Cut-off frequency and number of quantization bits required for correlation receiver in Nyquist OTDM scheme

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Abstract: We investigate the effect of the cut-off frequency and number of quantization bits of analog-to-digital converters on the signal quality in a Nyquist optical-time-division-multiplexing scheme using the impulse response of a correlation receiver. The cut-off frequency and number of quantization bits required at a baud rate of 160 GBd are determined through numerical simulations.

Keywords: OTDM, correlation receiver

Classification: Fiber-Optic Transmission for Communications

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1 Introduction

A Nyquist optical time division multiplexing (OTDM) scheme can realize both low inter-symbol interference and high spectral efficiency with ultra-high-speed transmission [1]. In order to achieve a high optical signal-to-noise ratio (OSNR) tolerance with high spectral efficiency, we proposed using a Nyquist OTDM scheme based on correlation detection [2, 3, 4]. The OSNR required for correlation detection is the same as that required for a matched filter (MF) [5]. To easily realize correlation detection, we have proposed and demonstrated a Nyquist OTDM scheme that uses an impulse response of the correlation receiver [6, 7]. In this scheme, the impulse response of the receiver, including balanced photo receivers (BPRs) and analog-to-digital converters (ADCs), acts as a first-order low pass filter (LPF) and an integration circuit. The signal quality depends on the cut-off frequency of the correlation receiver.

In this paper, we investigate the effect of the cut-off frequency, roll-off factor, and number of quantization bits of ADCs on the signal quality of a Nyquist OTDM scheme, and we determine the cut-off frequency and number of quantization bits required for a baud rate of 160 GBd.

2 Nyquist OTDM scheme using impulse response of correlation receiver

Fig. 1 shows a simulation model of the Nyquist OTDM scheme using the impulse response of a correlation receiver. An optical impulse train source and an optical modulator are used to generate a tributary signal. At the baud rate of the multiplexed signal, the spectra of the modulated signals are limited by optical root-raised cosine filters. The tributary signals are multiplexed by an OTDM multiplexer [4]. The real and imaginary parts of the received signals are detected using an optical 90° hybrid, two BPRs, and a reference signal. The timing of the reference signal of each correlation receiver is adjusted using an optical delay line (ODL) so as to overlap each tributary signal. For simplicity, the response time limitations of the correlation receiver, including the BPR and ADC, are considered to be first-order LPFs; these acted as the integration circuits. The BPR output, $V_{BPR}$, can be expressed as

$$V_{BPR}(t) = C_{BPR} s_{OTDM}(t) s_{REF}^*(t - t_D),$$

(1)

where $s_{OTDM}$, $s_{REF}^*$, and $t_D$ are the multiplexed signal, complex conjugate of the reference signal, and delay time of the ODL, respectively. $C_{BPR}$, meanwhile, is a constant that includes the photo-current sensitivity of the photo receivers and the gain of the trans-impedance amplifiers. The impulse response, $h_{LPF}$, of the LPF can be expressed as follows:
\begin{equation}
\h_{\text{LPF}}(t) = \frac{1}{t_C} \exp\left(-\frac{t}{t_C}\right), \quad (t \geq 0),
\end{equation}

\begin{equation}
t_C = \frac{1}{2\pi f_{3\text{dB}}},
\end{equation}

where \(t_C\) and \(f_{3\text{dB}}\) are the time constant and 3-dB cut-off frequency of the LPF, respectively. The output signal, \(V_{\text{LPF}}\), of the LPF can be expressed as follows:

\begin{equation}
V_{\text{LPF}}(t) = \int_{-\infty}^{t} h_{\text{LPF}}(t - \tau) V_{\text{BPR}}(\tau) d\tau
= \int_{t-MT}^{t} h_{\text{LPF}}(t - \tau) V_{\text{BPR}}(\tau) d\tau + \exp\left(-\frac{MT}{t_C}\right) V_{\text{LPF}}(t-MT),
\end{equation}

\(V_{\text{LPF}}\) interferes with the past tributary signals, as indicated by the second term of Eq. (4). Fig. 1(b) shows the waveform pattern of \(V_{\text{LPF}}\) at \(f_{3\text{dB}} = 2\) GHz. The amplitude is separated into eight levels at \(t = 50\) ps owing to the interference of the two tributary signals preceding the signal. The ADCs sample the output signals of the LPF with a sampling time of \(t = nMT + \delta t\), where \(M\) and \(T\) are the multiplicity and time slot of the multiplexed signal, respectively, and \(n\) and \(\delta t\) are the integer number and offset time of sampling, respectively. Using subtractors (two-tap finite impulse response filters) with the subtraction factor, \(C_{\text{SUB}} = \exp(-MT/t_C)\), the integrated voltage between \(t = (n-1)MT + \delta t\) and \(t = nMT + \delta t\) can be written as follows:
\[ V_{\text{SUB}}(n) = V_{\text{LPF}}(nMT + \delta t) - C_{\text{SUB}} V_{\text{LPF}}((n - 1)MT + \delta t) \]
\[
= \int_{(n-1)MT+\delta t}^{nMT+\delta t} h_{\text{LPF}}(nMT + \delta t - \tau) V_{\text{BPR}}(\tau) d\tau 
\]
\[
= C_{\text{BPR}} \int_{(n-1)MT+\delta t}^{nMT+\delta t} h_{\text{LPF}}(nMT + \delta t - \tau) s_{\text{OTDM}}(\tau) s_{\text{REF}}^*(\tau - t_D) d\tau. \quad (5)
\]

The interference at \( \delta t = 50 \text{ ps} \) is removed by the subtractors, as shown in Fig. 1(c). However, the \( h_{\text{LPF}} \) induces an undesirable influence in this integrated output. In addition, the accuracy of the subtracted output depends on the number of quantization bits, \( N \), of the ADCs. In this paper, we investigate the effect of both \( f_{3\text{dB}} \) and \( N \) of the ADCs on the signal quality and determine the number of quantization bits and cut-off frequency required at 160 GBd.

### 3 Effect of cut-off frequency, roll-off factor, and number of quantization bits on the signal quality

We investigated the effect of \( f_{3\text{dB}} \) and \( N \) on the signal quality at baud rate \( B = 160 \text{ GBd} \) and multiplicity \( M = 16 \). The signal was generated with a modulation format of binary phase-shift keying and a pattern length of \( 2^9-1 \) for the pseudo-random bit sequence. The wavelength of the signals was 1550 nm. To investigate how the signal degraded owing to the correlation receiver, we conducted numerical simulations for a high OSNR of 30 dB without signal degradation in the transmission lines. \( \delta t \) was adjusted so that the Q factor of the subtracted signal could be maximized. Notably, the theoretical limit of Q factor when using ideal MF is 18.92 dB at an OSNR value of 30 dB.

Fig. 2(a) shows the Q factor as a function of \( f_{3\text{dB}} \) and \( N \) at the roll-off factor of the RRC filters with \( \alpha = 0.1 \). The ripples of the Q factor occurred due to oscillations of the reference signal and finite integration time in Eq. (5). When the quantization error was ignored, the Q factor increased as the cut-off frequency decreased. The Q factor with the significantly low cut-off frequency was approximately the same as that obtained with the ideal MF. These results can be attributed to the LPF acting as an ideal integration circuit owing to the constant value of \( h_{\text{LPF}} \) when the cut-off frequency was significantly low. When the quantization error was not ignored, the Q factor decreased in the low cut-off frequency region. This was because the amplitude of the subtracted signal was small owing to the high subtraction factor when the cut-off frequency was small. Therefore, the Q factor degradation due to the quantization was enhanced in the low cut-off frequency region. To maximize the Q factor, it was essential to set the cut-off frequency to its optimum value.

Fig. 2(b) shows the Q factor at the optimum cut-off frequency as a function of \( \alpha \). When \( \alpha \) approached 0, the Q factor rapidly decreased. This is because the outer signal of the integration time in Eq. (5) increased as \( \alpha \) decreased [4]. To reduce the Q factor degradation from the ideal MF to below 0.5 dB for \( \alpha \geq 0.05 \), the required number of quantization bits was 5 bit. The variation of the optimum cut-off frequency in the high \( \alpha \) region occurred due to the ripple of the Q factor and the low dependence on the cut-off frequency, as will be described below.
Figs. 3(a) and (b) show the Q factor as a function of the cut-off frequency and $\alpha$ at $N = 5$ and 6 bit, respectively. In the high cut-off frequency region, the Q factor degradation from that of the ideal MF decreased as $\alpha$ increased. This was because a decrease in $\alpha$ led to a broadening of the waveform of the received and reference signals in the time domain. Therefore, the error due to the imperfect integration by the LPFs and subtractors increased as $\alpha$ decreased because the impulse response of the LPFs was not constant in the time domain. In order to suppress the Q factor degradation to below 0.5 dB for $\alpha \geq 0.05$, the required cut-off frequencies for the number of quantization bits were 1.7–3.2 GHz for $N = 5$ bit and 0.6–4.1 GHz for $N = 6$ bit.

4 Conclusion

We investigated the effect of the cut-off frequency, roll-off factor, and number of quantization bits of ADCs on the signal quality of a Nyquist OTDM. When the quantization error was taken into consideration, the optimized cut-off frequency of the ADCs was necessary to maximize the Q factor of the detected signals. The suitable range of the cut-off frequency became narrower as $\alpha$ became smaller. When the multiplicities and baud rate were 16 and 160 G Bd, respectively, the cut-off
frequency required to suppress the Q factor degradation to below 0.5 dB for $\alpha \geq 0.05$ were 1.7–3.2 GHz for $N = 5$ bit and 0.6–4.1 GHz for $N = 6$ bit.

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