Machine Learning Based Fiber Nonlinear Noise Monitoring for Subcarrier-multiplexing Systems

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Abstract: We propose a set of correlation features for machine learning based fiber nonlinear noise monitoring in subcarrier-multiplexing systems. Improved accuracy is demonstrated by adding correlations between subcarriers and data fusion processing across subcarriers.
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1. Introduction

Fiber nonlinearity is one of the major impairments in long-haul wavelength-division multiplexing (WDM) transmission systems. Therefore, monitoring the fiber nonlinear noise is important to guarantee the quality of transmission (QoT) and optimize the operation of optical networks [1,2]. For single carrier (SC) systems, it is proposed in [3] to use amplitude noise correlation (ANC) and phase noise correlation (PNC) [4,5] of the symbols in one channel as the input features of an artificial neural network (ANN) to monitor nonlinear signal-to-noise ratio (SNR_{NLI}). In [6], it is further proposed to combine nonlinear monitoring and modeling using an ANN to reach higher accuracy. However, these schemes have not been investigated in subcarrier-multiplexing (SCM) systems. Also, they might not be as effective as in SC systems since signals in SCM systems have lower baud rates, which may cause lower correlation values and shorter correlation lags [3] in ANC and PNC due to the significantly reduced chromatic dispersion (CD) impact. Moreover, in practical systems, the monitoring operation requires a short reporting period, which favors a smaller number of symbols involved in the calculation. In this scenario, SCM systems provide new opportunities for data fusion across multiple subcarriers to refine the measurement and shorten the monitoring period.

In this paper, we analyze the characteristics of the fiber nonlinear noise in SCM systems and propose new features to improve the monitoring performance. Firstly, we calculate the inter-subcarrier-correlation features (Inter-SCF) of the amplitude and phase noise between two subcarriers in one channel. Second, we calculate the average intra-subcarrier-correlation features (AISCF) over all subcarriers based the concept of data fusion to improve the monitoring accuracy when the number of symbols is limited. The improved accuracy in monitoring the SNR_{NLI} of a specific subcarrier by adding the Inter-SCF and ASCF to the inputs of an ANN is demonstrated by extensive simulations for both the cases with sufficient and limited number of symbols, respectively.

2. Principle

The correlation of amplitude noise and phase noise exhibits a similar trend as the nonlinear noise [3]. Therefore, these correlations can be used to monitor the SNR_{NLI} with the aid of an ANN. In SCM systems, we categorize the correlation features into three types: the intra-subcarrier-correlation features (Intra-SCF), the inter-subcarrier-correlation features (Inter-SCF), and the average intra-subcarrier-correlation features (AISCF), which represent the features of one subcarrier, two subcarriers and all subcarriers, respectively. The details of the correlation calculations are described as follows.

According to [3], the amplitude noise correlation $ANC_{ij}^{ab}(m)$ and phase noise correlation $PNC_{ij}^{ab}(m)$ between the ath and the bth subcarrier in one channel can be calculated by correlation function ($corr()$) [6] respectively as

$$ANC_{ij}^{ab}(m) = corr\left(\Delta A_i^a(k), \Delta A_j^b(k+m)\right) \qquad i \ and \ j \ \in \{X,Y\} \tag{1}$$

$$PNC_{ij}^{ab}(m) = corr\left(\Delta \theta_i^a(k), \Delta \theta_j^b(k+m)\right) \qquad i \ and \ j \ \in \{X,Y\} \tag{2}$$

where $\Delta A_{i/j}^{a/b}(k)$ and $\Delta \theta_{i/j}^{a/b}(k)$ refer to the amplitude noise and phase noise of the kth received symbol. i and j denote the i and j-polarization, respectively. In order to extract the information closely related to the nonlinear noise and reduce the influence of fluctuations, the results of each correlation sequence are summed up as

$$R_{ij}^{ab}(n) = 10log10(1/\textstyle\sum_{m=1}^{n}\left|ANC_{ij}^{ab}(m)\right|) \tag{3}$$

$$P_{ij}^{ab}(n) = 10log10\left(1/\textstyle\sum_{m=1}^{\mathrm{n}}\left|PNC_{ij}^{ab}(m)\right|\right) \tag{4}$$

where R_{ij}^{ab} and P_{ij}^{ab} represent the correlation feature of the amplitude noise and phase noise, respectively. Based on the properties of the covariance functions, the selection of lags n in (3) and (4) depends on the specific situation and should be optimized. The three types of features are clarified and discussed as follows.

1. The Intra-SCF is obtained when a equals b. For the ath subcarrier, the Intra-SCF includes $R_{xx}^{aa}(n)$, $R_{yy}^{aa}(n)$, $P_{xx}^{aa}(n)$, $P_{yy}^{aa}(n)$, $R_{xy}^{aa}(0)$ and $P_{xy}^{aa}(0)$, which are the same as the features in [3].

2. The Inter-SCF is calculated when a does not equal b, which includes $R_{xx}^{ab}(n)$, $R_{yy}^{ab}(n)$, $P_{xx}^{ab}(n)$ and $P_{yy}^{ab}(n)$, where b refers to all the other subcarriers in the same WDM channel.

3. The AISCF is the average value of the Intra-SCF of all subcarriers in one WDM channel. Since the monitoring period should be short in some applications, the noise in the system such as ASE noise will cause fluctuations in correlation calculations, which may influence the monitoring performance. In SCM systems, data fusion methods can be applied to refine measurements from all subcarriers. Since the subcarriers in one WDM channel tend to have similar nonlinear noise, here we use the average function to reduce the fluctuations in the correlation calculation. This methodology can be extended to the scenario where joint monitoring is designed across multiple WDM channels or superchannels. We conduct a series of simulations to validate the effectiveness of the new features in both the cases with sufficient and limited number of symbols, respectively, which are discussed as follows.

3. Simulations and discussions

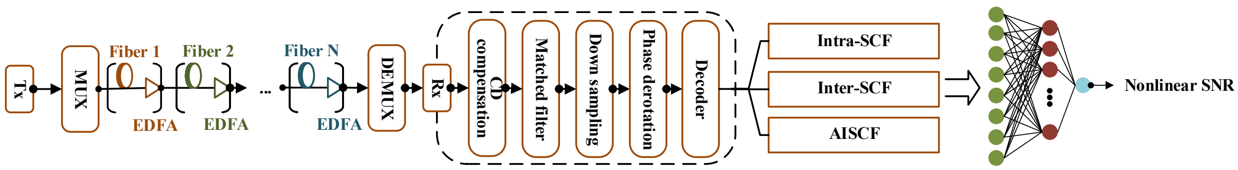


Fig. 1. Simulation setup.

As shown in Fig. 1, the simulation is conducted in a fixed-rate system with a symbol rate of 35Gbaud and a channel spacing of 50GHz. For the SCM system, the number of subcarriers is either 4 or 8. At the transmitter (Tx) side, we apply the root-raised-cosine (RRC) pulse shaping with a roll-off factor of 0.02. The aggregate symbol length is set to 2^{17} so that for each subcarrier the symbol length is 2^{15} and 2^{14} for the 4-subcarrier system and 8-subcarrier system, respectively. For each link, lumped Erbium-doped fiber amplifiers (EDFA) are adopted and the noise figure (NF) is 5dB. At the receiver (Rx) side, the center channel is filtered out to process. The chromatic dispersion compensation (CDC) and matched filter are applied followed by down sampling and phase derotation. Afterwards, the obtained symbols are used to calculate SNR, Intra-SCF, Inter-SCF and AISCF.

Table 1. Summary of simulation configurations.

Span fiber types	Span length/km	Span number	Launch power/dBm	Modulation format	Channel number
SSMF, PSCF, ELEAF, TWC	20:10:90	3:1:30	-4:1:4	QPSK/16QAM	1:2:15

700 samples for the 4-subcarrier system and 700 samples for the 8-subcarrier system are generated for training and testing. The channel configurations and link configurations of each sample are randomly selected from Table 1. The randomness in the selection follows a uniform distribution. To make the simulation close to the reality, some of the channels on the link are randomly set to be idle based on the same configuration in [6], and the power of all the occupied channels has a random fluctuation ϵ which follows the normal distribution $\epsilon \sim N(0.5,0.3)$dB.

For both the amplitude noise and phase noise, the correlation values calculated in SC systems are larger than that in SCM systems. When the number of subcarriers increases, both the correlation length and the correlation value decrease. Therefore, the length of correlations summed up for monitoring will be optimized individually to include most of the effective values while getting rid of the fluctuating values. The choices of lags are shown in Table 2.

Table 2. Summary of lag choices for correlation features.

	Intra-SCF		Inter-SCF	
System	Amplitude noise	Phase noise	Amplitude noise	Phase noise
4-subcarrier	5	30	1	30
8-subcarrier	3	20	1	20

We firstly evaluate the monitoring performance before and after adding the Intra-SCF in the system without the ASE noise. In this case the number of symbols involved in the calculation are sufficient to suppress all fluctuations. Similar to [3], the input features include the number of WDM channels, the net chromatic dispersion and the Intra-SCF. We use the MATLAB neural networks toolbox to build a one-hidden-layer ANN. All the ANN models have 60 neural nodes for the hidden layer to guarantee convergence in every situation. In the training process, we choose the Bayesian regularization as the training algorithm to avoid overfitting. For all the models, we use 70% samples as the training set and the rest 30% samples for testing. The training stage stops at about 120 epochs for most of time, which means that after training for 120 epochs, the value of evaluation metrics will reach the threshold and the model converges. For the 8-subcarrier system, the ML model takes more time to reach convergence since more features are used. Fig. 2 (b) and (c) show the monitoring performance. The monitoring accuracy at a 95% cumulative probability improves from 1dB to 0.75dB and 1.25dB to 0.95dB for the 4-subcarrier system and 8-subcarrier system, respectively, which indicates that the cross-correlations adds more information to the nonlinear monitoring. The performance will slightly fluctuate for different training attempts. The improvement in the 8-subcarrier system is larger than that in the 4-subcarrier system for most cases.

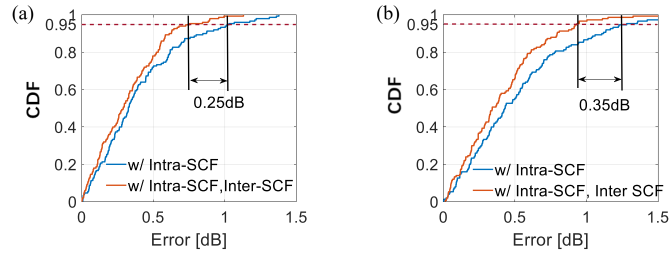
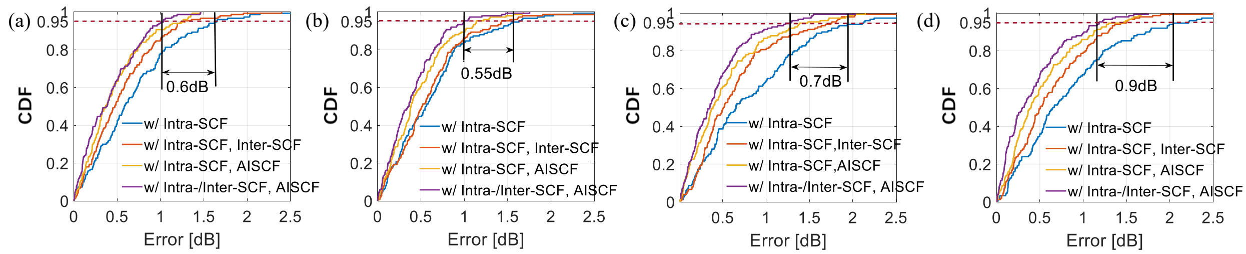


Fig. 2. The monitoring performance.

Next, we conduct the simulation when the monitoring period is assumed to be short, leading to a limited number of symbols for calculations. Also, the ASE noise is included in the system to generate more realistic measurement fluctuations. We compare the monitoring performance before and after adding the Inter-SCF and AISCF.



4 subcarriers /2048 symbols **4 subcarriers /4096 symbols** **8 subcarriers /2048 symbols** **8 subcarriers /4096 symbols**

Fig. 3. The comparison of the monitoring performance for different configurations.

Fig. 3 shows that the monitoring accuracy improves after involving the Inter-SCF and AISCF. With a decreasing symbol number, the monitoring performance with the Intra-SCF only becomes less accurate. After adding either the Inter-SCF or the ASCF, the monitoring accuracy is improved. By further adding the Inter-SCF and ASCF at the same time, the monitoring accuracy at a 95% cumulative probability improves by about 0.5dB and 0.8dB for the 4-subcarrier system and 8-subcarrier system, respectively. Our simulation covers different types of symbol length and the results are summarized in Table 3. The maximum monitoring deviation covering 95% samples reduces by about 0.5dB and 0.9dB in the 4-subcarrier system and 8-subcarrier system, respectively. In the 8-subcarrier system, the Inter-SCF can provide more features and the AISCF will suppress more fluctuations, resulting in a larger improvement. Fig. 4 shows the error histogram of the monitoring performance before and after adding the Inter-SCF and AISCF in the 8-subcarrier system with 2048 symbols, further indicating the usefulness of the Inter-SCF and AISCF.

Table 3. The maximum monitoring deviation covering 95% samples.

System	Correlation features	Symbol length			
		1024	2048	4096	8192
4-subcarrier system	Intra-SCF	1.6dB	1.6dB	1.55dB	1.6dB
	Intra-SCF+Inter-SCF	1.5dB	1.2dB	1.45dB	1.4dB
	Intra-SCF+AISCF	1.2dB	1.1dB	1.1dB	1.4dB
	Inter-/Intra-SCF+AISCF	1.1dB	1dB	1dB	1.1dB
8-subcarrier system	Intra-SCF	2.1dB	1.95dB	2dB	1.3dB
	Intra-SCF+Inter-SCF	1.7dB	1.75dB	1.4dB	0.9dB
	Intra-SCF+AISCF	1.2dB	1.3dB	1.3dB	1dB
	Inter-/Intra-SCF+AISCF	1dB	1.25dB	1.1dB	0.8dB

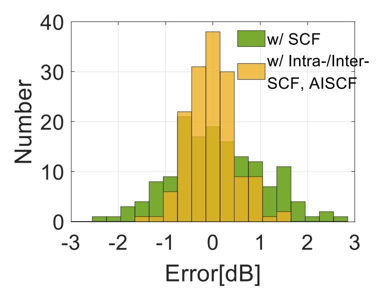


Fig. 4. The error histogram of the monitoring performance.

4. Conclusion

In this paper, we propose new features to monitor fiber nonlinear noise using machine learning in subcarrier-multiplexing systems. Our simulations show that the correlations between subcarriers and the data fusion processing across subcarriers can significantly improves the monitoring accuracy.

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