Evaluation of TCM and Clip Transmission Methods Applied to the Coexistence of OOK and PSK in the Downlink of Optical Access

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Abstract During the transition from current passive optical networks to next-generation systems, the error rate is expected to increase owing to the coexistence of on-off keying (OOK) which is used in the current optical network and phase-shift keying (PSK) for the next-generation system. Moreover, the currently used bias transmission method is problematic owing to excessive transmission power. Therefore, in this study, a trellis coded modulation, which is an error correction method, is proposed and evaluated, and a clip transmission method, which is a power reduction method, is applied to an environment where OOK and 8-PSK coexist. The effectiveness of the proposed approach was confirmed through a reduction in the received power of approximately 2.9 and 4.5 dB in PSK and OOK, respectively.

Keywords: coexistence environment, trellis coded modulation, clip transmission method, on-off keying, 8-phase shift keying

1. Introduction

Network traffic is increasing annually owing to the widespread use of services through network devices such as smartphones, Internet of Things devices, and streaming services. To cope with increasing traffic, research is being conducted on speeding up and increasing the capacity of optical access systems.

In particular, in addition to on-off keying (OOK), which is a modulation method based on the intensity of lights used in conventional passive optical networks (PONs), the use of phase-shift keying (PSK) and quadrature amplitude modulation (QAM) using a subcarrier phase has been proposed for speeding up and increasing capacity [1, 2]. However, terminals on current PONs do not have a digital signal processing function for PSK and QAM processing. Therefore, terminal replacement becomes necessary as the technology shifts. Since replacing all network terminals is time-consuming, the current and next-generation terminals will coexist for a certain period of time. Consequently, a conventional OOK signal and signals such as PSK and QAM coexist in an optical fiber.

Previous studies have reported that the error rate is high under such conditions, and the development of a method for achieving correct communication is necessary, when conventional and next-generation methods coexist [3].

2. Technical Problems and Solutions

This section describes the problems caused by the coexistence of old and new modulation schemes, as well as the solution method used in this study.

2.1 Coexistence of new and old technologies and technical issues

The PON environment that is commonly used is composed of an optical network unit (ONU) and optical line terminal (OLT), connected by an optical fiber and an optical splitter. Currently, the ONU and OLT communicate using the OOK modulation method, which is based on the intensity of light. However, it is expected that devices with new and old modulation schemes will coexist on the network owing to the advent of high-capacity and high-speed terminals. Figure 1(a) shows the coexistence of PSK and OOK, which are the next-generation and conventional modulation methods, respectively [4]. Constellation sharing is an effective communication method in the downlink direction in an environment where different modulation schemes coexist, as shown in Fig. 1(a).
This method uses a signal point arrangement that can support multiple modulation schemes. The signal modulation is performed by an electric circuit using subcarrier signals. Herein, we consider only downlink communication (limited to transmission from a single OLT). By contrast, constellation sharing cannot be applied to the uplink with the coexistence of OOK and PSK. Therefore, it will be realized by wavelength division multiplexing (WDM), but since this method is completely different from constellation sharing, the research target is limited to downlink only. This makes it possible to match the OOK and PSK phases, and the constellation shown in Fig. 1(b) can be obtained using digital signal processing. In addition, since subcarrier modulation occurs during the electrical stage, light modulation is the intensity modulation, as in conventional technology.

Because the PSK signals can secure a fixed distance, the errors are reduced. Thus, a trade-off relationship exists [3].

In addition, a bias transmission method has been conventionally used to convert an electrical signal into an optical signal. However, this method requires the addition of a DC component when converting the electrical signal to an optical signal, which increases the transmission power.

2.2 Solutions

Among the several types of error correction methods, this study employs trellis coded modulation (TCM). This method was selected to evaluate the suitability of TCM, which is used in wireless communications such as digital broadcasting, in a PON environment, which is a wired communication network. Moreover, it is relatively easy to implement, yet has a high error correction capability for random errors such as thermal noise.

The most significant feature of this method is set partitioning [5], where the signal constellation is divided into repeated subsets such that the distance between signal points becomes large. Using this method, when signals are mapped, it is expected that the distance between signals will increase, and error correction capability will improve.

Furthermore, to suppress the increased transmission power owing to the bias transmission method, the clip transmission method has been proposed [6]. Using this method, the negative electrical signal component is clipped to convert it into an optical signal without adding a DC component. Consequently, the optical power can be reduced. If the signal before clipping is $e(t)$ and the signal after clipping is $e^+(t)$, the mathematical expression is as shown in Eq. (1),

$$e^+(t) = \begin{cases} e(t) & (e(t) \geq 0) \\ 0 & (\text{otherwise}) \end{cases}$$  

In previous research [6], the clip transmission method was applied to uplink communication in the orthogonal subcarrier division multiplexing-PON (OSDM-PON) environment, which uses subcarriers orthogonal with each other in addition to the optical wavelength division to increase the capacity and speed. Conversely, herein, we confirmed the power reduction effect when clipping processing is applied to the downlink signal superimposed by OOK and PSK through digital signal processing.

This study evaluates whether the reduction in the error rate and power is possible in an environment where OOK and PSK coexist by combining the above two methods.
3. Simulation Environment

In this study, after confirming the effectiveness of the TCM and clip transmission methods, we confirmed the error rate characteristics when the constraint length and extinction ratio of the encoder were changed. The error rate characteristics were obtained through a simulation combining OptSim, an optical simulator, and MATLAB, a numerical calculation software. A block diagram of the simulation environment is shown in Fig. 2(a), and the encoder configuration when the constraint length is three is shown in Fig. 2(b). Table 1 shows a list of other typical parameters, and Table 2 shows the generator matrix of the encoder used when the constraint length is changed.

![Simulation Environment Diagram](image)

Fig. 2 Simulation environment

The symbol rates are 1 G Symbol/s, and the bit rates are 2 Gbps and 1 Gbps for PSK and OOK, respectively. The optical fiber used was a 1550-nm band single-mode fiber with a loss of 0.2 dB/km, a dispersion value of 16 ps/nm/km, a dispersion slope of 0.07 ps/nm²/km, and no chirp. The simulator used in this study implements a common single-arm Mach-Zehnder Amplitude Modulator with \( \sin^2 \) electrical-shaped Input-Output P-V (Power-Voltage) characteristic, with a loss of 3 dB. Furthermore, a PIN photodiode is set to receive, and the quantum efficiency is set to 0.7. As shown in Table 1, the components with an asterisk are optimized for 10 km to maximize the eye opening of the received signals at the ONU.

![Encoder Configuration Diagram](image)

Fig. 2 Encoder configuration (coding rate (PSK): 2/3, \( Z^{-1} \): delay element)

Table 1: Typical parameters of each component (*Optimized for 10 km)

| Component name          | Parameter name: value |
|-------------------------|-----------------------|
| Raised-cosine Filter*   | Roll-off factor: 1    |
| Bandwidth: 3.0 GHz      |                       |
| CW Laser                | CW Power: 5 dBm       |
| Modulator               | Excess Loss: 3 dB     |
| Chirp Factor: 0         |                       |
| Optical Fiber           | Loss: 0.2 dB/km       |
|                        | Dispersion: 16 ps/nm/km|
| PIN Photo-diode         | Quantum Efficiency: 0.7|
|                        | Dark Current: 0.1 nA  |
| Bessel Filter*          | Number of Poles: 6    |
|                        | Center Frequency: 10 GHz|
|                        | ~3 dB Bandwidth: 6.0 GHz|

Table 2: Encoder generator matrix

| Constraint length \( k \) | Generator matrix |
|-----------------------------|------------------|
| 3                           | \[
|                             | \begin{bmatrix} 1 & 0 & 1 \\ 1 & 1 & 1 \end{bmatrix} \] |
| 4                           | \[
|                             | \begin{bmatrix} 1 & 1 & 0 & 1 \\ 1 & 1 & 1 & 1 \end{bmatrix} \] |
| 5                           | \[
|                             | \begin{bmatrix} 1 & 0 & 0 & 1 & 1 \\ 1 & 1 & 1 & 0 & 1 \end{bmatrix} \] |

In Fig. 2(a), the broken and solid lines represent the MATLAB and OptSim function blocks, respectively. For the convolutional code, the encoder shown in Fig. 2(b) was used, and OOK and 8-PSK were superimposed. The error rate was evaluated at \( 10^{-3} \) points owing to the computer performance.

4. Simulation Results and Discussion

First, we confirmed the electrical and optical signals, and the electrical signal spectrum when the clip transmission method was applied and when it was not. Figures 3(a) and 3(b) show the electrical signals, and Figs. 3(c) and 3(d) show the optical signals. Figure 4 shows the power spectra before the clip at Point B of Fig. 2(a) and after the clip at Point A.

Figure 3 shows that, when the clip transmission method is applied, the negative portion of the electrical signal is cut and converted into an optical signal without bias. Additionally, Fig. 4 confirms that the transmission power was reduced.

Figure 5 shows the error rate characteristics of PSK and OOK when the constraint length \( k = 3 \), the optical fiber length \( l = 0 \) km, and the extinction ratio \( \varepsilon = 20 \) dB. Figure 5(a) shows the symbol error rate (SER) characteristic of PSK, and Fig. 5(b) shows the bit error rate (BER) characteristic of OOK. In both graphs, the blue line shows the results when TCM and Clip are applied, the orange line represents the results when only TCM is applied, and the green line...
(a) Electrical signal when clip is not applied
(b) Electrical signal when clip is applied
(c) Optical signal when clip is not applied
(d) Optical signal when clip is applied

Fig. 3 Signal waveform

Fig. 4 Power spectrum of electrical signals

Fig. 5 Error rate characteristics when \( l = 0 \)

represents the results when OOK and QPSK coexist. Note that OOK and QPSK coexistence do not apply error correction, and the same amount of information as when TCM is applied to OOK and 8-PSK can be transmitted. The average maximum and minimum values of the absolute value-processed received signal were used to determine the OOK.

Figure 5 confirms that the TCM and clip transmission methods are effective when the optical fiber length is 0 km. Specifically, in the case of PSK, the received power can be reduced by approximately 2 dB by applying TCM, and by applying the clip transmission method, it can be further reduced by approximately 1.8 dB. By contrast, in the case of OOK, because TCM is not applied, the improvement effect can be confirmed only when the clip is applied. The received power can be reduced by approximately 5.1 dB.

Because the effectiveness was confirmed when there was no optical fiber (\( l = 0 \)), the resulting error rate characteristics for an optical fiber length of 10 km are shown in Fig. 6.

Fig. 6 Error rate characteristics (\( k = 3, l = 10, \epsilon = 20 \))

Based on Fig. 6(a), the received power can be reduced by approximately 2.1 dB by applying TCM. Moreover, the received power can be further reduced by approximately 2.9 dB when applying the clipping process. Since the OOK does not apply error correction processing, the error rate improvement is based only on whether clip processing is applied, as shown in Fig. 6(b). Upon clip processing application, the received power can be reduced by approximately 4.5 dB.

Furthermore, Fig. 7 shows the constellations at fiber lengths of 0 and 10 km. Figure 7 confirms the constellation at Point C in Fig. 2(a) when the received power is approximately 15 dBm.

When the clip transmission method is not applied, the bias occupies most of the transmission power and thus the signal power is considered to be small and the overall radius is also small. The inner signal radius becomes very small when the clip transmission method is applied. The reason for this is the nonlinearity of the modulator \( \sin^2 \) characteristics. Therefore, the OOK improvement rate is considered to be larger than the PSK improvement rate because the distance to the decision boundary between the ON and OFF signals in-
creases. Furthermore, the shape of each constellation signal point is the same when the clip transmission method is not applied, but the signal point shape differs when both TCM and clip transmission methods are applied. Each signal point is radially spread out when the fiber length is 0 km compared to the case where the fiber length is 10 km. These constellation differences may lead to differences in the effect of error rate improvement when applying the clip transmission method shown in Fig. 5(a) and Fig. 6(a).

Furthermore, the clip transmission method effect was examined. Theoretically, the average optical transmission power ratio between the bias and clip transmission methods can be analyzed as follows. If the extinction ratio is defined as $\varepsilon$ and the radius of the outer signal is $r_2$, the inner signal radius can be calculated by $r_1 = \frac{r_2}{10^{\varepsilon/20}}$. When the $r_1$ and $r_2$ occurrence is an independent random process and the probability of each occurrence is 0.5, the ratio of the average optical transmission power $P_c$ of the clip transmission method and the average transmission power $P_b$ of the bias transmission method can be calculated using Eq. (2).

$$\frac{10 \log P_c}{P_b} = 10 \log \frac{\int_0^{r_1} (\sin x)^2 + \left(\frac{r_2}{10^{\varepsilon/20}} \sin x\right)^2 dx}{\int_0^{r_2} (\sin x + r_2)^2 + \left(\frac{r_2}{10^{\varepsilon/20}} \sin x + r_2\right)^2 dx}$$

(2)
Following the analysis, if the extinction ratio is 20 dB and the outer radius is 1, we obtain $10 \log \frac{P_c}{P_b} \simeq -9.97$ dB.

Therefore, the clip transmission method can reduce the transmission power by approximately 10 dB compared to the bias transmission method. However, in reality, only an improvement effect of approximately 3 dB was obtained. This is thought to be owing to distortion and noise owing to harmonics, and filter distortion when restoring the clipped waveform.

Furthermore, we evaluated the error rate at $10^{-4}$ points and confirmed that there was almost no difference in the degree of improvement from $10^{-3}$ points. Herein, the transmitted symbol was approximately $8 \times 10^4$; thus, the received power was compared at $10^{-3}$ points. However, Fig. 6 shows that there was negligible difference in the degree of improvement between the $10^{-4}$ points and the $10^{-3}$ points. From these results, because the error rate curve is approximately linear after $10^{-3}$, the same improvement effect can be expected even in the low error rate region.

These results confirm that the TCM and clip transmission methods are effective regardless of whether the optical fiber length is 0 or 10 km. However, in the case of TCM alone, the degree of improvement was almost the same, but when TCM and the clip transmission method were applied, the effect of improving the error rate was greater for the fiber length of 10 km than for 0 km due to the optimization of filters to 10 km as shown in Table 1.

Since the effects of the TCM and clip transmission methods were confirmed, the characteristics of the transmission method with different constraint lengths and extinction ratios were confirmed. Figure 8 shows the error rate characteristics when the constraint length is changed from $k = 3$ to 5, and Fig. 9 shows the error rate characteristics when the extinction ratio is 15 dB.

In Fig. 8, the blue line indicates $k = 3$, the orange line represents $k = 4$, and the green line shows $k = 5$. In addition, the solid line indicates when the TCM and clip transmission methods are applied, and the broken line shows when only the TCM is applied. The encoder used is shown in Table 1.

The error rate improved slightly by increasing the constraint length from that shown in Fig. 8. Moreover, Fig. 9 shows that when the extinction ratio is set to 15 dB, the PSK error rate characteristics can be improved without deteriorating the OOK error rate characteristics. It can be because the radius of the inner signal became larger by reducing the extinction ratio. Since the OOK decision method is a dynamic approach that uses the received signal maximum and minimum values, it is thought that almost no deterioration in the characteristics occurred.

5. Conclusion

In this study, TCM and the clip transmission method were applied to an environment of OOK and 8-PSK, assuming the coexistence of different modulation schemes owing to transitions in technology. The evaluation items are the error rates and power of 8-PSK and OOK. Consequently, the effectiveness of TCM and clip transmission methods was confirmed in the optical fiber length range of 0 to 10 km. In PSK, TCM had an improvement effect of approximately 2 dB, and the clip transmission method had an additional improvement effect of approximately 1.8 dB ($l = 0$) and 2.9 dB ($l = 10$).

By contrast, OOK improved by approximately 4.5 dB by applying the clip transmission method. OOK has a greater improvement effect than PSK because clipping reduces the inner signal radius and increases the distance between the ON and OFF signals. Furthermore, from the results when the constraint length and extinction ratio were changed, increasing the constraint length and decreasing the extinction ratio improved the PSK error rate.

From these findings, it is thought that the application of TCM and the clip transmission method to
a coexisting OOK and PSK environment is effective from the perspectives of both error rate and power level.

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