Advanced Turbo Code System with HPOS for FSO Strong Turbulence Channel

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Abstract

In this paper, the turbo code system with hybrid PPM-OOK signaling (HPOS) has been advanced by adding a new signal converter to improve the performance in the free space optical (FSO) strong turbulence channel. The proposed system is extended from the standard turbo code to the punctured turbo code. The bit error rate (BER) performance characteristics of the proposed system in the strong turbulence channel are evaluated by computer simulation. It was found that the proposed system with the new signal converter outperforms the conventional HPOS system. The BER performance of the proposed HPOS system is almost the same as that of the binary pulse position modulation (BPPM) punctured turbo code system, but its transmission efficiency of the proposed HPOS system is about 1.3 times higher.

1. Introduction

Owing to their potential high capacity, optical wireless communications (OWCs) are under the spotlight. There are many advantages of OWCs such as no interference with electronic systems, physical security measures, and license-free operation. OWCs can be used in many fields, for example, satellite communication, underwater communication, indoor visible light communication, and intelligent transport systems[1]-[2].

The introduction of the turbo code, one of the widely used error-correcting codes, is into OWCs to increase reliability has been investigated[3]. Owing to the nonlinearity of outputs from the diodes used as receivers, optical wireless communication systems generally use an IM/DD (intensity modulation with direct detection) scheme[4]. Binary pulse position modulation (BPPM) and on-off keying (OOK) are well known as typical binary modulation schemes of the optical wireless turbo code system[5]. Although the transmission efficiency of the OOK turbo code system is higher than that of the BPPM turbo code system, the OOK turbo code system is inferior to the BPPM turbo code system in bit error rate (BER) performance under the influences of the background noise and scintillation. Thus, the hybrid PPM-OOK signaling (HPOS) standard turbo code system (coding rate 1/3), which fuses the BPPM and OOK schemes, has been proposed. It has been reported that the proposed system shows the same BER performance as the BPPM turbo code system and a higher transmission efficiency than the BPPM turbo code system in a weak turbulence channel. However, the BER performance of the proposed system degrades in a strong turbulence channel[6]. To solve this problem, a new signal converter is proposed to enhance the decoder performance. The new signal converter uses a comparator to ensure that the input signal of the turbo decoder has the same noise variance for both the information bit and the parity check bit so that the noise variance of the parity check bit can be reduced. Thus, the decoder performance is expected to increase.

There are two main contributions of this paper. (1) we extend the HPOS turbo code system from the standard turbo code to the punctured turbo code. (2) We propose a new signal converter for enhancing the BER performance of the HPOS turbo code system in the strong space optical (FSO) turbulence channel. We evaluate the BER performance of the proposed HPOS punctured turbo code system with the new signal converter through computer simulation.

2. System Model

Figure 1 shows the structure of the new HPOS punctured turbo code system with a signal converter.

At the transmitter, the data is encoded by a punctured turbo encoder (coding rate 1/2). The encoder outputs one information bit stream \( I \) and one parity bit stream \( P \). \( I \) is modulated to streams \( S_1 \) and \( S_2 \) using BPPM and \( P \) is modulated to stream \( S_3 \) using OOK, respectively. Note that the BPPM signal has two streams, one for its left chip symbols and one for its right chip symbols. These three streams are converted to a transmitted frame by a parallel-to-serial (P/S) converter. This transmitted frame is called the HPOS frame. Figure 2 shows a sample of the HPOS frame. The transmitted HPOS frame has three chips: two chips stand for a BPPM symbol for an information bit and one chip stands for an OOK symbol for a parity bit. Each chip has a fixed time interval.

At the receiver, the received signal is reconverted to three streams, \( R_1 \), \( R_2 \), and \( R_3 \) by a serial-to-parallel (S/P) converter. The received on-off signal is converted to a polar (plus-minus) signal by the signal converter.

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the noise variance of the ‘on’ pulse chip is $\sigma_1^2$. Since the BPPM signal always has both ‘on’ and ‘off’ pulse, the noise variance of the converted polar information bit signal $i_{\text{est}}^{(k)}$, $\text{Var}_{i}$, is given by

$$\text{Var}_{i} = \sigma_1^2 + \sigma_0^2$$ (3)

The noise variance of the converted polar parity bit signal $p_{\text{est}}^{(k)}$, $\text{Var}_{p}$, is given by

$$\text{Var}_{p} = \begin{cases} 5\sigma_2^2 + \sigma_0^2 & (r_3^{(k)} = 'on') \\ 5\sigma_1^2 + 5\sigma_0^2 & (r_3^{(k)} = 'off') \end{cases}$$ (4)

The noise variances of the information and parity bits are different. We can also embody the conventional conversion method into the calculation of the log-likelihood ratio (LLR, i.e., channel value). The LLR in the FSO channel of the information bit at time $k$, $L_i(i_{\text{est}}^{(k)})$, (BPPM signal) is given by

$$L_i(i_{\text{est}}^{(k)}) = \ln \frac{P(i_{\text{est}}^{(k)}|i^{(k)} = 1)}{P(i_{\text{est}}^{(k)}|i^{(k)} = 0)} = \ln \left( \frac{1}{\sqrt{2\pi \text{Var}_i}} \exp \left( \frac{-((i^{(k)} - (\mu_1 - \mu_0))^2}{2\text{Var}_i} \right) \right)$$

$$= \ln \left( \frac{1}{\sqrt{2\pi (\sigma_1^2 + \sigma_0^2)}} \exp \left( \frac{-(r_1^{(k)} - r_2^{(k)} - (\mu_1 - \mu_0))^2}{2(\sigma_1^2 + \sigma_0^2)} \right) \right)$$

where $i^{(k)}$ is the correct transmitted information bit received at time $k$.

The LLR of the parity check bit at time $k$, $L_p(p_{\text{est}}^{(k)})$, (OOK signal) is given by

$$L_p(p_{\text{est}}^{(k)}) = \ln \frac{P(p_{\text{est}}^{(k)}|p^{(k)} = 1)}{P(p_{\text{est}}^{(k)}|p^{(k)} = 0)} = \ln \left( \frac{1}{\sqrt{2\pi \text{Var}_p}} \exp \left( \frac{-((p^{(k)} - (\mu_1 - \mu_0))^2}{2\text{Var}_p} \right) \right)$$

$$= \ln \left( \frac{1}{\sqrt{2\pi (\sigma_1^2 + 5\sigma_0^2)}} \exp \left( \frac{-(2r_3^{(k)} - (r_1^{(k)} - r_2^{(k)} - (\mu_1 - \mu_0))^2}{2(\sigma_1^2 + 5\sigma_0^2)} \right) \right)$$

where $p^{(k)}$ is the correct transmitted information bit received at time $k$. 

As the conventional conversion method, the information bit $i_{\text{est}}^{(k)}$ and parity bit $p_{\text{est}}^{(k)}$ at time $k$ are converted to polar signals as follows:

$$i_{\text{est}}^{(k)} = r_1^{(k)} - r_2^{(k)}$$

$$p_{\text{est}}^{(k)} = 2r_3^{(k)} - r_1^{(k)} - r_2^{(k)}$$ (1) (2)

where $r_1^{(k)}, r_2^{(k)},$ and $r_3^{(k)}$ are the first, second, and third received chips in the HPOS frame, respectively. We assume that the noise variance of the ‘on’ pulse chip is $\sigma_1^2$ and the noise variance of the ‘off’ pulse chip is $\sigma_0^2$. Since the BPPM signal always has both ‘on’ and ‘off’ pulse, the noise variance of the converted polar information bit signal $i_{\text{est}}^{(k)}$, $\text{Var}_{i}$, is given by

$$\text{Var}_{i} = \sigma_1^2 + \sigma_0^2$$ (3)

The noise variance of the converted polar parity bit signal $p_{\text{est}}^{(k)}$, $\text{Var}_{p}$, is given by

$$\text{Var}_{p} = \begin{cases} 5\sigma_2^2 + \sigma_0^2 & (r_3^{(k)} = 'on') \\ 5\sigma_1^2 + 5\sigma_0^2 & (r_3^{(k)} = 'off') \end{cases}$$ (4)
Note that the likelihoods used in the decoder are calculated using different equations. This affects the convergence property of the turbo decoder and causes the system to have a degraded decoding performance (error floor) in the strong turbulence channel. To solve this problem, in this study, we use a comparator to convert the parity bit. Figure 3 shows the structure of the new signal converter. At time \( k \), the information bit \( i^{(k)}_{\text{ext}} \) and parity bit \( p^{(k)}_{\text{est}} \) are converted according to the following rule:

\[
i^{(k)}_{\text{ext}} = r^{(k)}_1 - r^{(k)}_2
\]
\[
p^{(k)}_{\text{est}} = \begin{cases} r^{(k)}_3 - r^{(k)}_1 & \text{if } |r^{(k)}_3 - r^{(k)}_1| > |r^{(k)}_3 - r^{(k)}_2| \\ r^{(k)}_3 - r^{(k)}_2 & \text{otherwise} \end{cases}
\]

Finally, the data is decoded using a turbo decoder by inputting the converted polar signal. Using this conversion scheme, the information bit \( i^{(k)}_{\text{ext}} \) and parity bit \( p^{(k)}_{\text{est}} \) have the same noise variance, \( \sigma_i^2 + \sigma_p^2 \), such that the LLR can be calculated using the same equation,

\[
L(r^{(k)}_{\text{est}}) = \ln \left( \frac{P(r^{(k)}_{\text{est}}|s^{(k)} = 1)}{P(r^{(k)}_{\text{est}}|s^{(k)} = 0)} \right) = \ln \left( \frac{1}{\sqrt{2\pi(\sigma_i^2 + \sigma_p^2)}} \exp \left( -\frac{(r^{(k)}_{\text{est}} - \mu_1 + \mu_2)^2}{2(\sigma_i^2 + \sigma_p^2)} \right) \right)
\]

where \( r^{(k)}_{\text{est}} \) is the converted bit input into the decoder \( i^{(k)}_{\text{ext}} \) or \( p^{(k)}_{\text{est}} \), \( s^{(k)} = 1 \) is the corresponding transmitted bit \( i^{(k)} \) or \( p^{(k)} \). Thus, the decoder performance is expected to be improved by the new signal converter.

3. Performance Analysis

The bit error rate performance of the proposed HPOS punctured turbo code system is evaluated through computer simulation in the FSO strong turbulence channel. Table 1 shows the system parameters[7][8]. The channel model is taken from [6].

Figure 4 depicts the BER of the proposed new HPOS punctured turbo code system (with the new signal converter) in the FSO strong turbulence channel. We compare the proposed system with the HPOS punctured turbo code system (without a signal converter), conventional OOK punctured turbo code system, and conventional BPPM punctured turbo code system. We can see that the HPOS punctured turbo code system shows an obvious degradation (error floor) compared with the BPPM punctured turbo code system in the strong turbulence channel. In contrast, the proposed HPOS punctured turbo code system with the new signal converter shows almost the same BER as the BPPM punctured turbo code system. Thus, the enhancement of the new signal converter is effective. Because of the opposite effects of the scintillation and background noise, the BER of the OOK punctured turbo code system has a minimum point; we have the reason for this in detail in [6]. We can see that the OOK system shows very poor BER performance under the influence of the scintillation and background noise.

We also compare the BER performance characteristics of the punctured turbo code system with those of the standard turbo code system. From Fig. 4, we can see that the BPPM
punctured turbo code system has the highest BER performance. The punctured turbo code systems all outperform the standard turbo code systems.

The transmission efficiencies of the turbo code system with different signaling schemes are summarized in Table 2.

Table 2: Transmission efficiencies of the turbo code system with different signaling schemes

| Signaling Scheme         | Transmission efficiency |
|--------------------------|-------------------------|
| HPOS punctured turbo code| 1/3 [bit/chip]          |
| HPOS standard turbo code | 1/4 [bit/chip]          |
| BPPM punctured turbo code| 1/4 [bit/chip]          |
| BPPM standard turbo code | 1/6 [bit/chip]          |
| OOK punctured turbo code  | 1/2 [bit/chip]          |
| OOK standard turbo code   | 1/3 [bit/chip]          |

Although the OOK punctured turbo code system has the highest transmission efficiency, its BER performance is very poor. In contrast, the proposed HPOS punctured turbo code system has the same BER performance as the BPPM punctured turbo code system. Its transmission efficiency is about 1.3 times higher than that of the BPPM punctured and conventional HPOS standard turbo code system.

4. Conclusions

We enhanced the punctured turbo code system with hybrid PPM-OOK signaling (HPOS) by adding a new signal converter for the FSO strong turbulence channel. The BER performance characteristics of the proposed system in the strong turbulence channel were evaluated by computer simulation. It was found that the proposed system with the new signal converter outperforms the conventional HPOS system. The proposed HPOS punctured turbo code system has the same BER performance as the BPPM punctured turbo code system, but its transmission efficiency is about 1.3 times higher.

Acknowledgment

This study was supported in part by a Grant-in-Aid for Scientific Research (C).

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