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Analysis and Optimization on Weight Accuracy of the Adaptive Interference Cancellation

Yunshuo Zhang, Songhu Ge, Huanding Qin*, Hongbo Liu, Zhongpu Cui, and Jin Meng

National Key Laboratory of Electromagnetic Energy, Naval University of Engineering, Wuhan 430033, China

ABSTRACT: Weight and reference signal are utilized in adaptive interference cancellation (AIC) for vector weighting to generate the signal with equal amplitude and opposite phase to the interference signal. Weight accuracy becomes the core factor to determine the performance of the AIC. In this letter, we analyze the influence of the weight accuracy on interference suppression performance, propose the quantitative characterization method of the weight accuracy with weight noise as an indicator, study the performance and influencing factors of the weight accuracy, and propose the optimization design method. The characteristics of weight accuracy in interference cancellation are verified by theoretical simulation analysis. This work fills in the blank of weight accuracy analysis and has solid theoretical value for exploring the capability boundary of the AIC.

1. INTRODUCTION

With the development of communication technology, the demand for communication data is increasing, thus the communication bandwidth is gradually widened, and broadband communication has become the development trend of military and civilian communication systems. The real-time requirement of the communication and the limitation of spectrum resources limit the traditional time-frequency division communication mode [1]. Since uplink and downlink data are transmitted simultaneously in the same frequency band, the receiver is subject to high-power interference from local transmitters [2–6]. Therefore, adaptive interference cancellation (AIC) is needed.

The theoretical basis of AIC is derived from Widow et al.'s previous research on the least mean square (LMS) algorithm [7]. Thereinafter, researchers studied the variable step size LMS (VSSLMS) algorithm. Tian et al. established the model of the relationship between the step factor and error signal using the hyperbolic tangent function [8]. Huang and Lee proposed the normalized VSSLMS algorithm [9], but this method increased the complexity. Mayyas proposed the VSSLMS algorithm based on the mean square error of the minimum weighting coefficient [10]. Jalal et al. proposed the VSSLMS algorithm based on Sigmoid [11]. However, when the VSSLMS algorithm was extended to convergence, the step size would change rapidly, resulting in Sigmond's characteristics. Zhang et al. proposed an improved VSSLMS algorithm based on the hyperbolic agent function [12]. Lu et al. proposed an improved VSSLMS algorithm based on the hyperbolic tangent function [13], which can improve the convergence speed and reduce the complexity. Most research on the VSSLMS algorithm generally focused on improving the convergence speed and reducing the complexity but rarely analyzed the weight accuracy.

Based on the VSSLMS algorithm [13], this letter establishes the quantitative relationship between the weight accuracy and interference cancellation radio (ICR) and proposes a quantitative characterization method of the weight accuracy with weight noise (WN) as the indicator, thereby giving the optimization method. This study fills in the blank of weight accuracy analysis and can provide theoretical guidance for optimizing weight and digital signal processing in engineering design.

2. SYSTEM MODEL

With the rapid development of electronic technology, in a co-platform communication system, such as aircraft, ships, and combat vehicles, the types and quantities of electronic equipment are increasing, and the frequency band is getting wider, which result in complex electromagnetic environment and increasingly serious radio frequency (RF) interference problems. Taking ships as an example, the transmitter emits high-power signals. The local receiver is highly sensitive, and it is easy to be affected by radiation interference from the transmitted signal, which deteriorates the signal-to-noise ratio of the receiver or even blocks the receiver. Therefore, the transmitter is the source of interference, and the receiver is the protected device. The adaptive interference cancellation system can solve electromagnetic compatibility problems of co-platform [14, 15].

This section presents an adaptive interference cancellation system (AICS) based on the VSSLMS algorithm [13]. The block diagram of an AICS is shown in Fig. 1. The AICS includes vector modulation module and digital control module. The vector modulation module weights the reference signal to obtain the cancellation signal. The digital control module performs correlation operation to obtain the weight value.

* Corresponding author: Huanding Qin (q_fighting@163.com).

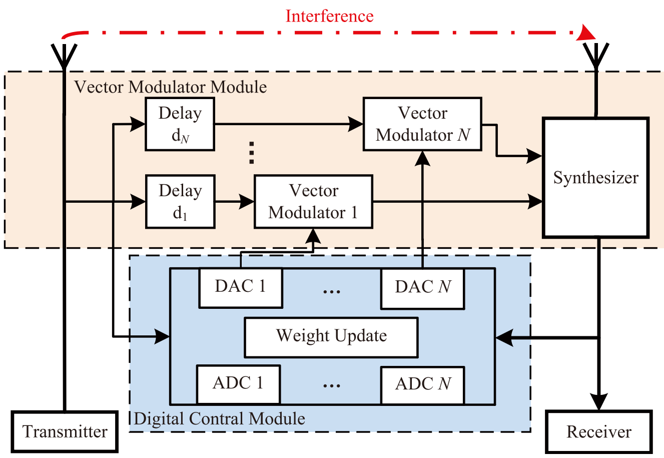

FIGURE 1. The block diagram of the AICS.

The classical adaptive filtering theory is adopted for AICS, and its structure block diagram is shown in Fig. 2. Considering the useful signal, the desired signal consists of the input signal $x(n)$, external noise $\varepsilon(n)$, and interest signal $s(n)$. The input signal is weighted by the adaptive filter to generate the cancellation signal $y(n)$. The error signal $x_e(n)$ is the difference between the desired signal $d(n)$ and cancellation signal $y(n)$. The error signal contains the interest signal. However, there is no correlation between the interest signal and input signal, so when the weight calculation is performed, the interest signal can be ignored. $x_e(n)$ feeds back to the adaptive filter to update the weight coefficient vector and $y(n)$, thereby, the output signal is closer to the interest signal to achieve the purpose of adaptive filtering.

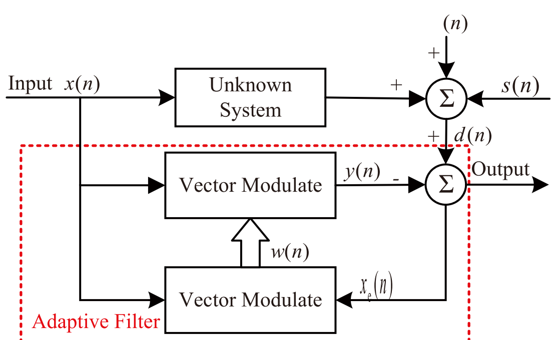

FIGURE 2. The principle block diagram of the adaptive filter.

The mathematical model of the adaptive filter is

$$\begin{cases} y(n) = \mathbf{w}^H(n)\,\mathbf{x}(n) \\ x_e(n) = d(n) - \mathbf{w}^H(n)\,\mathbf{x}(n) \\ \mathbf{w}(n+1) = \mathbf{w}(n) + \mu\mathbf{x}^*(n)\,\mathbf{x}_e(n) \end{cases} \tag{1}$$

where $\mathbf{w}(n) = [w(n), \cdots, w(n+N-1)]^T$ is the weight coefficient; $\mathbf{x}(n) = [x(n), \cdots, x(n+N-1)]$ is the reference signal vector; N is the order of the adaptive filter; μ is the step size; superscripts H and $*$ represent the conjugate transposition and conjugate of the matrix, respectively.

Jamming signals enter the receiver through direct and reflection paths, forming multi-path interference. The impulse response of the multipath interference channel is $h(n) = h_0\delta(n-\tau_0) + \cdots h_i\delta(n-\tau_i) + h_{L-1}\delta(n-\tau_{L-1})$. h_i $(i = 0, 1, 2, \cdots, L-1)$ is the amplitude attenuation coefficient of the ith reflection path; τ_i is the delay of the corresponding reflection path; and L is the total number of reflection paths.

The reference signal is an $N * 1$ vector, and the reference signal is x_i, which represents the reference signal of the ith time domain filter. Then the reference signal is $\mathbf{x}(n) = [x(n), \cdots, x(n+N-1)]$, and the weight coefficient is $\mathbf{w}(n) = [w(n), \cdots, w(n+N-1)]^T$.

The residual error signal power is minimized by adjusting the weight vector. The cancellation parameter optimization criteria can be expressed as

$$w_{\text{opt}} = \arg\min_{w} E\left\{(x_e(n))^2\right\} \tag{2}$$

where $E\left\{(x_e(n))^2\right\}$ is the residual error signal power.

According to Wiener filtering theory, the optimal weight vector is $\mathbf{w}_{\text{opt}} = \mathbf{R}^{-1}\mathbf{q}$. $\mathbf{R}$ is the autocorrelation matrix, and $\mathbf{q}$ is the cross-correlation vector of the reference signal and interference signal. The weight iterative formula is $\mathbf{w}(n+1) = \mathbf{w}(n) + \mu\mathbf{x}^*(n)x_e(n)$. μ is the step size, which affects the convergence speed. The weight accuracy determines the residual error, and the higher the weight accuracy is, the smaller the residual error is.

In the earlier research [13], the novel fast and robust variable step size LMS based on improved hyperbolic tangent function (IHVSS-LMS) is proposed. IHVSS-LMS adopts an improved hyperbolic tangent function and uses adjustable parameters and iteration number to jointly adjust the step size, which improves the convergence speed and reduces the computational complexity. After verification, the IHVSS-LMS can not only effectively accelerate the convergence speed by at least 3 times, but also improve the ICR by more than 3 dB.

According to [13], the convergence speed is fast, and the complexity is low when μ is

$$\begin{cases} \mu(n) = \mu_{\min} + \mu_{\max}\left[1 - \exp\left(-k/\left(n^2+1\right)\right)^{2a+1}\right] \\ \mu(n+1) = \beta\mu(n) + (1-\beta)/\left(\gamma + \sigma_x{}^2(n)\right) \end{cases} \tag{3}$$

where $\mu_{\min}$ is the minimum value of step size, and $\mu_{\max}$ is the maximum value. α, k, and β $(0 < \beta < 1)$ are the adjustment parameters; $\sigma_x^2(n)$ is the input signal power; and γ $(0 < \gamma < 1)$ is a small positive number, which is added to prevent the mutation of the input signal power from causing the divergence.

Due to the error of digital filter adjustment, the actual weight deviates from the optimal weight, resulting in the ICR degradation. The weight accuracy represents the deviation between the actual weight value and optimal weight value. The smaller the deviation is, the higher the weight accuracy is. Assume that the weight accuracy is $\Delta\mathbf{w}$. Then, the actual weight value can be expressed as $\mathbf{w}_{\text{opt}} + \Delta\mathbf{w}$. Thus, the residual error signal power is

$$P_{\Delta e} = P_e + \mathbf{w}_{\Delta}^H\mathbf{R}\mathbf{w}_{\Delta} \tag{4}$$

where P_e is the residual error signal power of the optimal weight.

The weight accuracy causes the increase of the error signal power and the decrease of the ICR. The weight accuracy is related to the sampling rate and DAC precision. Suppose that the weight accuracies caused by the sampling rate and DAC precision are δ_1 and δ_2. The two are independent of each other, so the single weight accuracy can be regarded as $[-\delta_1/2, \delta_1/2]$ and $[-\delta_2/2, \delta_2/2]$. The weight accuracy of the digital filter is an independent and identically distributed random complex variable and meets the following relationship.

$$\begin{cases} E\{w_{\Delta i}\} = 0 \\ E\{w^*_{\Delta i} w_{\Delta k}\} = \begin{cases} \left(\delta_1^2 + {\delta_2}^2\right)/6, & i = k \\ 0, & i \neq k \end{cases} \end{cases} \tag{5}$$

where $w_{\Delta i}$ is the weight accuracy of the ith tap.

The residual error signal power can be obtained considering the average influence of the weight accuracy. Therefore, the average ICR is

$$\text{ICR}_\Delta = \frac{P_I}{P_e + \left(\delta_1^2 + \delta_2^2\right) N\Phi\left(0\right)/6} \tag{6}$$

where P_I is the power of the input signal, and $\Phi(0)$ is the power of the reference signal.

The limited weight accuracy results in the decline of the ICR. In order to reduce the decline of the ICR, the amplitude adjustment interval should be as small as possible.

To describe the influence of weight accuracy on ICR, WN is defined as

$$\text{WN} = \frac{\text{ICR}}{\text{ICR}_\Delta} = \frac{P_e + \left(\delta_1^2 + \delta_2^2\right) N\Phi\left(0\right)/6}{P_e} \tag{7}$$

WN is the difference between the ICR within the optimal weight and the ICR within other weights. The higher the weight accuracy is, the smaller the WN is. When the weight is the optimal value, WN is zero.

3. WEIGHT ACCURACY OPTIMIZATION

In the digital control module, the adjustment deviation of the weight is related to the sampling rate f_s and the bits of DAC L_{bits}. Therefore, the weight value wi is the function of f_s and L_{bits}, and the optimization of weight accuracy can be described as $\min \delta$, s.t. $F(f_s, L_{\text{bits}})$. Increasing the sampling rate and DAC bits can effectively increase the weight accuracy and make the weight as close to the optimal weight as possible. However, blindly increasing f_s and L_{bits} will significantly increase computational complexity, as shown in Fig. 3.

It can be seen that the convergence speed of the system decreases with the increase in the number of sampling points. In general, the slowest convergence rate of the system needs to meet the lower limit of design requirements. Taking the convergence speed that the system can tolerate as low as 1/3 of the convergence speed under the optimal weight value as an example, the accuracy optimization problem of the interference cancellation weight value can be further described as

$$\begin{cases} \min\limits_{N,\Phi(0)} \delta = f\left(f_s, L_{\text{bits}}\right) \\ \text{s.t. } \max t_\Delta \leq 3t_{\text{opt}} \end{cases} \tag{8}$$

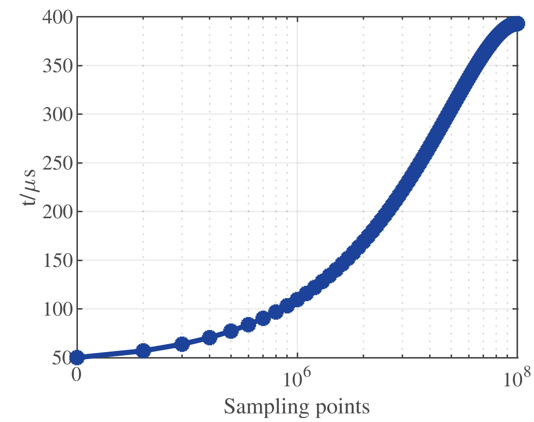

FIGURE 3. Convergence time under different points.

Besides, in real receiving scenarios, the weight accuracy mainly depends on the adaptive control algorithm, which will affect the ICR and the convergence speed. Therefore, taking the convergence time that the AICS can tolerate as high as three times of the optimal convergence time as an example, the optimization of the weight accuracy can be equivalent to the optimization of the adaptive control algorithm. We can set the upper limit of the WN and make the WN stable near the upper limit as

$$\begin{cases} \min\limits_{N,\Phi(0)} \delta = f\left(f_s, L_{\text{bits}}\right) \\ \text{s.t. } \max t_\Delta \leq 3t_{\text{opt}}, \text{WN} \leq 5\,\text{dB} \end{cases} \tag{9}$$

4. SIMULATION VERIFICATION

4.1. Interference Suppression Effect under Weight Accuracy

At first, based on [13], the simulation analysis of interference suppression effect under optimal and inaccurate weights is carried out, and the results are shown in Fig. 4. It can be seen that with the deterioration of weight accuracy, the ICR gradually decreases, and the WN gradually increases. The results are consistent with (6) and (7).

Then, we carry out two simulations of different sampling points (DAC bits is 18) and DAC bits (The sampling number is 5e^7). For the same digital signal, when different bits of DAC are used, the higher the bits are, the higher the accuracy of the analog quantity is. For the same dimension, the number of decimal places can be used to describe the DAC number equivalent. The larger the DAC number is, the more the decimal places are. In the actual experiment, changing the DAC bits requires replacing the DAC chip. In order to facilitate comparison and analysis, this paper uses the decimal places of weights for equivalent simulation.

The results are shown in Fig. 5. With the increase of the number of sampling points and DAC bits, the ICR of the system increases, and the WN decreases. However, considering the system running time and computational complexity, the sampling points and DAC bits should not be set too large in the actual system.

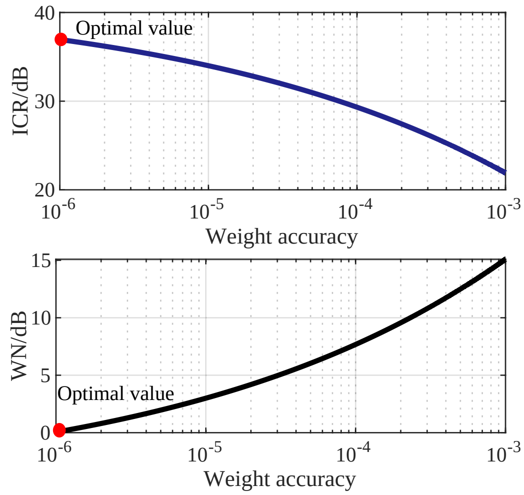

FIGURE 4. Interference suppression effect under optimal and inaccurate weights.

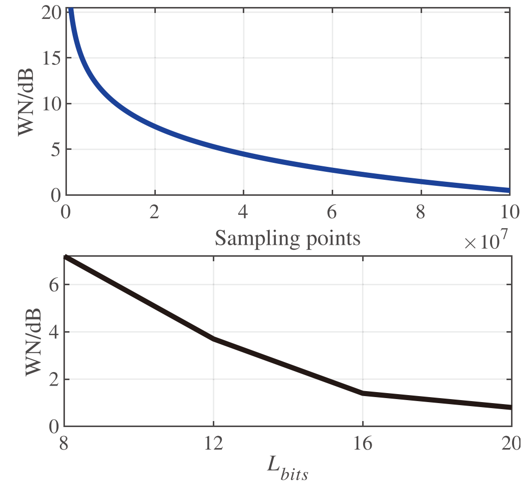

FIGURE 5. WN of different sampling points and DAC bits.

TABLE 1. Simulation parameters.

Algorithms	Step Size	Parameters
[9]	$\sigma_\varepsilon{}^2(n) = \sigma_e{}^2(n) - 1/\sigma_x{}^2(n) + \mathbf{r}_{ex}{}^T(n)\,\mathbf{r}_{ex}(n)$, $\mu(n) = \alpha\mu(n-1) + (1-\alpha)\,\sigma_e{}^2(n)/\beta\sigma_\varepsilon{}^2(n)$	$\alpha = 0.99$ $\beta = 30$
[11]	$\delta_e(n) = \delta_e(n-1) + \lvert e(n)\rvert, \sigma_x{}^2(n) = x^H(n)\,x(n)$, $\mu(n) = \left(e^{\tilde{\delta}_e(n)}\Big/\left(e^{\tilde{\delta}_e(n)}+1\right)\right)\left(\delta_e{}^2(n) + \sigma_x{}^2(n)\right)^{-1}$	$\theta = 0°$
[13]	$\mu(n+1) = \alpha\left(\mu_{\min} + \mu_{\max}\left[1 - \exp\left(-k/(n^2+1)\right)^3\right]\right) + (1-\alpha)/(\gamma + \sigma_x{}^2(n))$	$\alpha = 0.8$ $k = 100$

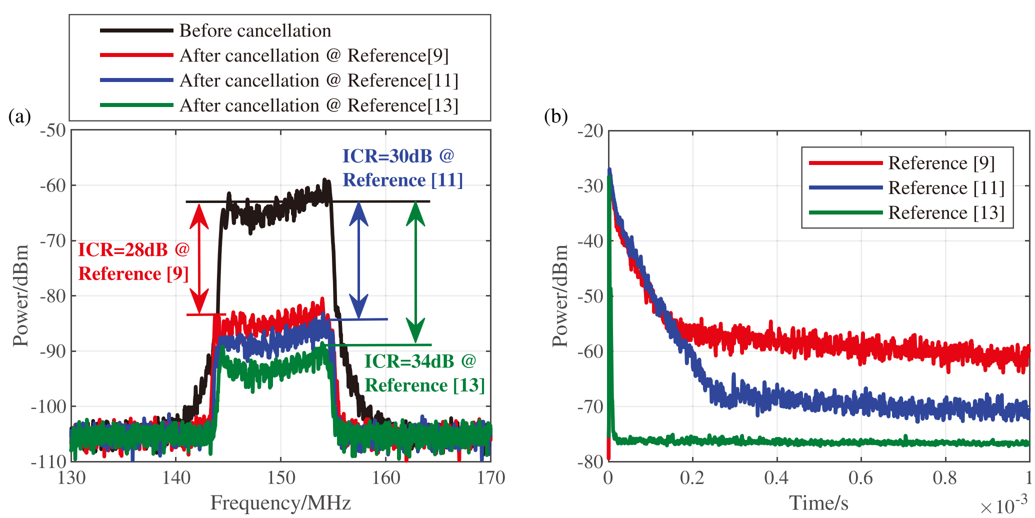

FIGURE 6. Interference suppression effect. (a) ICR. (b) Convergence time.

4.2. Interference Suppression Effect under Optimal Weight

AICS adopts the step size update method in [13] and compares it with the algorithm in [9] and [11] for verification. When the signal to interference noise ratio (SINR) is 30 dB, the parameters of the three algorithms are shown in Table 1. The signal bandwidth is 10 MHz; the RF frequency is 150 MHz; and the signal power sent by the transmitter antenna is −10 dBm. The taps number of the AICS is 3, and the interval between taps is 10 ns.

When the weight is in optimal value, the interference suppression effect of the three algorithms is shown in Fig. 6. We can see that the three algorithms can effectively suppress the interference. Among them, the ICR in [13] is about 5 dB higher

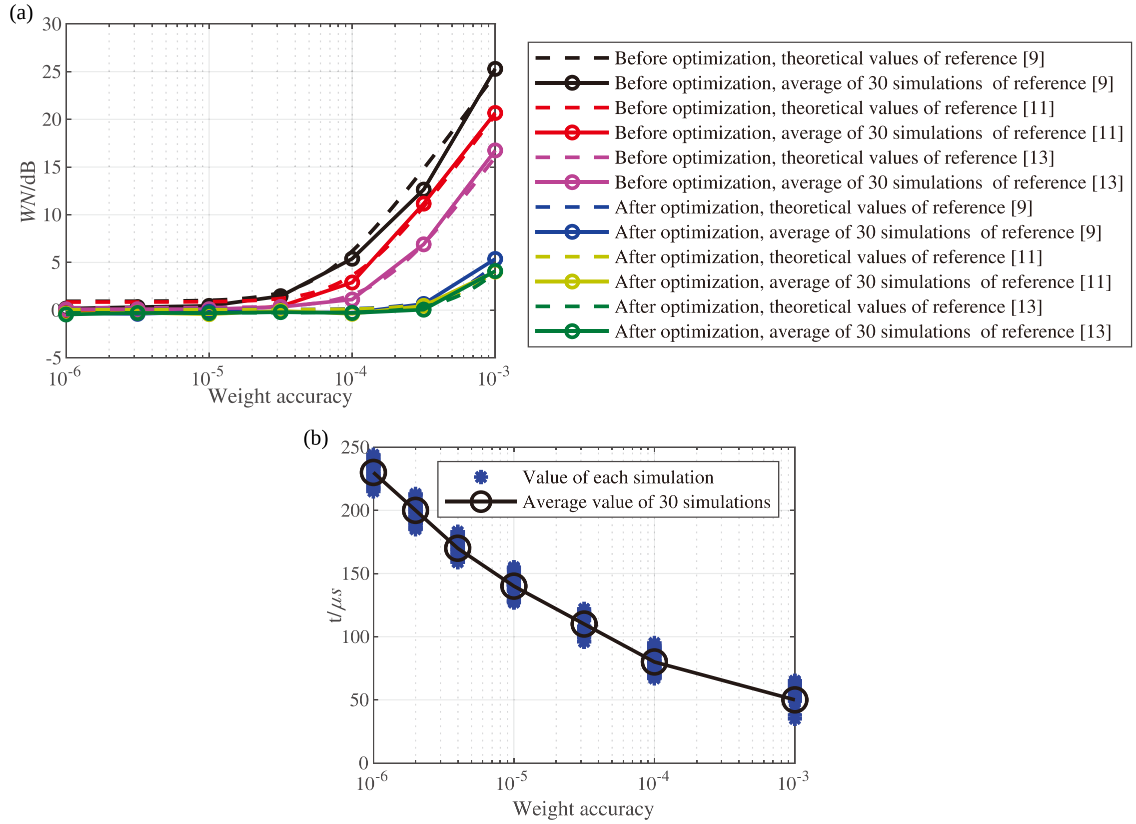

FIGURE 7. Interference suppression effect before and after weight accuracy optimization. (a) WN. (b) Convergence time.

than the other two algorithms, and the convergence speed is also faster than the other two algorithms. In this letter, the ICR under the optimal weight is taken as the benchmark of the WN, that is, the WN under the optimal weight is 0.

4.3. Interference Suppression Effect before and after Weight Accuracy Optimization

The optimization of sampling rate and DAC precision essentially optimizes the minimum resolution of the weight allowed by the adaptive control algorithm. This section simulates the WN and the convergence times under different weight accuracies before and after optimization. The results are shown in Fig. 7.

From Fig. 7(a), the simulation results of the three algorithms are consistent with the theoretical analysis. When the weight accuracy is higher than $1e^{-5}$, the WN is within 5 dB. And the proposed optimization design method does not significantly affect the related algorithms cited in [9, 11, 13]. However, when the weight accuracy is lower than $1e^{-5}$, the ICR decreases significantly, and the WN increases as the weight accuracy worsens. When the weight accuracy is $1e^{-3}$, the WN in [9, 11, 13] is 25 dB, 20 dB, and 15 dB, respectively. After optimization, the weight accuracy is in the range of $1e^{-6}$ to $1e^{-3}$, and the WN is less than 5 dB, which verifies the effectiveness of the weight accuracy optimization.

When the weight accuracy is higher than $1e^{-5}$, the WN is within 5 dB, and its impact is acceptable. When the weight accuracy is lower than $1e^{-5}$, the ICR decreases significantly, and the WN increases as the weight accuracy worsens. When the weight accuracy is $1e^{-3}$, the WN exceeds 15 dB. After optimization, the weight accuracy is in the range of $1e^{-6}$ to $1e^{-3}$, and the WN is less than 5 dB, which verifies the effectiveness of the weight accuracy optimization.

From Fig. 7(b), with the improvement of the weight accuracy, the number of sampling points increases, and the convergence time gradually increases. Especially when the weight accuracy is $1e^{-6}$, the convergence time reaches 230 μs, which is still within the acceptable range compared with the optimal convergence time.

5. CONCLUSION

In this letter, the influence of the weight accuracy on interference suppression performance in AICS is analyzed. The method to quantitatively characterize the weight accuracy using WN as an indicator is also proposed. By deriving the quantitative relationship between the weight accuracy and the ICR, the WN problem is transformed into the step size update problem; thereinafter, the optimization method of the weight accuracy is studied. The main conclusions include:

1) It is theoretically feasible to utilize WN as a quantitative representation of the weight accuracy.

2) The problem of weight accuracy can be transformed into the optimization of the sampling rate, DAC precision, and adaptive control algorithm. The higher the precision

of the control step is, the smaller the WN is, and the better the interference suppression performance is.

3) The weight accuracy and convergence speed require to be compromised, and the AICS should be reasonably designed according to the actual needs.

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