Residual dispersion equalization using correlation detection in Nyquist OTDM scheme

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Abstract:
We propose a wavelength-dispersion equalizing scheme that counteracts the signal degradation caused by residual dispersion in Nyquist optical time-division multiplexing. To counteract the signal degradation, this scheme uses optical correlation receivers and a distorted reference signal. At a Q factor of 6.4 dB, the permissible values of the residual dispersion increased from 14.5 ps/nm to 99.5 ps/nm at a baud rate of 160 Gbd.

Keywords: OTDM, residual dispersion, correlation detection
Classification: Fiber-Optic Transmission for Communications

References
[1] M. Nakazawa, T. Hirooka, P. Ruan and P. Guan, “Ultrahigh-speed “orthogonal” TDM transmission with an optical Nyquist pulse train,” Optics Express, vol. 20, no. 2, pp. 1129-1140, Jan. 2012. DOI:10.1364/OE.20.001129
[2] F. Ito, “Demultiplexed detection of ultrafast optical signal using interferometric cross-correlation technique,” J. Lightwave Technol., vol. 15, no. 6, pp. 930-937, June 1997. DOI:10.1109/50.588661
[3] J. G. Proakis and M. Salehi, Digital Communications, 5th ed., McGraw Hill, New York, 2005, pp. 177-179.
[4] Y. Miyoshi, H. Kubota and M. Ohashi, “Nyquist OTDM scheme using optical root-Nyquist pulse and optical correlation receiver,” Electronics Express, vol. 11, no. 2, 20130943, Jan. 2014. DOI:10.1587/elex.10.20130943
[5] Y. Miyoshi, H. Kubota and M. Ohashi “Signal degradation due to finite integration time for correlation detection in Nyquist OTDM scheme,” Commun. Express, vol. 6, no 4, 142-147, Apr. 2017 DOI:10.1587/comex.2016XBL0203
[6] G. P. Agrawal, “Nonlinear fiber optics 5th ed.,” Academic Press, New York, 2012, pp. 78-81.
[7] K. Morimoto, Y. Miyoshi, H. Kubota and M. Ohashi, “Correlation Detection Scheme for Suppression of Residual Dispersion in Nyquist OTDM,” Proc. of the 22nd Opto-Electronics and Communications Conference, Singapore,
1 Introduction

A Nyquist optical time division multiplexing (OTDM) scheme can realize low inter-symbol interference and high spectral efficiency with a high baud rate [1]. To achieve a high optical signal-to-noise ratio (OSNR) tolerance with high spectral efficiency, we previously proposed a Nyquist OTDM scheme based on correlation detection [2–5]. However, the signal spread caused by residual dispersion increases with increasing baud rate [6]. The signal spread causes inter-symbol interference that degrades the signal quality. Therefore, a precise dispersion compensation is needed to suppress the signal degradation.

This paper proposes and investigates a residual-dispersion equalization scheme that detects distorted optical signals with residual dispersion using a distorted reference signal and optical correlation receivers [7]. This scheme reduces the required accuracy of the dispersion compensation. We then investigate the permissible value of the residual dispersion by numerical simulation.

2 Principle of residual dispersion equalization

Figure 1 shows a Nyquist OTDM scheme using correlation detection. A tributary signal is generated by an optical impulse train source and an optical modulator. The spectrum of the modulated signal is limited by an optical root-raised cosine (RRC) filter with a 3-dB bandwidth of $1/T$, where $T$ is the time slot of the multiplexed signal. The tributary signal is multiplexed by an OTDM multiplexer [5]. The chromatic dispersion, which distorts the multiplexed signal in the single mode fiber (SMF), is compensated by a dispersion compensation fiber (DCF). The mismatch between the SMF and DCF causes a residual dispersion that distorts the received signal. The spectrum of the received signal is given by

$$S_{\text{RX}}(\omega) = S_{\text{OTDM}}(\omega) \exp \left\{ -j \frac{acR_d}{\omega_0^2} (\omega - \omega_0)^2 \right\},$$

where $S_{\text{OTDM}}$, $c$, $\omega_0$ and $R_d$ are the multiplexed signal before transmission, velocity of light, carrier frequency, and residual dispersion, respectively [6]. The lowercase $s$ and uppercase $S$ denote a signal in the time and frequency domains, respectively. To simplify the discussion, we ignore the loss and Kerr effects in the optical fibers.

An optical correlation receiver, which comprises optical 90° hybrid and two balanced photo receivers (BPRs) with integrators, de-multiplexes and detects the
real and imaginary parts of the received signal. The detected signal is given by

\[ s_{\text{OUT}}(t) = C_{\text{BPR}} \int_{-\frac{MT}{2}}^{\frac{MT}{2}} s_{\text{RX}}(\tau) s_{\text{REF}}^*(\tau) d\tau, \] (2)

where \( s_{\text{REF}}^* \) denotes the complex conjugate of the reference signal. When the multiplicity is sufficiently high and the influence of adjacent signals can be ignored, Eq. (2) can be approximated by an infinite time integral using Parseval’s theorem:

\[ s_{\text{OUT}} \approx C_{\text{BPR}} \int_{-\infty}^{\infty} s_{\text{RX}}(\tau) s_{\text{REF}}^*(\tau) d\tau \approx C_{\text{BPR}} \int_{-\infty}^{\infty} S_{\text{RX}}(\omega) S_{\text{REF}}^*(\omega) d\omega, \] (3)

where the constant \( C_{\text{BPR}} \) includes the photo-current sensitivity of the photo receivers and the gain of the trans-impedance amplifiers. Previously, a conventional reference signal was generated by an impulse train source and transmitted by the same optical RRC filter. The residual dispersion induces inter-symbol interference and signal amplitude reduction.

To suppress the degradation caused by residual dispersion, we propose an equalization scheme that counteracts the residual dispersion using the distorted reference signal with the same residual dispersion. The spectrum of the distorted reference signal is given by

\[ S_{\text{REF-D}}(\omega) = S_{\text{REF-RRC}}(\omega) \exp \left\{ -j\frac{\pi c R_e}{\omega_0^2} (\omega - \omega_0)^2 \right\}, \] (4)
where \( S_{\text{REF-RRC}} \) is the conventional reference signal using the optical RRC filter. The distorted reference signal can be generated by an optical short-pulse source and an optical pulse-shaping filter [8]. From Eqs. (1), (3) and (4), the detected signal with the distorted reference signal is expressed as:

\[
S_{\text{OUT}} = C_{\text{BPR}} \int_{-\infty}^{\infty} S_{\text{RX}}(\omega)S_{\text{REF-D}}^{*}(\omega) d\omega, \\
\approx \int_{-\infty}^{\infty} S_{\text{OTDM}}(\omega) \exp \left\{ -\frac{j \pi c R_d}{\omega_0^2} (\omega - \omega_b)^2 \right\} d\omega \\
S_{\text{REF-RRC}}^{*}(\omega) \exp \left\{ \frac{j \pi c R_d}{\omega_0^2} (\omega - \omega_b)^2 \right\} d\omega \\
= C_{\text{BPR}} \int_{-\infty}^{\infty} S_{\text{OTDM}}(\omega) S_{\text{REF-RRC}}^{*}(\omega) d\omega,
\]

The distorted reference signal can counteract the residual dispersion effect. In practice, the temporal integration limits are finite [5], and the waveforms of the received and reference signals are broadened by residual dispersion. The finite integral time and signal broadening might degrade the signal quality.

### 3 Relationship between residual dispersion and Q factor

We investigated the permissible range of the residual dispersion under the influence of finite integral time and temporal broadening of the signals. The signal generation was modulated by binary phase-shift keying, and the pattern length of the pseudo-random bit sequence was \( 2^9 - 1 \). The signal wavelength was 1550 nm. The roll-off factor, multiplicity and baud rate were 0.1, 16 and \( 16 \times 10 \) Gbd, respectively. The OSNR of the received signal was 30 dB. The noises of the BPDs and the integrators were ignored.

Figure 2 shows the relationship between the residual dispersion and the quality factor (Q factor) using the conventional reference signal \( S_{\text{REF-RRC}} \) and the proposed reference signal \( S_{\text{REF-D}} \). To investigate only the effect of the residual dispersion, the fiber loss and Kerr effects in the transmission line were ignored. In this case, the Q factor depended on the absolute value of the residual dispersion. The Q factor of the proposed reference signal was reduced by the limited integral time \( MT = 100 \) ps and the temporal expansion of the signals by residual dispersion. In an ideally matched filter with zero residual dispersion, the theoretical upper limit of the Q factor is 18.92 dB. In the proposed scheme, the permissible values of the residual dispersion at a 6.4-dB Q factor increased from 14.5 ps/nm to 99.5 ps/nm. The Q factor of 6.4 dB was the forward error correction (FEC) limit of the triple-concatenated FEC in soft decision decoding [9].

Figure 3 plots the relationship between the residual dispersion and the Q factor of signals distorted by Kerr effects in the transmission fiber. The nonlinear parameter \( \gamma \), fiber loss \( \alpha \), length \( L \), and dispersion coefficient \( D \) were 2.0 W\(^{-1}\)km\(^{-1}\), 0.2 dB/km, 100 km, and 17 ps/km-nm, respectively. In both the conventional and proposed schemes, the Q factor degraded with increasing average launch power \( P_{\text{in}} \). This degradation was caused by Kerr effects, which distort the signals in the absence of residual dispersion. At a Q factor of 6.4 dB, the permissible values of the residual
dispersion within the $P_{in}$ range 0–13 dBm increased from 14.2–14.5 ps/nm in the conventional method to 98.4–99.5 ps/nm in the proposed method. The improvement was that expected after removing the residual dispersion, leaving only the Kerr effect.

Fig. 2. Relationship between residual dispersion and Q factor without signal distortion due to Kerr effects.

Fig. 3. Relationship between residual dispersion and Q factor with signal distortion due to Kerr effects.

4 Conclusion
We proposed a scheme that equalizes the residual dispersion in OTDM, and thereby suppresses signal degradation. The Q factor of the detected signal was improved by distorting the reference signal with the same residual dispersion. We also investigated the effect of finite integration time and temporal broadening of the signals due to residual dispersion. At a Q factor of 6.4 dB, the proposed scheme increased the permissible value of the residual dispersion from 14.5 ps/nm to 99.5 ps/nm at the baud rates of 16 × 10 GBd. The same improvement was observed with and without signal distortion caused by Kerr effects.

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