errors, due to the severe circumvents, have the little influence on the tracking convergence, which may enhance the tracking stability and relax the hardware restrictions in the phased-array antenna design.

5. Conclusions

In this paper, we proposed an improved tracking method based on SPSA for the moving signal source in the phased-array antenna with a single-channel receiver. It is shown that the proposed tracking method is more efficient than SPSA and FDSA tracking algorithm. Besides the ease of implementation, the proposed algorithm is robust and effective by picking fit coefficients, due to the right searching direction. And it also gives cost-effective solution without any hardware restriction.

Acknowledgements

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