論文の内容の要旨

Optical Performance Monitoring in Digital Coherent Receivers

（ディジタルコヒーレント受信器を用いた光パフォーマンスモニタリング）

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Optical performance monitoring (OPM) is an important issue for proper operation of next-generation optical networks. Among various monitored parameters, the optical signal-to-noise ratio (OSNR) and fiber transmission impairments such as chromatic dispersion (CD), polarization mode dispersion (PMD), and polarization dependent loss (PDL) are paid special attention, because they serve information of the channel quality, which helps to manage the network. Several methods have been proposed for monitoring tasks, which are based on pilot tones, RF tones, asynchronous histogram, and fiber nonlinear effects. Most of them need costly devices, tap optical power from the channel, and introduce transmission overhead. On the other hand, in this research, we investigate OPM based on digital coherent receivers, which overcomes such difficulties and ensures cost-efficient, robust and reliable monitoring.

Linear channel impairments such as CD, PMD, and PDL are monitored from the transfer functions of adaptive filters. A digital coherent receiver allows polarization demultiplexing and equalization of all these impairments by using four finite-impulse-response (FIR) filters structured in a two-by-two butterfly configuration. After the filters are adapted by a suitable algorithm, we can construct a frequency-dependent two-by-two matrix with four elements, which are transfer functions of the adapted four FIR filters. The inverse of this matrix is called the monitoring matrix and can be approximated as the transfer matrix of the channel, and contains combined effects of CD, PMD and PDL. A precise algorithm is required to separate out the impairments from this matrix. We propose a simple and unified algorithm to separate out CD, differential group delay (DGD), PDL, and second-order PMD from the monitoring matrix. The components of second-order PMD, polarization-dependent chromatic dispersion (PCD) and depolarization (DEP) of principal states of polarization are obtained separately. This algorithm has an advantage that individual impairment can be estimated directly from the monitoring matrix without any matrix decomposition; thus it enables accurate estimation of the impairments,

even when the transmitted signal suffers from distortion stemming from various origins. Also, no additional hardware is required for our proposed algorithm.

For filter adaptation, we use the constant-modulus algorithm (CMA), as it enables long-tap-filter adaptation efficiently even in the presence of large laser phase noise unlike the commonly used decision-directed least-mean-square (DD-LMS) algorithm. However, CMA can suffer from the singularity problem which means both the output ports of butterfly configuration converge to the same polarization tributary. Consequently, we avoid the singularity problem by introducing the training mode in CMA. In the training mode, the LMS algorithm is used to determine in which output port of the butterfly configuration each polarization tributary appears, and after such initial training the algorithm is switched to the blind CMA to enable high-order-filter adaptation. The multi-impairment monitoring algorithm and the singularity-free operation of CMA with the training mode, which we have proposed in this thesis, are verified by dual-polarization quadrature phase-shift keying (QPSK) transmission experiments.

For such an impairment-monitoring method, the delay tap length of filters should be long enough to compensate for all the impairments. However, the computational complexity of FIR filters increases with the number of taps. The frequency-domain approach can reduce this computational cost by block-by-block processing and fast implementation of discrete Fourier transform (DFT). However, the adaptive frequency-domain equalizer (FDE) has hardly been investigated for optical communication systems. We have proposed a novel adaptive FDE based on CMA, which maintains all the advantages of the adaptive TDE based on FIR filters. Even in the block processing mode of FDE, it can work on the twofold-oversampled input sequence by introducing even and odd sub-equalizers. Therefore, when we configure this filter in the butterfly structure, we can achieve adaptive equalization together with polarization demultiplexing and adjustment of the arbitrary initial sampling phase of analog-to-digital converters (ADCs) so that the best symbol-spaced sequence is produced. The equalization performance of the proposed adaptive FDE as well as multi-impairment monitoring from the equalizer is verified by dual-polarization QPSK transmission experiments.

We have proposed a novel OSNR monitoring method. This is based on the analysis of higher-order statistical moments of adaptive-equalizer output in digital coherent receivers. After equalization and clock recovery by an adaptive equalizer, symbol-spaced signal samples and noise samples have well-defined but dissimilar statistical properties. In our proposed algorithm, we measure the second- and fourth-order moments of the adaptive-equalizer output. Then, by using the known statistics of the phase-modulated signal in the QPSK format and amplified spontaneous emission (ASE) noise, we estimate the OSNR. The proposed method is simple and accurate. We also experimentally verify this monitoring algorithm with 10-Gsymbol/s QPSK transmission experiments.