Signal degradation due to finite integration time for correlation detection in Nyquist OTDM scheme

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Abstract: Integration time of the correlation receiver for a Nyquist optical time-division multiplexing (OTDM) scheme is limited by the multiplicity of the OTDM scheme. We investigate the signal degradation caused by the finite integration time of the correlation receiver. The signal degradation factor is analyzed by separating it into noise resistance degradation and intersymbol interference. We also conduct numerical simulations to estimate the required multiplicity number and roll-off factor for suppressing the signal degradation.

Keywords: OTDM, correlation receiver, optical Nyquist pulse

Classification: Fiber-Optic Transmission for Communications

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1 Introduction

A Nyquist optical time-division multiplexing (OTDM) scheme is expected to realize low inter-symbol interference (ISI) and high spectral efficiency with ultra-
high-speed transmission [1]. To achieve high optical signal-to-noise ratio (OSNR) tolerance with high spectral efficiency, we have previously proposed a Nyquist OTDM scheme based on correlation-detection [2, 3]. This correlation-detection scheme was proposed to reduce the required OSNR to satisfy a target quality factor (Q factor). The required OSNR of ideal correlation detection is the same as that of a matched filter [4]. To perform correlation detection similar to that of an ideal matched filter, infinite integration time and a reference signal of an isolated single pulse are required. However, to demultiplex the multiplexed signal without ISI by the previous and next tributary signals, the integration time is limited by the multiplicity. In this study, we investigate the signal degradation caused by the finite integration time of the correlation receiver. We analyze the factors of signal degradation by separating it into ISI and noise resistance (NR) degradation. We also perform numerical simulations to identify the multiplicity and roll-off factor required to suppress the signal degradation.

2 Nyquist OTDM scheme and model of signal degradation due to finite integration time

Fig. 1(a) shows a block diagram of the Nyquist OTDM scheme using correlation detection. The tributary signal is generated by an optical-impulse-train source and an optical modulator. The modulated impulse train can be written as:

\[ s_{\text{MOD}(t)} = \sum_{i=-\infty}^{\infty} d_{ik} \delta(t - iMT), \] \tag{1}

where \( i \) and \( k \) are integer. \( d_{ik} \) is the signal for modulation, and \( M \) and \( T \) are the multiplicity and the time slot of the multiplexed signal, respectively. When the modulation format is binary phase-shift keying (BPSK), the value of \( d_{ik} \) is 1 or \(-1\). \( \delta \) is a delta function. The spectra of the modulated signals are limited by optical root-raised cosine (ORRC) filters for the baud rate of the multiplexed signal. The output signal of the transmitters can be written as

\[ s_{\text{TX}(t)} = \sum_{i=-\infty}^{\infty} h_{\text{ORRC}} d_{ik} \delta(t - iMT). \] \tag{2}

The impulse response \( h_{\text{ORRC}} \) and frequency response \( H_{\text{ORRC}} \) of an ORRC filter can be written as

\[ h_{\text{ORRC}}(t) = 4a \frac{\cos((1 + a) \frac{2\pi}{T}t) + \sin((1 - a) \frac{2\pi}{T}t)}{\pi \sqrt{T}} \frac{1}{1 - \left(\frac{4aT}{T}\right)^2} \exp(j2\pi f_c t), \] \tag{3}

\[ H_{\text{ORRC}}(f) = \begin{cases} 1, & (0 \leq |f - f_c| < \frac{1+n}{2\gamma}) \\ \sqrt{1 + \cos\left(\frac{2\pi}{T} |f - f_c| - \frac{1+n}{2\gamma}\right)}, & (\frac{1+n}{2\gamma} \leq |f - f_c| < \frac{1+n+\alpha}{2\gamma}) \\ 0, & (\frac{1+n+\alpha}{2\gamma} < |f - f_c|) \end{cases} \] \tag{4}

where \( \alpha \) is a roll-off factor. \( f_c \) is a career frequency. The OTDM signal is generated by time-interleaving of the tributary signals with a delay \( kT \) as follow.
The reference signal is generated by an optical-impulse-train source and an ORRC filter. The reference signal can be written as

$$s_{\text{REF}}(t) = \sum_{i=-\infty}^{\infty} h_{\text{ORRC}} \delta(t - iMT).$$

The real and imaginary parts of the received signals are detected using an optical 90° hybrid, two balanced photo receivers, and the reference signal. The reference-signal timing of each correlation receiver is adjusted by an optical delay line (ODL) to overlap with each tributary signal. The integration circuit and analog-to-digital converter (ADC) detect the integrated signal with a finite integration time from $t = iMT + kT - MT/2$ to $t = iMT + kT + MT/2$. To suppress ISI from the previous and next reference signals, the integration time is limited by the multiplicity $M$ and time slot $T$. The detected signal can be written as

$$u_{ik} = C \int_{iMT + kT - \frac{MT}{2}}^{iMT + kT + \frac{MT}{2}} s_{\text{OTDM}}(\tau)s_{\text{REF}}^*(\tau - kT) d\tau,$$

where $C$ is a constant that includes the photo-current sensitivity of the photo receivers and the gain of the trans-impedance amplifiers (TIA), and $s_{\text{REF}}^*$ is the
complex conjugate of the reference signal. Therefore, the length of the integration time is limited to the $MT$. However, to realize ideal correlation detection as a matched filter for maximizing signal quality and satisfying the Nyquist criterion for strictly zero ISI, infinite integration time and a reference signal of an isolated single pulse with a waveform of $h_{\text{ORRC}}$ are necessary. The finite integration time causes signal quality degradation because of ISI and NR degradation.

Fig. 1(b) shows the relationship between OSNR and quality factor (Q factor). The Q factor is defined as

$$Q = \frac{|\mu_1 - \mu_{-1}|}{\sigma_1 + \sigma_{-1}},$$  \hfill (8)

where $\mu_1$ and $\mu_{-1}$ are the average amplitudes of the detected signals at $d_k$ of “1” and “−1”, respectively. $\sigma_1$ and $\sigma_{-1}$ are standard deviations of detected signals at $d_k$ of “1” and “−1”, respectively. The Q factor using ideal matched filter $Q_{\text{MF}}$ for modulation format of BPSK can be written as that provided in [4],

$$Q_{\text{MF}}^2 = \frac{(\mu_1 - \mu_{-1})^2}{(\sigma_{\text{MF}1} + \sigma_{\text{MF}-1})^2} \frac{BW_{0.1\text{nm}}OSNR}{B},$$  \hfill (9)

$$= \frac{BW_{0.1\text{nm}}OSNR}{B},$$  \hfill (10)

$$P_{\text{NR}} = \frac{BW_{0.1\text{nm}}}{B}.$$  \hfill (11)

where $\sigma_{\text{MF}1}$ and $\sigma_{\text{MF}1-1}$ are the standard deviations of the the detected signals using an ideal matched filter. $BW_{0.1\text{nm}}$ is a frequency bandwidth with an optical bandwidth of 0.1 nm at the carrier wavelength. $OSNR$ is the average power ratio of the multiplexed optical signal and the additive white Gaussian noise (AWGN) with an optical bandwidth of 0.1 nm, and $B(=1/T)$ is the baud rate of the multiplexed signal.

The signal degradation factor is analyzed by separating it into NR degradation and ISI components. The degraded Q factor due to NR degradation can be written as

$$Q_{\text{NR}}^2 = \frac{P_{\text{NR}}(\sigma_{\text{MF}1} + \sigma_{\text{MF}1-1})^2}{(\mu_1 - \mu_{-1})^2},$$  \hfill (12)

where $P_{\text{NR}}$ is a Q penalty due to the NR degradation. The degraded Q factor due to ISI can be written as

$$Q_{\text{ISI}}^2 = \frac{(\mu_1 - \mu_{-1})^2}{(\sigma_{\text{ISI1}} + \sigma_{\text{ISI1-1}})^2},$$  \hfill (13)

where $\sigma_{\text{ISI1}}$ and $\sigma_{\text{ISI1-1}}$ are the standard deviations caused by the ISI. The total square stranded deviation including the NR degradation and ISI assumes the summation of the square stranded deviations. The total Q factor $Q_{\text{TOTAL}}$ including the NR degradation and ISI can be expressed using $P_{\text{NR}}$ and $Q_{\text{ISI}}$ as follows:

$$Q_{\text{TOTAL}}^2 = \frac{(\mu_1 - \mu_{-1})^2}{P_{\text{NR}}(\sigma_{\text{MF}1} + \sigma_{\text{MF}1-1})^2 + (\sigma_{\text{ISI1}} + \sigma_{\text{ISI1-1}})^2}$$  \hfill (14)

$$= \frac{P_{\text{NR}}Q_{\text{MF}}^2Q_{\text{ISI}}^2}{P_{\text{NR}}Q_{\text{MF}}^2 + Q_{\text{ISI}}^2}.$$  \hfill (15)

In addition, $P_{\text{NR}}$ and $Q_{\text{ISI}}$ do not depend on $T$, because the integration time and impulse response of ORRC filter are also proportional to $T$. 

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3 Degraded Q factor due to ISI and Q penalty due to NR degradation

We investigated the values of $P_{NR}$ and $Q_{ISI}$ using numerical simulations. The transmission signal was generated with the modulation format of BPSK and pseudo-random bit sequence (PRBS). The pattern length of PRBS was $2^9 - 1$. The center wavelength of the ORRC filters was 1550 nm. The thermal noise, shot noise and quantization error of BPRs and ADCs were ignored. The $Q_{ISI}$ was found by numerical analysis of the Q factor without AWGN. The $P_{NR}$ was found by Monte Carlo simulations with AWGN.

Fig. 2(a) and (b) show $Q_{ISI}$ and $P_{NR}$ as functions of the roll-off factor $\alpha$ of the ORRC filter and $M$, respectively. The ripples in Fig. 2(a) and (b) are because of the oscillations of the reference signal and finite integration time. The value of $Q_{ISI}$ increased with increase in $\alpha$ and $M$, whereas $P_{NR}$ decreased. This was because the outer signal of the integration time was decreased with increase in $\alpha$ and $M$.

Fig. 3(a) and (b) show the required OSNR at required Q factors $Q_{TOTAL}$ of 18.0 dB (high) and 6.4 dB (low), respectively at a baud rate of 160 Gbaud. The two $Q_{TOTAL}$ value assume a bit error rate of $10^{-15}$ without forward error correction (FEC) and with triple-concatenated FEC using soft decision decoding, respectively [5]. When $Q_{ISI}$ approached $Q_{TOTAL}$ as shown in Fig. 2(a), the required OSNR rapidly increased, as shown in Fig. 3(a). When $Q_{TOTAL}$ was sufficiently smaller.
than $Q_{\text{ISI}}$, the required OSNR increased by the value of $P_{\text{NR}}$, as shown in Fig. 3(b). To suppress both signal degradations due to the NR degradation and ISI for a target Q factor below 20 dB, $P_{\text{NR}} \leq 0.1$ dB and $Q_{\text{ISI}} \geq 30$ dB can be obtained by $\alpha \geq 0.2$ at $M = 4$ and $\alpha \geq 0.03$ at $M = 16$, respectively.

4 Conclusion

We investigated the signal degradation due to the finite integration time of the correlation receiver. The signal-degradation factor was analyzed by separating it into ISI and NR degradation components. Both signal-degradation factors decreased with increase in $\alpha$ and $M$. To suppress both signal degradations at a target Q factor below 20 dB, $P_{\text{NR}} \leq 0.1$ dB and $Q_{\text{ISI}} \geq 30$ dB were obtained by $\alpha \geq 0.2$ at $M = 4$ and $\alpha \geq 0.03$ at $M = 16$, respectively.

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