論 文 内 容 の 要 旨

1. Introduction

Broadband signal transmission is an essential technique for next-generation high data rate wireless communication systems [1], such as 3GPP long term evolution (LTE) and worldwide interoperability for microwave access (WiMAX). The transmission performance of the coherent detection for such broadband communication systems heavily relies on the channel estimation [2]. As high effectiveness and easy implementation channel estimation algorithms, adaptive filter algorithms are attractive in practical engineering applications [3]. Moreover, the least mean square (LMS) algorithm, normalized LMS (NLMS) algorithm and their variants have been widely studied and applied in channel estimation due to their low computational complexity and reliable recovery capability [4]. On the other hand, a broadband channel can be regarded as a sparse channel, particularly for indoor and hilly terrain wireless communication, in which multipath taps are widely separated in time, which can generate a large delay spread [5-6]. Generally speaking, for such a sparse channel, most of its taps coefficients are zero or close to zero. This means that in a sparse channel only a few taps with large delay are dominant, which are denoted as active taps, while other taps with their zero or close zero magnitudes are inactive. However, these classical adaptive filters perform poorly in such sparse channel. Recently, corresponding algorithms [5-7] are developed in order to improve the estimation accuracy in compressed sensing (CS) era. However, these CS algorithms are sensitive to the noise in the channel [8]. Motived by the CS algorithms, a series of zero-attracting algorithms [9-11] are proposed by the incorporation of CS theory and the standard LMS algorithm, and they have been investigated for echo cancellation and system identification applications. However, little research has paid attention to the variable-step-size (VSS) zero-attracting LMS algorithms, zero-attracting affine projection algorithm and zero-attracting proportionate-type NLMS algorithms. In this thesis, norm-based zero-attracting algorithms were further developed for sparse channel estimation applications, with a focus on fast convergence speed and low steady-state error compared to the classical adaptive filter algorithms.

To address the problem mentioned above, four norm-based zero-attracting (ZA) algorithms are developed based on variable-step-size technique [12], affine projection algorithm [3] and proportionate NLMS algorithm [13] for sparse channel estimation applications based on the multipath communication system shown in Fig. 1. An adaptive reweigthed zero-attracting sigmoid functioned variable-step-size LMS (ARZA-SVSS-LMS) algorithm (Algorithm Ⅰ) is proposed using a sigmoid function and an adaptive parameter adjustment method [14] in order to provide variable-step-size and variable ZA strength, respectively, by which the convergence speed and the steady-state performance is improved. The parameter effects and estimation performance of the proposed ARZA-SVSS-LMS algorithm are experimentally investigated though computer simulation in a designated sparse channel. Next, A smooth approximation l0-norm constrained affine projection algorithm [15] (SL0-APA) (Algorithm Ⅱ) is proposed to exploit the sparsity characteristic of the broadband multipath channel, and to improve the estimation performance of affine projection algorithm (APA) based on the smooth l0-norm approximation in [16]. In addition, a discrete weighted zero-attracting affine projection algorithm (DWZA-APA) [17] (Algorithm Ⅲ) is presented to reduce the computational complexity of the previously proposed reweighted zero-attracting affine projection algorithm (RZA-APA) [18]. Motivated by the SL0-APA algorithm [15], a lp-norm constrained proportionate normalized least mean square (LP-PNLMS) algorithm [19] (Algorithm Ⅳ) is proposed to avail both the benefits of the proportionate normalized least mean square (PNLMS) algorithm [13] and zero-attracting algorithms [9-11]. These four improved adaptive filter algorithms are verified over sparse channels to show the estimation performance, including the convergence speed and steady-state performance. Overall, the purpose of this thesis is to improve the adaptive filter algorithms for sparse channel estimation applications.

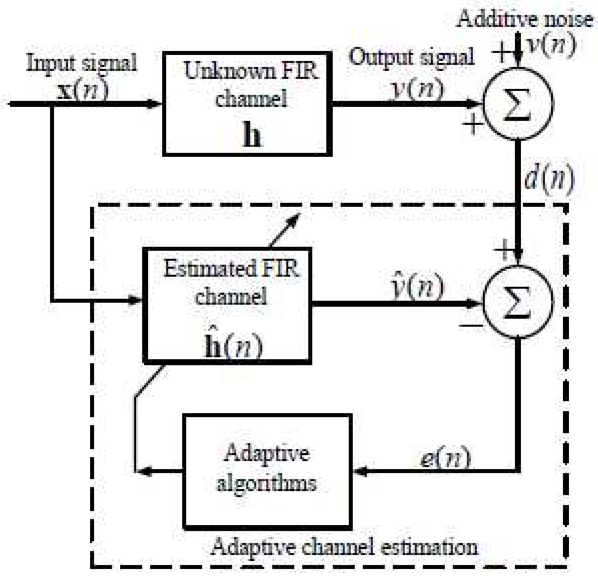

Fig.1 Typical sparse multipath communication system.

2. Variable-s

LMS algorithm has low complexity and easy implementation, and has been widely studied for system identification and echo cancellation applications. Therefore, a number of past adaptive filter researches are mainly focused on LMS algorithms, for example, VSS-LMS and NLMS algorithms. However, the estimation performance of these classical LMS algorithms deteriorates when they are used for sparse signal identification. Therefore, how to deal with the sparse signal with improved performance using LMS algorithms is desirable and attractive. Motived by the CS theory, zero-attracting LMS (ZA-LMS) and reweighted ZA-LMS (RZA-LMS) algorithms are proposed and applied for echo cancellation. These ZA-LMS algorithms can achieve better steady-state performance and faster convergence speed than the standard LMS algorithm when the signal is exact sparse at high signal-to-noise ratio (SNR). With the reduction of the sparsity, the advantages of these ZA-LMS algorithms disappear. Therefore, an ARZA-SVSS-LMS algorithm is proposed to further enhance the robustness of the ZA-LMS algorithms in terms of the convergence speed and steady-state performance. The proposed ARZA-SVSS-LMS algorithm is realized on the basis of the VSS technique and adaptive parameter adjustment method [14]. In order to implement the ARZA-SVSS-LMS algorithm, the ARZA-SVSS-LMS algorithm is described step-by-step. To begin with, a sigmoid functioned variable-step-size LMS (SVSS-LMS) algorithm is proposed, which is an improved VSS-LMS algorithm. Next, the ZA techniques used in ZA-LMS and RZA-LMS algorithms are incorporated into the proposed SVSS-LMS algorithm in order to form the zero-attracting SVSS-LMS (ZA-SVSS-LMS) algorithm and reweighted ZA-SVSS-LMS (RZA-SVSS-LMS) algorithm. At last, an adaptive parameter adjustment method is adopted to form the ARZA-SVSS-LMS algorithm by adaptively adjusting the zero-attracting strength in the RZA-SVSS-LMS algorithm.

The proposed ARZA-SVSS-LMS algorithm and its related transitional algorithms are verified via a sparse channel with the channel length $N = 16$ and the sparsity level of K. The parameter effects and the sparsity levels, namely $K = 1$, $K = 4$, $K = 8$, are taken into account to investigate the estimation performance of the proposed ARZA-SVSS-LMS algorithm. The simulation results show that the proposed ARZA-SVSS-LMS algorithm can achieve faster convergence speed and lower steady-state error compared to the standard LMS algorithm and previously proposed sparsity-aware LMSs. In addition, the ARZA-SVSS-LMS algorithm is shown to have lower steady-state error than the RZA-SVSS-LMS algorithm when the non-zero taps increases at both low SNR and high SNR for sparse channel estimation.

3. Sparsity-aware affine projection algorithms

3.1 Smooth approximation l0-norm constrained affine projection algorithm [15]

As is known to us, the LMS algorithm converges slowly, which is difficult to track rapid time-varying channels. Affine projection algorithm (APA), which has a moderate complexity, is another popular adaptive filter algorithm that has faster convergence speed than the standard LMS algorithm. In order to make use of the advantage of the APA and to utilize the sparsity of the sparse channel, a smooth approximation l0-norm constrained affine projection algorithm (SL0-APA) is proposed inspired by the zero-attracting LMS algorithms and smooth approximation l0-norm (SL0) in CS-era [16]. The proposed SL0-APA algorithm is realized via incorporating a SL0 into the cost function of the standard APA to form a zero attractor. The SL0-APA algorithm is mathematically proposed and experimentally investigated on the basis of the multipath communication system.

In order to evaluate the SL0-APA, an experiment is set up to verify the estimation performance and compared these results with the standard APA as well as the previously proposed zero-attracting APA (ZA-APA) and reweighted ZA-APA (RZA-APA) [17]. The simulation results demonstrated that the proposed SL0-APA can achieve faster convergence speed and better steady-state performance than the standard APA, ZA-APA and RZA-APA. This is due to that the SL0-APA mainly exerts penalty on the inactive taps that are zero or close to zero, which attracted these inactive taps to zero quickly, and hence accelerated the convergence speed and improved the steady-state performance. Furthermore, the theoretical analysis of the convergence speed and the mean square error are given in order to understand the SL0-APA further. The theoretical analysis is presented and compared to the simulation results so as to verify the effectiveness for both small step-size and large step-size. The theoretical results agreed well with the simulation ones, which mean that the theoretical analysis can effectively predict the mean square error. In addition, the computational complexity of the SL0-APA is also presented in comparison with the NLMS, APA, ZA-APA and RZA-APA. From the comparison of the complexity and the estimation performance, we found that the SL0-APA with moderate complexity is superior to the standard APA and the ZA-APA and RZA-APA in terms of the convergence speed and the steady-state performance. In addition, we observed that the sparsity can help to reduce the complexity of the SL0-APA.

3.2 Discrete weighted zero-attracting affine projection algorithm [18]

Form the study of the previously proposed RZA-APA [17], which is an improved ZA-APA algorithm by the use of sum-logarithm function to design the zero attractor, we found the RZA-APA has high complexity that comes from the calculation of the gradient of this sum-logarithm function. Thereby, a discrete weighted zero-attracting affine projection algorithm (DWZA-APA) is proposed by the introduction of a piece-wise linear function in order to reduce the division operation in the RZA-APA. The proposed DWZA-APA is implemented by exerting a strong zero-attracting on the inactive taps whose magnitudes are less than a very small designated threshold and giving a weak and uniform zero-attracting to other taps whose magnitudes are greater than this threshold.

The proposed DWZA-APA is verified over a sparse channel and a sparse-cluster channel to show its estimation performance in terms of convergence speed and steady-state performance. The simulation results demonstrate that the DWZA-APA can achieve faster convergence speed and lower steady-state error than the RZA-APA for sparse channel estimation, while have a better steady-state performance and a comparable convergence speed for sparse-cluster channel estimation. Furthermore, the proposed threshold can be easily adjusted for different sparse signal applications in order to achieve good estimation performance. In addition, the DWZA-APA has only N multiplications, which is lower than the RZA-APA.

4. Improved proportionate normalized least mean square algorithm [19]

Proportionate normalized least mean square (PNLMS) algorithm is another type of sparse NLMS algorithm using the proportionate adaption, which assigns the independent step-size to the active taps and achieves faster convergence speed at the initial stage. After the active taps convergence, the convergence speed slows down. To improve the PNLMS algorithm, an lp-norm constrained PNLMS (LP-PNLMS) algorithm is proposed on the basis of the zero-attracting algorithms, which is different from the previous proposed improved PNLMS algorithms and zero-attracting algorithms. Most of the previously proposed improved PNLMS algorithms aim to improve either the gain matrix or the step-size, while the proposed LP-PNLMS incorporates a gain matrix scaled lp-norm into the cost function of the PNLMS algorithm to design a zero attractor. The LP-PNLMS algorithm is mathematically described in detail based on the Lagrange multiplier method.

The proposed LP-PNLMS algorithm is investigated over a sparse channel to obtain the estimation performance in comparison with the basic PNLMS and other improved PNLMS algorithms [20]. The simulation results show that the proposed LP-PNLMS algorithm can achieve the same convergence speed as the PNLMS algorithm at the initial stage, and converge faster than that of PNLMS algorithm after the convergence of the active taps. Furthermore, the LP-PNLMS algorithm has lower steady-state error than the PNLMS and its related popular algorithms, namely improved PNLMS (IPNLMS) and μ-law PNLMS algorithm (MPNLMS) algorithms [20]. With the increase of the channel length N, the LP-PNLMS is superior to the IPNLMS and MPNLMS algorithms in terms of both the convergence speed and the steady-state performance. In addition, the computational complexity of the proposed LP-PNLMS is discussed. From the analysis of computational complexity, we see that the LP-PNLMS algorithm has comparable complexity in comparison with the IPNLMS and MPNLMS algorithms. Also, from the proposed ARZA-SVSS-LMS algorithm and the SL0-APA mentioned above, we believe that the variable-step-size technique [21] and the SL0 approximation technique [15-16] can be adopted to further improve the estimation performance of the LP-PNLMS algorithm.

5. Conclusion

This thesis first studied the two important adaptive filter algorithms: classical adaptive filter algorithms including LMS and APA, and sparsity-aware adaptive filters including the zero attracting algorithms and the proportionate-type adaptive filter algorithms. This thesis aims to improve or design new adaptive filter algorithms with the faster convergence speed and better steady-state performance for sparse channel estimation applications. Some improved algorithms were proposed to solve the above problem. In summary, this thesis made the following contributions to improve sparse adaptive filters: 1) propose an ARZA-SVSS-LMS algorithm on the basis of the variable-step-size technique and adaptive parameter adjustment method to render the RZA-LMS algorithm robust in terms of the estimation performance. Some simulation results revealed the enhanced estimation performance; 2) develop a SL0-APA to utilize the sparsity property of the sparse channel and to inherent the convergence speed of the APA. It was found that the SL0-APA can achieve faster convergence speed and lower steady-state error compared to the related sparsity-aware APA and NLMS algorithms; 3) provide a DWZA-APA by the use of piece-wise linear function instead of the sum-logarithm used in RZA-APA to reduce its complexity. Simulation results show that the DWZA-APA possesses lower complexity and achieves better estimation performance in comparison with the RZA-APA; 4) propose a LP-PNLMS algorithm to improve the convergence speed of the inactive taps in the PNLMS algorithm utilizing the zero-attracting technique. In the LP-PNLMS algorithm, a gain matrix scaled lp-norm is incorporated into the cost function of the PNLMS algorithm to generate a zero attractor. The simulation results demonstrated that the LP-PNLMS algorithm achieves faster convergence speed and lower steady-state error because it inherents the advantages from both the PNLMS algorithm and the zero-attracting algorithms. As the use of adaptive filter is attracting widespread interest in both the industrial and academic fields, it is important to develop sparse adaptive filter algorithms on the basis of the property of the sparse channel to improve the communication service. In addition, the proposed algorithms and methods can be used to improve other adaptive filters.