Lightning Induced Polarization Effect Model and Polarization Equalization Using Kalman filter

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***Abstract*—Based on the delay field and Heidler function, we established a lightning-induced PMD+RSOP fiber channel model, We also proposed an extended Kalman filter algorithm to equalize the signal impairments induced by the proposed fiber channel model, under the situations of different DGD and baud rates. The numerical simulation shows that EKF outperforms CMA.**

Keywords—lightning-induced fiber cascading model, retarded field model, cascaded channel model, EKF, Heidler function

I. Introduction

In modern coherent polarization division multiplexing (PDM) system in optical fiber, lightning in the rainy days causes transient polarization variations due to Faraday effect in the fibers, resulting in the receiver unlocking [1]. Tracking and equalizing this effect becomes an important issue to ensure the stable operation of communication systems under thunderstorms. In previous studies [2], the rotation of the state of polarization (RSOP) caused by lightning strikes has received focused attention, while the coupling effect between the inherent polarization mode dispersion (PMD) in the channel and the effects of lightning strikes is often neglected. In order to more comprehensively consider the effect of lightning strikes on signal transmission, this paper focuses on the effect of lightning striking on the optical ground wires (OPGWs), namely the transient variations of RSOP and PMD in the channel, emulating the RSOP and PMD in fibers. To this end, a coherent PDM-QPSK system is built in the digital simulation platform. Heidler model [3], retarded field model [4] , and a specially built segmented cascaded channel model are used to emulate the polarization variations induced by lightning strikes on signal transmission. Finally, we employ the extended Kalman filtering (EKF) [6] algorithm to track and equalize the RSOP and PMD in the channel and plot the outage probability of the bit error rate (BER) at different baud rates with different DGD. The results are compared with the generalized CMA algorithm, and it is demonstrated that the extended Kalman filtering algorithm is more effective in compensating for the effects of lightning strikes. Meanwhile, the out-of-bounds probability diagram can be used to obtain the maximum communication baud rate allowed by the communication system under certain lightning strike conditions and channel conditions, which provides a reference for the specific settings of modern coherent high-speed information transmission systems.

II. Modeling

A. Lighting Current Model

Due to the Faraday effect, when the optical signal passes through the fiber section affected by the lightning strike, the magnetic field caused by the lightning strike current will cause the SOP to rotate through the angular ϕ by the relation:

$$\phi = V \int_0^l B(z,t)dz \tag{1}$$

where V is Verdet constant for material and varies with wavelength and temperature, B is the magnetic induction intensity in the direction of propagation, and l is the length of propagation.

The OPGW can be equivalent to a solenoid for their similar structure. Therefore, when the lightning strike current passes through the OPGW, the magnetic field it generates is aligned with the direction of signal propagation (or in the opposite direction), and its magnetic induction intensity B at a given point and time is determined by the formula:

$$B(z,t) = \frac{\mu}{d} i(z,t) \tag{2}$$

where μ is the permeability, d is OPGW spiral pitch, and i is current intensity. Besides, we assume positive in the direction of propagation and negative in the opposite direction.

For lightning strikes, the most common type is downward negative lightning; its peak current can reach 150kA, the current rise time is 1-5us, and the current fall time is much longer. The time-domain current of the lightning strike is usually described using the Heidler function:

$$I(t) = \frac{I_{max}}{\eta} \frac{(t/\tau_1)^n}{1+(t/\tau_1)^n} e^{-\frac{t}{\tau_2}} \tag{3}$$

where τ_1 and τ_2 are the current rising and falling time, $I_{\max}$ is the peak current, η and n are constants, selected as 1 and 10 [3].

Since the speed of light in the optical fiber is different from the speed of the lightning current in the OPGW, and both are not infinite, the impact caused by the magnetic field in the optical fiber is not instantaneously established. More accurate spatial and temporal distribution of SOP under lightning situation is given by the so-called retarded field model. According to the literature [4], for the optical signal arriving at the origin point at time t_0, the impact on its SOP using formula (1) and (2) can be expressed as :

$$\phi(t_0) = \frac{c\mu_0 V}{d} \cdot \left[\frac{1}{n+1} Q\left(t_0 - \frac{(n+1)L_1}{c}\right) + \frac{1}{n-1} Q\left(t_0 + \frac{(n+1)L_1}{c}\right) - \frac{2n}{n^2-1} Q(t_0)\right] \tag{4}$$

where c is the speed of light, n is the fiber refractive index, L_1, L_1 is the length of OPGW, $Q(t)$ is the notation for the time antiderivative $Q(t) = \int_{-\infty}^{t} I(t)\mathrm{d}t$

B. Cascaded Channel Model with Lightning Segment

The overall channel modeling is divided into five segments, as shown in Fig.1. The Faraday effect caused by a lightning strike is expressed by the following formula:

$$\mathrm{R}_{\text{strike}} = \begin{pmatrix} \cos\phi & -\sin\phi \\ \sin\phi & \cos\phi \end{pmatrix} \tag{5}$$

Formula (6) (7) can express the cumulative RSOP damage and the influence of PMD in the fiber. In reality, forces of nature such as wind, lightning, and temperature may alter the SOP . To simulate the whole process of lightning striking, a three-parameter RSOP rotation matrix is added to simulate the change of RSOP caused by other factors. At the same time, the PMD matrix is added to explore the coupling effect between the inherent PMD in the optical fiber and the impact of lightning strikes.

$$\mathrm{T}_i = \begin{pmatrix} e^{i\alpha}\cos\kappa & -e^{i\beta}\sin\kappa \\ e^{-i\beta}\sin\kappa & e^{-j\alpha}\cos\kappa \end{pmatrix} \tag{6}$$

$$\mathrm{D}_i = \begin{pmatrix} e^{i\omega\Delta\tau/2} & 0 \\ 0 & e^{-i\omega\Delta\tau/2} \end{pmatrix} \tag{7}$$

Fig. 1. The cascaded channel model with lightning segment.

C. Extended Kalman Filter

Kalman filter is an optimal algorithm for a dynamic system, which mainly consists of process equation and measurement equation. If the equation between the state vector and measurement vector is nonlinear, then the observation matrix can be approximated as linear equations by performing a first-order Taylor expansion. This kind of the Kalman filter that uses first-order approximation is called the extended Kalman filter [6]. In this paper, we use the extended Kalman filter to compensate for PMD and track RSOP.

PMD is a frequency domain impairment and can be represented as $\vec{\boldsymbol{\tau}} = (\tau_1,\tau_2,\tau_3)^T$ in Stokes space. RSOP requires three-parameter modeling [5], and is determined by (κ,α,β). Therefore, we chose $\hat{\mathbf{x}} = (\tau_1,\tau_2,\tau_3,\kappa,\alpha,\beta)^T$ as state vector for the extended Kalman filter and use a window-spilt structure. The symbols in the window are first transformed to the frequency domain by fast Fourier transformation (FFT), then the PMD is compensated in the frequency domain. The compensated frequency domain signal is converted to the time domain signal by IFFT, and finally the RSOP is compensated in the time domain. The compensation of PMD and RSOP can be completed by sliding the window sequentially and repeating the above operation. The general architecture of the extended Kalman filter is shown in Fig.2. The state vector is $\hat{\mathbf{x}}$ and $\mathbf{z}$ is the measurement vector. $\mathbf{Q}_{k-1}$ is the process noise covariance matrix. $\mathbf{R}_k$ is the measurement noise covariance matrix. h represents the equation between the state vector $\hat{\mathbf{x}}$ and the measurement vector $\mathbf{z}$. $\mathbf{H}_k$ is defined as the Jacobi matrix of observation equation expanded at prior estimation point $\hat{\mathbf{x}}_{k|k-1}$. $\mathbf{G}_k$ is the Kalman gain. $\mathbf{P}_k$ represents the covariance matrix of state vector. Subscript $k \mid k-1$ and $k\,(\text{or}\,k-1)$ in figure mean prior estimation and posterior estimation. Some parameters need to be initialized for the startup process of EKF. The initial state vector $\hat{\mathbf{x}}_0 = [0,0,0,0,0,0]^T$; The initial error covariance $\mathbf{P}_0 = \mathrm{diag}(10^{-5},10^{-5},10^{-5},10^{-5},10^{-5})$ $\mathbf{Q} = \mathrm{diag}(8\times10^{-5},8\times10^{-5},8\times10^{-5},2\times10^{-8},2\times10^{-8},2\times10^{-8})$ $\mathbf{R} = \mathrm{diag}(0.1,0.1)$.

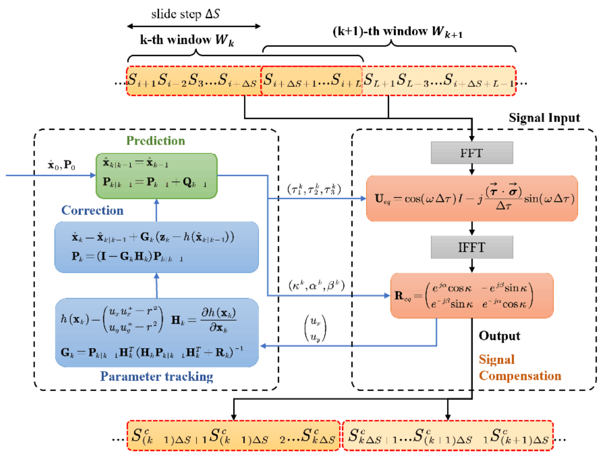
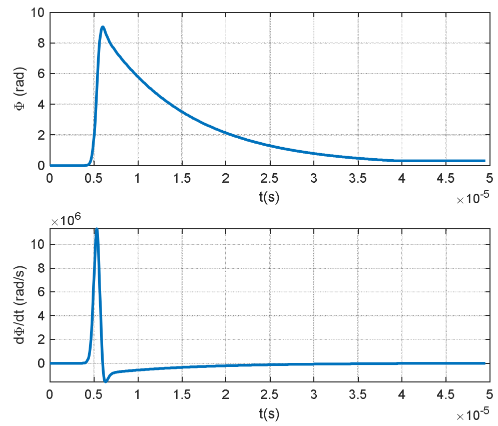


Fig. 2. The flow block for EKF scheme.

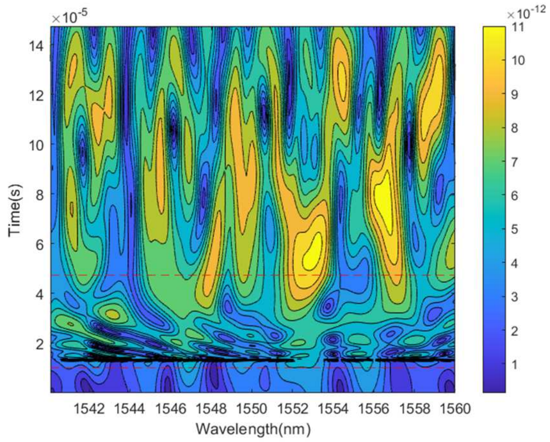
III. Simulation

According to the Heidler function, we simulated a typical $\phi - t$ curve and RSOP-time curve (Fig.3.a). Based on $\phi - t$ curve, The DGD distribution was simulated based on wavelength and time starting at t=2μs and lasting for 10μs after lightning, with channel parameters of $\omega_\alpha = \omega_\beta = \omega_\kappa = 15k$ rad, an average DGD of $\bar{\tau}$=5ps, and a DGD standard deviation of σ_τ=0.2 (Fig.3.b). The average ACF distribution based on 100 simulation results was also plotted (Fig.3.c).

(a)



(b)



(c)

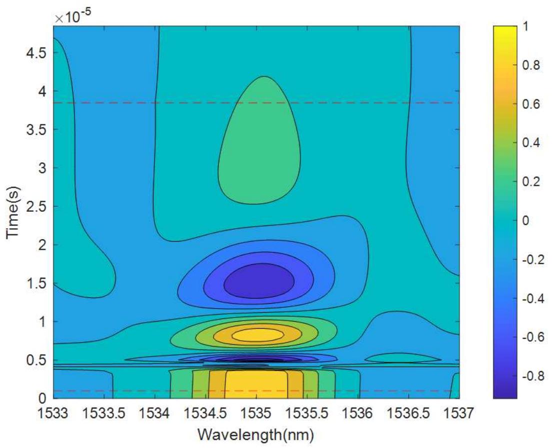


Fig. 3. (a) The angle and angular velocity of RSOP caused by lightning. (b) DGD distribution based on wavelength and time, red dashes mark lighting's beginning and end. (c) ACF distribution based on wavelength and time; red dashes also mark the beginning and the end of lightning.

To compare the equalization effects of the EKF and CMA algorithms under lightning influence, the cascaded model was employed to simulate the probability of BER$\geqslant 3.8\times10^{-4}$ for the two algorithms under different DGD and Baud rates. The channel adopted QPSK modulation, raised cosine pulses with a roll-off factor of 0.1, and an OSNR of 14dB. For each combination of Baud rate and DGD, we repeated the experiment 1000 times, with 2^{20} symbols used for each BER calculation. The comparison between the EKF and CMA algorithms under different baud rates and DGD values is shown in Fig.4. When DGD was between 4ps and 8ps, the EKF achieved a 20Gbps higher average Baud rate than the CMA for a 5% and 10% out-of-bound probability. This shows that under extreme lightning conditions, the equalization effect of the EKF algorithm is superior to that of the CMA algorithm.

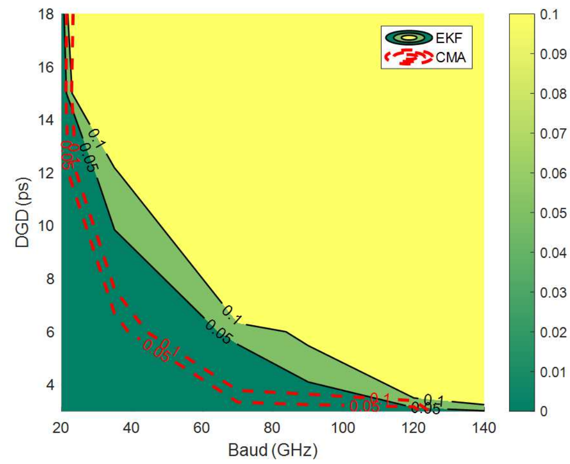


Fig. 4. Probability of BER $\geq 3.8\times10^{-4}$ under different baud rates and DGD values. Colormap and black lines represent the performance of EKF, while the red dashes represent the performance of CMA.

IV. Conclusion

In this article, we constructed a cascaded model for simulating lightning channel and provided the bit error rate (BER) out-of-bounds probability graph under different differential group delay (DGD) and Baud rates for both the constant modulus algorithm (CMA) and extended Kalman filter (EKF) algorithm. We found that under extreme lightning strike conditions, the EKF algorithm had an average 20Gbps higher Baud rate than the CMA algorithm for BER out-of-bounds probabilities of 5% and 10% at DGD conditions of 4ps-8ps. The BER out-of-bounds probability graph also provided the maximum allowable Baud rate for communication systems under certain lightning strike and channel conditions, providing a reference for the specific settings of high-speed coherent communication systems.

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