論文の内容の要旨

論文題目　Digital Compensation for Transmission Impairments in Coherent Optical Receivers
（コヒーレント光受信器におけるディジタル信号処理を用いた伝送制限要因の補償に関する研究）

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In recent years, the digital coherent receiver have been studied extensively in the field of optical fiber transmission. Since such a receiver can restore the full information of the optical electric field, we can realize spectrally-efficient systems using polarization-division multiplexing and multilevel-modulation formats such as quadrature-phase-shift keying (QPSK) and higher-order quadrature-amplitude modulation (QAM). On the other hand, system impairments have to be overcome in order to elongate the maximum transmission distance of such signals. The most crucial system impairments are the laser phase noise, the frequency offset, chromatic dispersion, polarization-mode dispersion, polarization-dependent loss/gain, and fiber nonlinearity. The digital coherent optical receiver enables post-compensation for these impairments with sophisticated digital-signal processing (DSP). Such post-compensation is one of the most important functions of the digital coherent optical receiver, and this dissertation is dedicated to the research and development of post-compensation schemes and to realize ultra-long haul transmission systems with high spectral efficiency.

Recently, the digital coherent optical receiver for the dual-polarization QPSK signal has been introduced to the commercial system. However, most of the demodulation algorithms employed in the QPSK receiver cannot directly be applied to the higher-order QAM signals. In order to achieve further spectrally-efficient systems, novel demodulation algorithms for higher-order QAM signals are indispensable. Another issue is that fiber-nonlinearity compensation is not conducted in such receivers since it requires the high computational cost. To achieve long-haul transmission distance with higher-order QAM signals, we must compensate for fiber nonlinearity.

Considering these problems inherent in the current digital coherent receivers, we propose novel demodulation algorithms applicable to all of transmission systems in a unite manner. The results of the research are as follows.

First, we propose a novel dual-stage decision-directed phase estimator, which is based on the one-tap finite-impulse-response (FIR) filters and the decision-directed least-mean-square (DD-LMS) algorithm with the training mode. This scheme can eliminate phase fluctuations induced both by the phase noise and by the frequency offset in all of multilevel-modulation systems; in particular, it enables perfect frequency-offset elimination without any power penalty as far as the whole signal spectrum is properly converted into the digital domain. Our proposed scheme consists of the first-stage estimator tracking the phase noise and the second-stage estimator tracking the frequency offset. These estimators are designed so as to operate without mutual interaction with the following procedures: (1) The fast phase change by the frequency offset is estimated from the second-stage estimator and is removed from the error signal in the DD-LMS algorithm controlling the first-stage estimator. (2) The frequency offset estimated from the second-stage estimator is eliminated from the tap coefficient of the first-stage estimator by using a phase integrator. Using such a scheme, the proposed phase estimator can work in a stable manner even with frequency offsets much larger than the symbol rate. Based on computer simulations and experiments, the effectiveness of the proposed phase estimator is confirmed in higher-order QAM systems.

Second, we propose a novel configuration of the FIR filter adapted by the DD-LMS algorithm with the training mode, in which fast phase fluctuations are removed from the error signal used for tap adaptation of FIR filters. With such a scheme, we can employ arbitrary-long delay taps in FIR filters even under the influence of fast phase fluctuations. Our proposed scheme can operate under polarization-mode dispersion and polarization-dependent loss/gain without any singularity problem owing to the training sequence for initialization of the tap coefficients. In addition, our scheme can easily be applied to any multilevel modulation formats, since it employs the DD-LMS algorithm in all of the tap-adaptation processes. Through computer simulations and experiments, we show that the proposed FIR-filtering scheme is robust against the phase noise and the frequency offset in higher-order QAM systems.

Third, we propose a novel Kerr-effect compensator with the low computational cost. In order to improve the performance of a split step, we modify a configuration of a single split-step compensator by employing dispersive elements and filters. Using such a modified split step, we can achieve the best demodulation performance with the lowest computational cost. Next, we propose a novel Kerr-effect-compensation scheme, in which the modified split steps are aligned in parallel in the frequency domain. With such a scheme, parallel signal processing is achieved, which is suitable for hardware implementation. We confirm that the proposed scheme significantly elongates the maximum transmission distance of QAM signals both in dispersion-managed systems and in dispersion-unmanaged systems.

Our proposed post-compensation schemes can be applied to any transmission systems. The results we obtained open up the possibility of ultra-long haul transmission systems with high capacity and have enormous significance in the development of future optical fiber networks.