Dynamic Electronic Dispersion Equalization in Coherent Optical Networks Using Variable-Step-Size Least-Mean-Square Algorithm

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Abstract—In coherent detection employing digital signal processing, chromatic dispersion (CD) can be compensated effectively in the electrical domain. In practical optical transport networks, the signal lightpaths between two terminal nodes can be different due to current network conditions. Accordingly, the transmission distance and the accumulated dispersion in the lightpath cannot be predicted. Therefore, the adaptive compensation of dynamic dispersion such as the use of least-mean-square (LMS) algorithm is necessary in such optical fiber networks to enable a flexible routing and switching. In this paper, we present a detailed analysis on the adaptive dispersion compensation using the LMS algorithms in coherent optical transmission networks. Numerical simulations have been carried out accordingly. It can be found that the variable-step-size LMS equalizer can achieve the adaptive CD equalization with a lower complexity, compared to the traditional LMS algorithm.

Index Terms—optical fiber communication, coherent detection, dynamic electronic equalization, chromatic dispersion, least mean square algorithm, variable step size least mean square algorithm

I. INTRODUCTION

The performance of high speed optical fiber networks is significantly affected by the system impairments from chromatic dispersion (CD), polarization mode dispersion (PMD), laser phase noise, and fiber nonlinearities [1-12]. Due to the high transmission spectral efficiency and the robust tolerance to fiber nonlinearities, coherent optical detection employing advanced modulation formats and digital signal processing (DSP) has become one of the most promising solutions for the next-generation high speed optical fiber networks [13-26]. Since both the amplitude and the phase information from the received signal can be extracted in the coherent optical detection, transmission impairments, such as chromatic dispersion, polarization mode dispersion, laser phase noise, and fiber nonlinearities can be compensated or mitigated effectively using the powerful DSP algorithms [27-61]. The chromatic dispersion can be well compensated and equalized using the time-domain and the frequency-domain digital filters in the coherent receivers, which have become the most promising alternative approaches to dispersion compensation fibers (DCF) [1,2,27-32].

These implementations lead to a dramatic reduction in the complexity and costs, as well as a better tolerance to the fiber nonlinearities, for the high speed optical fiber transmission networks.

Some digital equalizers have been implemented based on a fixed amount of fiber dispersion to realize a static compensation for inter-symbol interference (ISI), where an accurate knowledge of chromatic dispersion in the transmission link is critically required [27-31]. However, in the switched optical fiber networks, the signal lightpath between two terminal nodes can change over time according to different network conditions, where the transmission distance and the accumulated dispersion in the lightpath cannot be predicted in advance. Therefore, the adaptive compensation for the chromatic dispersion in the coherent optical transmission networks should be considered significantly. Recently, the adaptive CD equalization in the dynamically switched optical networks has attracted the research interest, and some approaches such as the least-mean-square (LMS) algorithm, the constant modulus algorithm (CMA), the delay tap sampling technique, the overlap frequency domain equalization, and the auto-correlation of signal power waveform have been investigated to enable a flexible routing and switching in such optical fiber networks [33-36]. Among these methods, the time-domain LMS equalizer can give a relative simple specification and a large dynamic range, as well as a good tolerance to small laser phase noise, which becomes a very promising solution for the adaptive CD electronic equalization in the dynamically switched and routed optical fiber networks [35-38].

In this paper, we present a detailed analysis on the adaptive chromatic dispersion compensation using the LMS algorithm, in the coherent optical fiber transmission networks. Numerical simulations have been carried out in the dual-polarization quadrature phase shift keying (DP-QPSK) coherent transmission system, based on the VPI and the Matlab software platforms [62,63]. The influence of step size in the LMS adaptive equalization for compensating chromatic dispersion is investigated, and the impact of step size on the tap weights convergence in
the LMS equalizer is also analyzed in detail. The LMS filter shows a better CD compensation performance by using a smaller step size, but this will result in a slower iterative computation to achieve the convergence of the tap weights. To solve this contradiction, a variable step size least mean square (VSS-LMS) algorithm is further proposed to realize the dynamic equalization of the chromatic dispersion in the coherent optical fiber networks. The performance of the VSS-LMS for adaptive CD compensation is analyzed and compared to the traditional LMS filter, and the required number of taps and the distribution of converged tap weights in both equalizers for a specific fiber dispersion are also investigated. It can be found that the VSS-LMS adaptive equalizer can give an optimum CD equalization performance compared to the traditional LMS algorithm, where a good compromise between the CD compensation performance and the converging speed of the tap weights can be obtained. Therefore, the VSS-LMS equalization can achieve an optimization between the CD equalization performance and the computational complexity, where the best CD compensation with a low complexity can be realized.

II. PRINCIPLE OF LEAST MEAN SQUARE BASED ADAPTIVE DISPERSION COMPENSATION

In this section, the principle of the traditional LMS algorithm and the variable step size LMS algorithm are described, and the influence of step size on the update and the convergence of the taps weights are also discussed in detail.

A. Structure of Least Mean Square Based Adaptive Equalizers

The schematic of the adaptive equalizer based on the LMS algorithm with a tap weights number of \( N \) is illustrated in Fig. 1, where \( T \) is the sampling period, \( W_i \) \((i=1,2,\ldots,N)\) represents the tap weight coefficient in the LMS based equalizer, \( x_i \) is the input sample sequence, \( y \) is the equalized output sample, \( d \) is the desired output sample, and \( e \) is the estimation error between the output \( y \) and the desired output \( d \).

![Figure 1. Block diagram of the LMS algorithm based adaptive equalizer for dispersion compensation.](image)

As shown in Fig. 1, the adaptive equalizer includes a tapped delay line for storing the data samples from the input signal sequence. During each sample period, the adaptive equalizer calculates the convolution between the tap weights in the delay line and the input samples, and then the tap weights are updated for the calculation in the next sample period. The tap weights are updated according to the estimation error between the output signal and the desired signal, and the speed of the update depends on the step size parameter. Meanwhile, the adaptive equalizer can be applied in the decision-direct (DD) or the training symbol modes, and the decision-direct update is employed in our analysis and numerical simulations.

B. Principle of LMS Adaptive Algorithm

The LMS equalizer is a branch of the adaptive algorithm, which is designed by finding the filter coefficients to produce the least mean squares of the error signal (the difference between the desired output and the actual output signal). The LMS algorithm is an iterative adaptive method which can be applied in the highly time-varying signal environment. It is a stochastic gradient descent approach, since the tap weights in the LMS filter are only accommodated based on the current estimation error. The traditional LMS algorithm incorporates an iterative procedure which makes successive corrections to the tap weights vector in the negative direction of the gradient vector which eventually results in a minimum mean square error. The equalized output signal and the tap weights vector of the LMS adaptive equalizer can be expressed as follows [36-38],

\[
y(n) = w_{LMS}^H(n)x(n) \tag{1}
\]

\[
w_{LMS}(n+1) = w_{LMS}(n) + \mu_{LMS} x(n)^* e_{LMS}^*(n) \tag{2}
\]

\[
e_{LMS}(n) = d_{LMS}(n) - y(n) \tag{3}
\]

where \( x(n) \) is the vector of the complex input signal, \( y(n) \) is the equalized complex output signal, \( w_{LMS}(n) \) is the vector of the complex tap weights, \( d(n) \) is the desired output symbol, \( e(n) \) is the estimation error between the output signal \( y(n) \) and the desired symbol \( d(n) \), \( \mu_{LMS} \) is the step size parameter which controls the convergence characteristics of the LMS algorithm, \( H \) represents the Hermitian transform, and \( * \) means the conjugate operation. The tap weights vector \( w(n) \) is firstly initiated with an arbitrary value \( w(0) \) at \( n=0 \), and then is updated in a sample-by-sample (or symbol-by-symbol) iterative manner to achieve the eventual convergence, when the estimation error \( e(n) \) approaches zero.
In order to guarantee the convergence of the tap weights vector \( \mathbf{w}(n) \) in the LMS equalizer, the step size parameter \( \mu_{\text{LMS}} \) in the adaptive filter needs to satisfy a condition of \( 0 < \mu_{\text{LMS}} < 1/\lambda_{\text{max}} \), where \( \lambda_{\text{max}} \) is the largest eigenvalue of the correlation matrix

\[
R = x(n)x^H(n) [36-38].
\]

The convergence speed of the algorithm is inversely proportional to the eigenvalue spread of the correlation matrix \( R \). The convergence of the LMS tap weights will be slow, when the eigenvalues are spread. The eigenvalue spread of the correlation matrix \( R \) is evaluated by calculating the ratio between the largest eigenvalue and the smallest eigenvalue. The LMS algorithm will converge quite slowly, when the step size \( \mu_{\text{LMS}} \) is very small. One the other hand, the LMS algorithm will converge faster for a larger value of step size \( \mu_{\text{LMS}} \). However, the LMS algorithm can be less stable since sometimes the step size may exceed \( 1/\lambda_{\text{max}} \).

C. Principle of variable step size LMS adaptive algorithm

Generally, the traditional LMS algorithm is quite robust for dispersion compensation and it requires a small computational effort. However, the accommodation of the step size will impact both the convergence speed and the residual error in the traditional LMS equalizer. The performance of the traditional LMS algorithm can be enhanced and optimized, if the step size of this adaptive equalizer can be adjusted properly. For the best situation, a larger step size is applied at the beginning stage to accelerate the convergence speed, and a smaller step size is applied after the rough convergence to generate the smallest residual error. Correspondingly, the variable step size LMS algorithm is developed to improve the performance of the traditional LMS algorithm in terms of the convergence speed and the residual error level [37,38,64-66]. The step size parameter in the VSS-LMS algorithm changes with the variation of the mean square error, which allows the adaptive equalizer to track the changes in the transmission system as well as to produce a small steady residual error. The equalized output signal \( y(n) \) and the tap weights vector of the variable step size LMS adaptive filter can be expressed as the following equations [37,38],

\[
y(n) = \mathbf{w}^{\text{VSS-LMS}}(n)x(n) \tag{4}
\]

\[
\mathbf{w}^{\text{VSS-LMS}}(n+1) = \mathbf{w}^{\text{VSS-LMS}}(n) + \mu_{\text{VSS-LMS}}(n)x(n)e_{\text{VSS-LMS}}^*(n) \tag{5}
\]

\[
\mu_{\text{VSS-LMS}}(n+1) = \alpha \mu_{\text{VSS-LMS}}(n) + \gamma e^2_{\text{VSS-LMS}}(n) \tag{6}
\]

where \( x(n) \) is the vector of the complex input signal, \( y(n) \) is the equalized output signal using the VSS-LMS filter, \( \mathbf{w}^{\text{VSS-LMS}}(n) \) is the vector of the complex tap weights, \( d(n) \) is the desired output symbol, \( e(n) \) represents the estimation error between the output signal \( y(n) \) and the desired symbol \( d(n) \), and \( \mu(n) \) is the step size coefficient of the VSS-LMS algorithm for adjusting the convergence properties and the residual error, and is updated with the variation of the estimated error \( e(n) \). The parameters \( \alpha \) and \( \gamma \) are the coefficients for controlling the step size to be updated with the change of estimation error \( e(n) \), and the range of the parameters are \( 0 < \alpha < 1 \) and \( \gamma > 0 \). The convergence speed of the VSS-LMS adaptive algorithm can be accommodated by choosing different values for the energy attenuation factor \( \alpha \).

The step size \( \mu(n) \) is always positive and is controlled by the size of the estimated error and the parameters \( \alpha \) and \( \gamma \), according to Eq. (6). A typical value of \( \alpha=0.97 \) was found to work well in our numerical simulations, and the parameter \( \gamma \) is usually chosen as \( \gamma = 4.8 \times 10^{-4} \). In general, a large estimated error increases the step size to provide a faster tracking. When the estimated error decreases, the step size will be decreased accordingly to reduce the misadjustment in estimation [36-38]. Compared to traditional LMS algorithm, the VSS-LMS algorithm can give an improved performance at a cost of only four more multiplications or divisions in each iteration.

D. Implementation of DP-QPSK numerical transmission system

As illustrated in Fig. 2, the numerical transmission setup of 28-Gbdu DP-QPSK coherent optical communication system is implemented using the VPI and Matlab platforms. All the simulations are carried out based on nonlinear Schrödinger equation (NLSE) using the split-step Fourier solution. In the transmitter, the pseudo random bit sequence (PRBS) data from the 28-Gbit/s pattern generators are modulated into two orthogonally polarized QPSK optical signals by using the Mach-Zehnder modulators and the polarization beam splitter (PBS). The orthogonally polarized signals are then fed into the standard single mode fiber (SSMF) transmission channel by using a polarization beam combiner to form the 28-Gbdu DP-QPSK optical signal. In the receiver end, the received optical signals are mixed with the local oscillator (LO) laser to be demodulated and compensated using diverse digital filters. In this work, we neglect the attenuation, the polarization mode dispersion,
the laser phase noise, and the fiber nonlinearities, since the investigation is only focused on the chromatic dispersion equalization. The bit error rate is evaluated based on the $2^{18}$ bits, with a PRBS pattern length of $2^{15}-1$.

**III. SIMULATION RESULTS**

To investigate the performance of VSS-LMS filter, the compensation of chromatic dispersion from a standard single mode fiber (SSMF) with a CD coefficient $D = 16$ ps/km/nm are numerically assessed, and the results are compared to the traditional LMS adaptive filter. The tap weights are updated iteratively in both the traditional LMS algorithm and the variable-step-size LMS algorithm, here we mainly focus on the converged tap weights in the two equalizers. The converged tap weights of the LMS adaptive filter with 37 taps and step size of 0.1 for compensating the chromatic dispersion in the 60 km fiber are illustrated in Fig. 3. We could see that in the LMS adaptive filter, the central tap weights take more dominant roles in the chromatic dispersion equalization in all the tap weights magnitudes, real parts and imaginary parts diagrams. For a fixed fiber dispersion, the tap weights in LMS adaptive filter approach to zero, when the corresponding taps order exceeds a certain value, and this value indicates the least required taps number for compensating the chromatic dispersion effectively. This also illustrates the optimization characteristic of the least mean square adaptive algorithm. It could be seen from Fig. 3 that the required taps number in the LMS equalizer for equalizing 60 km fiber dispersion is 23 taps.

The performance of chromatic dispersion compensation employing the LMS adaptive filter with step size value $\mu = 0.1$ using 9 taps for 20 km fiber dispersion and 2305 taps for 6000 km fiber dispersion are shown in Fig. 4. We could see from the figure that the two CD equalization results have little penalty compared with the back-to-back measurement when the fiber loss is neglected in the simulation work.

The simulation results of chromatic dispersion compensation employing LMS adaptive filter with different step size values using 401 taps for 1500 km fiber dispersion are shown in Fig. 5. It could be seen from Fig. 5 that the CD compensation results have a better performance with the step size decreasing, while a smaller step size will lead to the slower converging speed. Also we could see that the BER performance behave very closely with each other, when the step size value is below $\mu = 0.1$, and the BER behavior become worse when the step size increases above $\mu = 0.1$. Therefore, the step size in the LMS adaptive equalizer is usually selected as $\mu = 0.1$ to obtain the optimization.
The converged tap weights of the variable-step-size LMS adaptive filter for 60 km fiber dispersion with 37 taps and step size varying from 0.06 to 0.6 are illustrated in Fig. 6. We could see that in the variable-step-size LMS adaptive filter, the central tap weights also take more dominant roles in the CD equalization in all the tap weights diagrams. It could also be found that the converged tap weights in the variable-step-size LMS filter vary consistently with the LMS adaptive filter tap weights, whereas the tap weights magnitudes in the variable-step-size LMS equalizer are larger than the tap weights magnitudes in the LMS equalizer.

In order to optimize the convergence speed and the compensation effect, the variable-step-size LMS algorithm is introduced and employed in the adaptive filter. The performance of the CD compensation for 60 km fiber dispersion using the variable-step-size LMS equalizer compared with LMS equalizer are illustrated in Fig. 7. The VLMS adaptive equalizer could achieve the same CD compensation performance with the LMS adaptive equalizer, meanwhile, the VLMS filter using the step size varying from 0.06 to 0.6 that accelerates the algorithm converging speed.
In the above analysis and discussions, only the chromatic dispersion was taken into consideration. Actually, the PMD equalization can also be performed using the LMS algorithm. Thus the combination of CD equalizer and PMD equalizer can be implemented using the variable-step-size LMS algorithm.

Meanwhile, the CMA algorithm can also be used for the adaptive chromatic dispersion compensation, while the LMS algorithm is also tolerant to small amount of phase noise. However, for larger phase noise or equalization enhanced phase noise [44,45], the CMA algorithm is more effective, since the performance of LMS algorithm will be significantly degraded by the large phase noise.

V. CONCLUSIONS
The variable-step-size least mean square equalizer is developed to compensate the chromatic dispersion in the 112-Gbit/s PDM-QPSK coherent optical transmission system. The variable-step-size LMS adaptive filter could make a compromise between the algorithm converging speed and the CD compensation performance compared to the traditional LMS adaptive filter. The tap weights in the LMS filter and the VLMS filter are analyzed, and the chromatic dispersion compensation effects using the two adaptive filters are compared by evaluating the BER versus OSNR behavior using numerical simulations.

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