Effects of Decision Ambiguity Level on Optical Receiver Sensitivity

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Abstract—We describe the effect of a finite-decision ambiguity level on optical receiver sensitivity. A new analytic expression for the receiver sensitivity including the effect of the decision ambiguity level is obtained by modifying the well-known expression assuming an ideal decision circuit. Also obtained is a requirement for linear channel transimpedance gain or decision ambiguity level for less than 1-dB power penalty of receiver sensitivity.

I. INTRODUCTION

HIGH-SENSITIVE optical receivers are important for long haul optical transmission systems. The sensitivity predictions have been carried out by assuming Gaussian noise statistics and hard limiting decision circuit [1]–[3]. This assumption is nearly correct when the transmission bit rate is relatively low, where decision circuits having sufficiently low ambiguity level are available for receiver implementation. However, recent progress in transmission technologies shows that more than 10 Gbit/s transmission is possible. The ambiguity level of decision circuit at such a high bit rate is not negligibly small due to the immaturity of electronic device technology [4]. In this case, the prediction of receiver sensitivity by assuming hard limiting decision circuit deviates from actual sensitivity.

In this letter, we describe the effect of a finite ambiguity level on receiver sensitivity. A new sensitivity expression including a finite ambiguity level is derived. A requirement on the linear channel transimpedance for less than 1-dB sensitivity penalty due to the decision ambiguity level is also obtained.

II. THEORY

The effects of a finite decision ambiguity level on the optical receiver sensitivity are not negligibly small for high speed receiver, since the ambiguity level increases with increasing the data rate [4]. The input and output characteristics of decision circuit is shown in Fig. 1 with voltage distributions of input signal. In this letter, we assume that incorrect decision is made only in the threshold range for simplicity. To obtain the quality factor $Q$ including the effects of a finite ambiguity level, we follow the sensitivity calculation method with Gaussian noise [1], [3]. We can obtain the quality factor $Q$ for input signal power $P_s$ ($i = 0, 1$) to the receiver form the quality factor definition of logic level 0 and 1:

$$Q = \frac{\sqrt{S(1)} - \sqrt{S(0) - D_a/T_i}}{\sqrt{N(1)} + \sqrt{N(0)}}$$  \hspace{1cm} (1)

where $D_a$ denotes the decision ambiguity level, $T_i$ the transimpedance of the linear channel, $S(i) = (\alpha P_s(i))^2$ and $N(i) = \alpha C P_s(i) + I_{circ} + N_{op} = \alpha C P_s(i) + \beta$ the detected signal power and the noise power at logic level “i,” respectively. $I_{circ}$ is the circuit noise, and $N_{op}$ the sum of amplified spontaneous emission (ASE) noise and ASE-ASE beat noise [1], [2]. The coefficients $\alpha = \eta e(M) L_a GL/h\nu$ and $C = 2eB_{d}(M)[F(M) + 2\eta_{op}(G - 1)L_o]$ represent the conversion efficiency from the signal power into photodetector to the current and the signal dependent noise effects, respectively. The detector quantum efficiency is represented by $\eta$, the avalanche photodetector (APD) gain $M$, the gain of optical amplifier (e.g., erbium doped fiber amplifier) $G$, the input coupling loss of the amplifier $L_i$, the output coupling loss $L_o$, the electrical bandwidth of the receiver $B_{dl}$, the amplifier spontaneous emission factor $\eta_{op}$, and the excess noise factor of the APD $F(M)$.

As can be seen in (1), the signal power is reduced by the ratio of the decision ambiguity level to the linear channel transimpedance. This explicitly causes the sensitivity penalty because more received power is required to maintain a given $Q$ value. The receiver sensitivity $P_{av}$ involving the finite decision
ambiguity level can be obtained by solving the following equation

\[ X^4 - 2CQ^2E_rX^3 + \left[ Q^4C^2 - 4\beta Q^2 - 2CQ^2 \frac{D_a}{T_l} \right] X^2 + 2C^2Q^4 \frac{D_a}{T_l} X + C^2Q^4 \frac{D_a^2}{T_l^2} = 0 \]  

where \( X = 2\alpha P_{av} E_r - \frac{D_a}{T_l} \) and \( E_r = \frac{(1 + r)}{(1 - r)} \), and \( r \equiv \frac{P_s(0)}{P_s(1)} \) represents the inverse of the extinction ratio. In the case of small \( \frac{D_a}{T_l} \), an explicit equation for the receiver sensitivity can be obtained by treating these terms as a small perturbation, and given by

\[ P_{av} = P_{avo} + \frac{D_a}{T_l} \frac{1 + r}{2\alpha(1 - r)} \times \left[ 1 + \frac{1}{1 + \frac{\beta(1 - r)^2}{c^2Q^2 \left\{ \frac{1}{(1 + r)^2} + \frac{c^2Q^2}{1 + r} \sqrt{\beta + C^2Q^2 \frac{1}{(1 - r)^2}} \right\}}} \right] \]

where \( P_{avo} \) is the intrinsic sensitivity of the optical receiver with ideal decision circuit, i.e., zero ambiguity level [2], which is expressed as

\[ P_{avo} = CQ^2 \frac{1 + \frac{\beta}{c^2Q^2 \left( \frac{1}{(1 + r)^2} + \frac{c^2Q^2}{1 + r} \sqrt{\beta + C^2Q^2 \frac{1}{(1 - r)^2}} \right)}}{2\alpha(1 - r)^2} \]  

It may be noted that (4) is a well-known expression for sensitivity of the receiver employing an optical preamplifier and an APD [2].

In (3), the second term in the right-hand side represents the effect of the decision ambiguity level on the receiver sensitivity and causes a power penalty. In order to design an optical receiver having high sensitivity, the second term should be minimized. As a guideline, the required linear channel transimpedance for less than 1-dB power penalty for a given ambiguity level can be given by

\[ \frac{1}{T_l} \leq \frac{0.52\alpha P_{avo}(1 - r)}{D_a(1 + r) \left[ 1 + \frac{\beta(1 - r)^2}{c^2Q^2 \left\{ \frac{1}{(1 + r)^2} + \frac{c^2Q^2}{1 + r} \sqrt{\beta + C^2Q^2 \frac{1}{(1 - r)^2}} \right\}} \right]} \]

It is worth noting that (5) is the general expression for the required transimpedance, which is applicable to the optical receiver using an optical preamplifier, a PIN photodetector, and an APD. It also includes the effect of the extinction ratio. When the optical signal is ideal, i.e., \( P_s(0) = r = 0 \), (5) can be simplified to

\[ T_l \geq \frac{D_a}{P_{avo} \left( 0.52\eta e(M)L_eG\lambda/h\nu \right)} \left[ 1 + \frac{1}{(1 + 2\sqrt{\beta}/CQ)} \right] \]

The required transimpedance is directly proportional to \( D_a \) and inversely proportional to the intrinsic sensitivity \( P_{avo} \). This means that the highly sensitive optical receiver requires higher transimpedance. The numerical value of the numerator of (6) is between 1 and 2. It approaches 1, when the signal independent noise \( \beta \) becomes a dominant noise source. Otherwise it approaches to 2 for the receiver with a large amount of signal-dependent noise, which is denoted by \( C \).

III. RESULTS

We have solved (2) numerically for three optical receiver types using a PIN photodiode, an APD, and an optical preamplifier (EDFA). The calculated receiver sensitivities at 10 Gbit/s are shown in Fig. 2 as a function of linear channel transimpedance. The effect of decision ambiguity level on the power penalty increases as the transimpedance decreases. It also increases with decreasing the circuit noise because the intrinsic sensitivity decreases. It implies that the optical receiver with a small circuit noise requires a large transimpedance to take advantage of the small circuit noise. For the PIN detector based receiver, the required transimpedance at 1-dB power penalty is 92 dBΩ for 10 pA/(Hz)^{1/2} noise current. For the APD receiver, the improvement of the intrinsic sensitivity is approximately the gain of the APD. Thus the required transimpedance at 1-dB penalty is almost the same as the PIN detector case.

However, for the optically amplified receiver with a high amplifier gain, the intrinsic sensitivity improvement is not as much as the amplifier gain due to the saturation of signal-to-noise ratio [5]. Thus, the required transimpedance at 1-dB penalty decreases [see (6)]. The required transimpedance at 1-dB penalty is reduced from 92 dBΩ to 74 dBΩ in the case of using 30-dB gain amplifier. The rate of decrease in the required transimpedance is approximately the ratio of the optical amplifier gain and the receiver intrinsic sensitivity improvement due to the optical amplifier.
The output voltage of the linear channel that is the maximum available input voltage of the decision circuit is another consideration for receiver design. Fig. 3 shows the required transimpedance and the output voltage of the linear channel for the optically amplified receiver with 80 pA/(Hz)^1/2 noise current. When the amplifier gain is low, i.e., 10 dB, the required transimpedance is 75.2 dBΩ and the output voltage is around 0.72 V. At this point, the sensitivity of the receiver is -16.3 dBm. As the amplifier gain increases, the required transimpedance decreases, while the receiver sensitivity and the linear channel output increase. The increase of the output voltage arises from the increase of the signal dependent noise. When the amplifier gain is 40 dB, the required transimpedance decreases to 55.6 dBΩ. The output voltage, however, increases to 1.36 V. In this case, the sensitivity of the receiver is -33.7 dBm. This high output voltage may saturate the linear channel output amplifier or the decision circuit input and causes damage of the decision circuit. Accordingly, it may cause an extra penalty.

We also show effects of extinction ratio on the required transimpedance, the output voltage of the linear channel, and the corresponding sensitivity in Fig. 4. As the extinction ratio increases, the required transimpedance and the receiver sensitivity slightly increase, while the linear channel output voltage decreases. If the extinction ratio is larger than 15 dB, the changes are negligible. Thus, more than 15-dB extinction ratio is required for the transmitted signal to achieve high sensitivity.

IV. CONCLUSION

In conclusion, we have described the effects of decision ambiguity level on the sensitivity of optical receiver. We have derived an analytic expression for the receiver sensitivity and a requirement for the linear channel transimpedance to realize optical receiver with less than 1-dB power penalty caused by decision ambiguity level. We have also shown that the required linear channel transimpedance considerably decreased by employing the optical amplifier.

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REFERENCES