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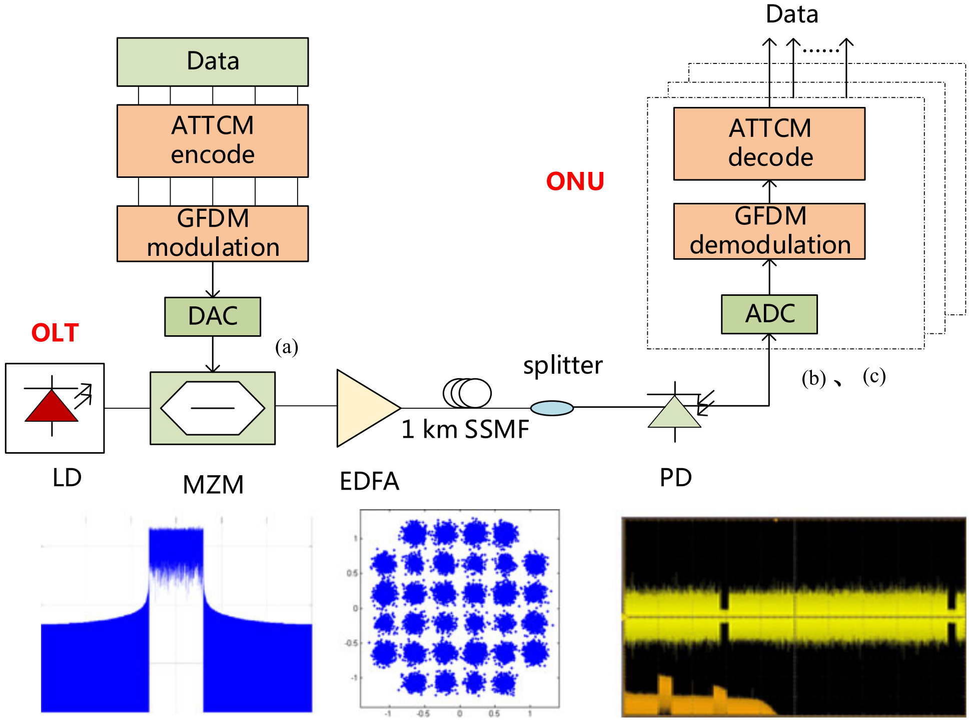

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A Novel Concatenated Coded Modulation Based on GFDM for Access Optical Networks

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Abstract: In this paper, we proposed a novel concatenated coded modulation composed of adaptive turbo code with trellis-coded modulation (ATTCM) that is based on generalized frequency division multiplex (GFDM) system. The proposed scheme has low complexity and provides high spectrum efficiency and significant coding gain. An experiment with 4 Gbit/s novel concatenated coded modulation GFDM system is successfully demonstrated with the proposed method. It is shown that the novel concatenated coding modulation signal (ATTCM 32QAM) provides 2.3 dB coding gain over that of TCM32QAM signal at bit error rate of 1e–3. This paper indicates a prospect solution for the future fifth generation optical access system.

Index Terms: Optical communications, optical access system, concatenated coded modulation, generalized frequency division multiplex.

1. Introduction

At present, the dramatic growth of services demands of the optical fiber communication increases rapidly. Optical access network is a strong candidate for connecting the backbone network with the end users, which provides high speed and high reliability for bandwidth hungry applications [1], [2].Currently commercial access systems mainly apply lean single carrier, However, the increasing demands of users are pushing forward to extend bandwidth resources, the multicarrier technology has been proposed in the past few years, fourth generation (4G) cellular systems based on OFDM technology have been optimized to provide high data rates and reliable coverage to mobile users [3]. Nevertheless, OFDM is susceptible to inter-carrier interference and synchronization errors. Additional overhead such as cyclic prefix (CP) is needed to alleviate the interference [3]. While generalized frequency division multiplexing (GFDM) based on multicarrier filter bank is a strong modulation technique for the fifth generation (5G) standard [4]–[7]. The main characteristic

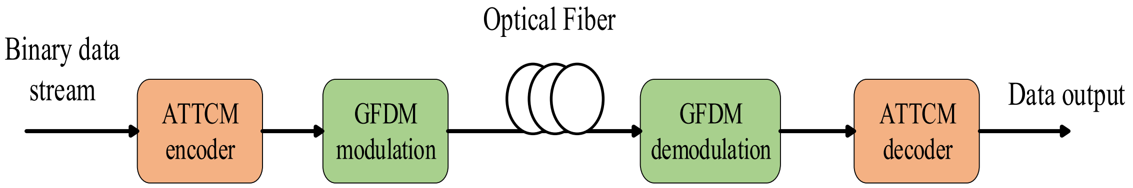

Fig. 1. Schematic diagram of concatenated coded GFDM signal.

of GFDM is low out of band emission, insensitive to frequency offset and phase noise. Cyclic prefix is added to each GFDM block instead of each GFDM symbol. The peak-to-average power ratio (PAPR) can be reduced by designing the flexible pulse shaping of individual subcarriers [6], [7].

In addition, GFDM technology with high spectral efficiency enables the access system to support a huge number of optical network units. They are more susceptible to transmission impairments from channel and components in optical access network, which leads to inter-symbol interference (ISI) and degrade the performance of the system [6]. Therefore, the forward error correction (FEC) codes can be employed to improve the BER performance by providing extra gain to the optical access network; it is a powerful technique to increase the system's margin [8]–[10]. Turbo code as one of the FEC code, has very good performance for error correction. It not only has superior performance in high noise environment, but also has strong anti-fading and anti-interference ability. Moreover, the ability to provide communication near the shannon limit in various harsh conditions has been demonstrated. Turbo code has been as deep space communication standard by the United States advisory committee of space data system which provides an important background for the research of Turbo code implementation [11]. However, Turbo code has the problem of error floor, this phenomenon will seriously affects the high reliability in the actual communication. While the technology of combing turbo code with trellis coded modulation (TCM) can improve spectrum efficiency and has robust error correction quality with simple construction where the error floor problem can be avoided, which makes it an attractive solution for optical access network in the near future [12]–[16].

In this paper, we propose and experimentally demonstrate a novel concatenated coded modulation (adaptive turbo trellis-coded modulation (ATTCM)) in 4 Gbit/s GFDM optical access system. The code weight decision algorithm (CWD) is used for adaptive code. The decoder of ATTCM used Log-MAP algorithm and reduced the complexity of the receiver. By combing these techniques, the proposed scheme provides significant performance improvement for access system.

2. Principle of System Model

The schematic diagram of concatenated coding modulation GFDM is illustrated in Fig. 1. It is composed of ATTCM module and GFDM modulation. The principle of each part is described in the following section.

2.1 ATTCM Encoder and Decoder

In the section of ATTCM encoding, we firstly use code weight decision algorithm (CWD) before injecting the input data into the encoder as shown in Fig. 2. The code weight decision algorithm is used for improving the code weight of the input data bits. Let the input data pass the encoder directly if the weight of the code is larger than a certain value of its length ($W > L/n$, W presents the code weight, L is the length of the input data, n is positive integer), otherwise, all bits of the input data will be inverted and the inverted bits will be marked. The encoder implementation sends three sub-blocks of bits. The first sub-block is a complete set after fulfilling the condition $W > L/n$. The second and the third sub-blocks are encoded respectively where the third part is sent to an interleaver. These two redundant but different sub-blocks are encoded by the same RSC (Recursive Systematic Convolution) encoder. Since the encoder is systematic, the output of the upper encoder

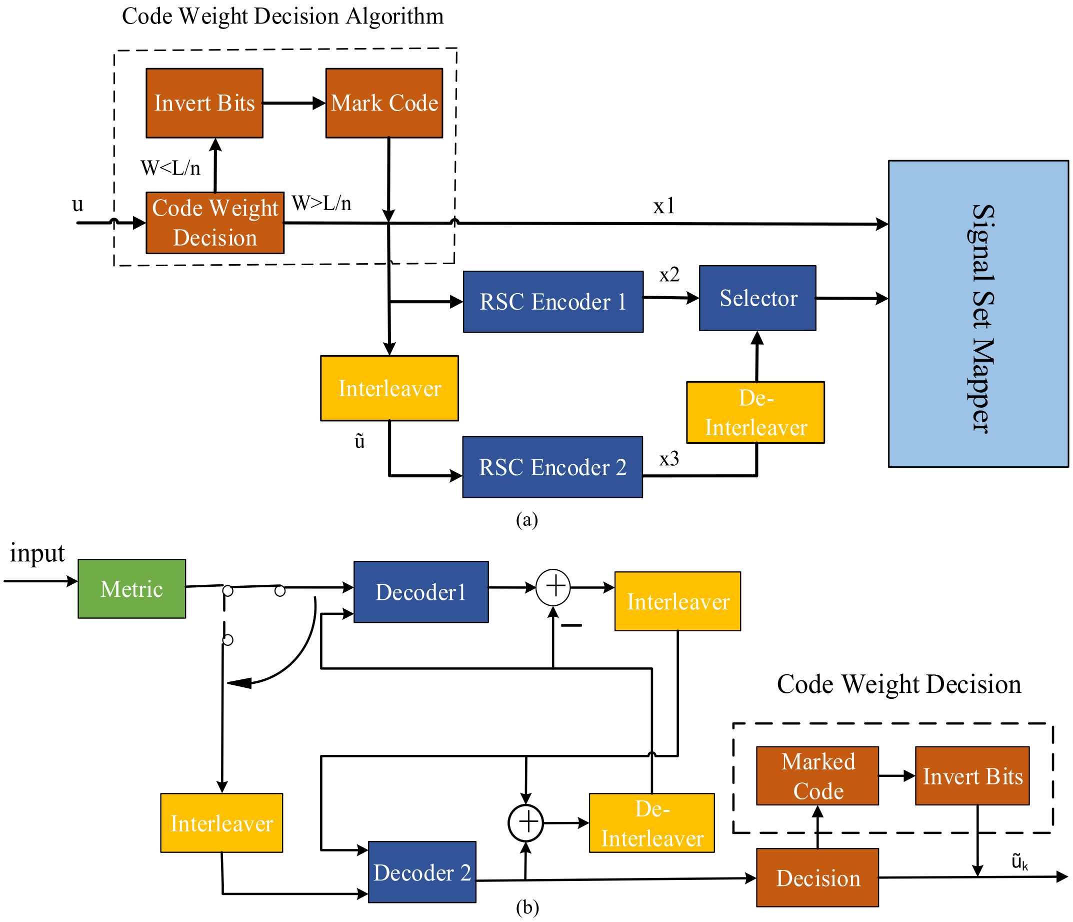

Fig. 2. The scheme of ATTCM with CWD algorithm (a) ATTCM encoder (b) ATTCM decoder.

and the output of the de-interleaver are different only in the parity bits, while the remaining bits are identical. A selector is then used to alternatively switch between the parity bits from the upper and lower encoder. Finally, two combined sub-blocks are then mapped to M-ary symbol.

Fig. 2(b) shows the ATTCM decoding section. At the beginning, the symbol log-likelihood ratios(LLRs) are calculated and the corresponding soft metric is provided to the decoder. For the first decoding stage, the soft metrics corresponding to the odd symbols (t is odd) are fed to the decoder1, the symbol-by-symbol maximum a-posteriori (MAP) algorithm is employed, and the resulting information forms the a-priori information which will be fed to the next stage. For the second decoding stage, the soft metrics of the even symbols together with the a-priori information produced by the first decoding stage is interleaved and fed to the decoder2. At the output of this decoder, the a-priori information is calculated as in the first decoding stage before being de-interleaved and forwarded to the decoder1. Then the iteration process is repeated until a prescribed maximum number of iterations is researched. Finally, the a-posteriori information at the output of the decoder2 is sent to a decision unit, resulting in an estimation of the transmitted systematic information bits [17]. The marked code is inverted so that the code can be restored as it is, the unmarked codes output without any operation.

According to the principle of MDL (Minimum description length), the main task of the decoder is to calculate the transmission probability of different symbols under the received sampling condition. For uk (k is time index) bit, the posterior probability is expressed as [18]:

$$P_r\{\mu_k = i/r\}, i = 0, 1 \tag{1}$$

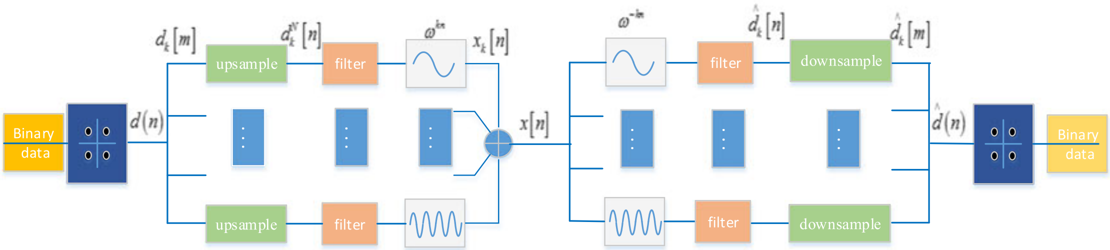

Fig. 3. The schematic diagram of GFDM signal.

The soft decision output of the information symbol is:

$$A\left(u_k\right)=\ln\left\{\frac{\Pr\left\{u_k=1/R\right\}}{\Pr\left\{u_k=0/R\right\}}\right\} \tag{2}$$

To facilitate the calculation of soft decision output, three probabilities are defined:

$$\begin{aligned}
&\alpha_k^i(m),\,\beta_k(m),\,\gamma_k^i(R_k,m',m)i=0,1\\
&\alpha_k^i(m)=\frac{\Pr\left\{u_k=i,s_k=m,R_1^k\right\}}{\Pr\left\{R_1^k\right\}}=\Pr\left\{u_k=i,s_k=m/R_1^k\right\}\\
&\beta_k(m)=\frac{\Pr\left\{R_{k+1}^N/s_k=m\right\}}{\Pr\left\{R_{k+1}^N/R_1^k\right\}}\\
&\gamma_K^i\left(R_K,m',m\right)=\Pr\left\{u_K=i,R_K,s_K=m/s_{K-1}=m'\right\}
\end{aligned} \tag{3}$$

For M-ary symbol, the information bits and error correcting bits have been synthesized into a M-ary symbol to be modulated and transmitted. At the receiver after demodulation, only the soft decision information of the symbol can be provided, and the information bits can not be completely independent. Therefore, in the MAP decoding, the system information and the error correction information are considered together, that is to say, they can not be separated from each other in the decoding. Then, the final soft decision output can only be divided into two parts:

$$\Lambda_k\left(u_k\right)=L_{2k}+\ln\frac{\sum_m\sum_{m'}\gamma_k^i\left(y_{1k},m',m\right)\alpha_{k-1}\left(m'\right)\beta_k\left(m\right)}{\sum_m\sum_{m'}\gamma_k^0\left(y_{1k},m',m\right)\alpha_{k-1}\left(m'\right)\beta_k\left(m\right)} \tag{4}$$

In (4), the first item is the internal information, which is directly related to the external information transmitted by another decoding unit, and the second item is considered as external information, which will be transmitted to another decoding unit.

2.3 GFDM Principle

Fig. 3 illustrates the principle of the transmitter and receiver of GFDM. Binary data is modulated into QAM format and divided into KM complex symbols. Each symbol $d_k[m]$ is spread across k subcarriers and m time slots for transmission, where $k=0\ldots$K-1, $m=0\ldots$ M-1 are given. The complex data symbols $d_k[m]$ are up-sampled by a factor N, resulting in:

$$d_k^N\left[n\right]=\sum_{m=0}^{M-1}d_k\left[m\right]\delta\left[n-mN\right],\,n=0,\ldots,NM-1 \tag{5}$$

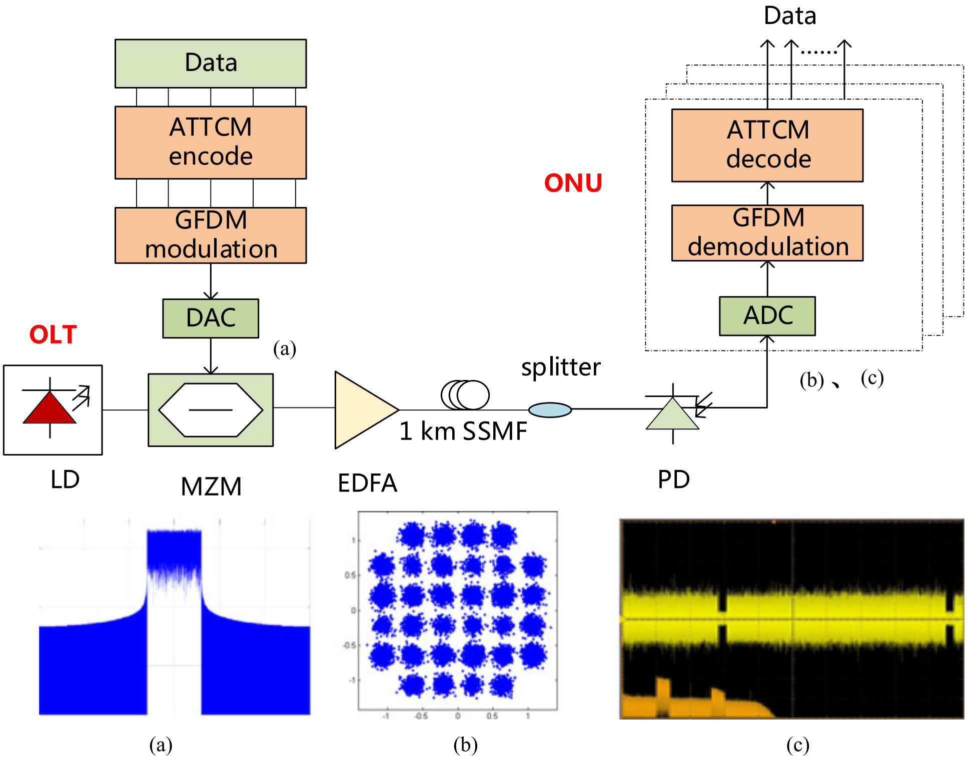

Fig. 4. Experiment setup for optical access network.

Where $\delta[\cdot]$ is the Dirac function, N is the up-sampling factor. Therefore, after up-sampled by N, digital pulse shaping and up-conversion, the transmitted GFDM signal can be expressed as [19]:

$$x[n] = \sum_{m=0}^{M-1}\sum_{k=0}^{K-1} d_k^N[n] g_T[n],\ g_T[n] = g[(n-mN)|MN]e^{j2\pi\frac{kn}{N}} \tag{6}$$

Each subcarrier signal $g_T[n]$ is a shifted version of a circular filter g[n], by mN and k/N in the time and frequency domain, respectively.

At the receiver, GFDM demodulation performed in frequency domain which is opposite to the modulation module, shown in Fig. 3. Suppose y[n] are the received signal, thus the resulting signal at $n = m$N is given by the expression [19].

$$\tilde{d}_k[m] = (y[n]e^{-j2\pi\frac{kn}{N}}) \otimes g_{Rx}[n]|_{n=mN} \tag{7}$$

Where $\otimes g_{Rx}[n]$ denotes circular convolution with matched filter relative to n which is essential for tail biting at the receiver. In frequency domain, the formula (7) will be calculate by FFT and IFFT conversion flexibly. After digital filtering, the signal is down-sampled turning sample index into QAM symbol [20].

3. Experimental Setup and Results

The experiment setup is presented in Fig. 4. At the optical line terminal (OLT), the central wavelength at 1550 nm is generated by an external cavity laser (ECL) with the line-width of 100 kHz and the output power of 14.5 dBm. Intensity modulation at the transmitter of the OLT is realized by a 30 GHz Mach-Zehnder modulator (MZM) biased at 6.1 V. The concatenated coded modulation GFDM signal is generated by the Arbitrary Waveform Generator (AWG) and then fed into the RF port of MZM. The spectrum of GFDM electrical signal is shown in Fig. 4(a). Successively, the optical signal is

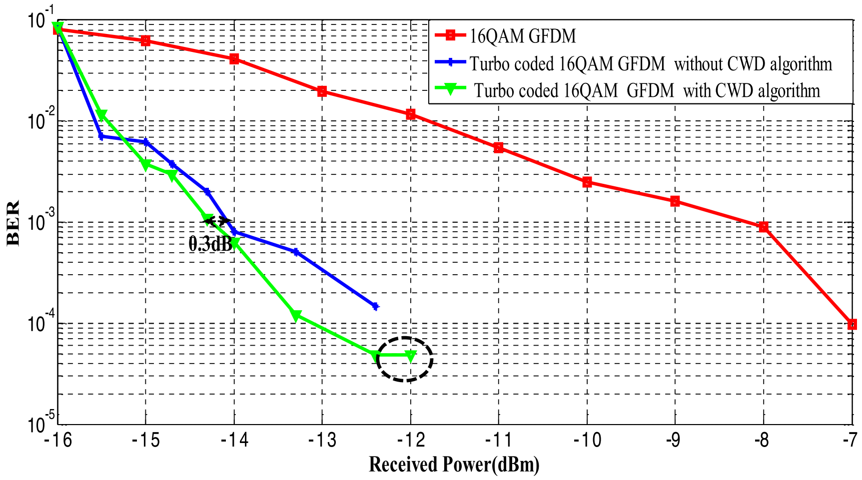

Fig. 5. BER performance for adaptive turbo code with 16QAM GFDM.

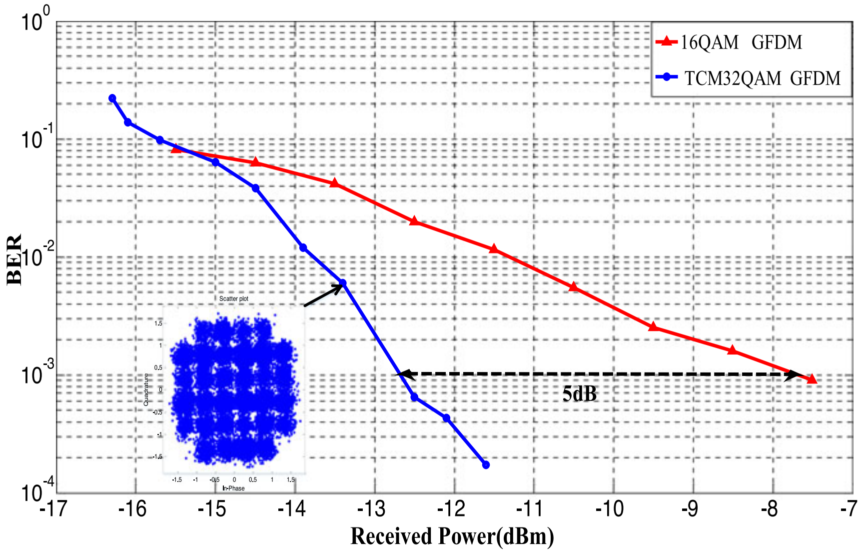

Fig. 6. BER performance for TCM32QAM GFDM with 16QAM GFDM.

further amplified by a commercial Er-doped fiber amplifier (EDFA) before it is launched into 1 km standard signal mode fiber (SSMF).

At the receiver side, the optical signal is detected by the photo detector with 15 GHz bandwidth, and the collected signal from oscilloscope (DPO72004C) is shown in Fig. 4(b) and (c). The soft decision algorithm and MMSE algorithm is used to recover the original data in offline.

In the experiment, in order to specify the coding gain of the code weight decision, we compare the performance of turbo code with and without CWD algorithm in 16QAM-GFDM system. From Fig. 5, we observe that the coding gain of 0.3 dB (BER = 1e-3) is obtained for adaptive turbo code using CWD algorithm than traditional turbo code without using CWD algorithm in 16QAM-GFDM system. The performance improvement of adaptive turbo code is recorded as 6 dB compared with uncoded 16QAM at BER = 1e-3. However, From the Fig. 5 we can see with the increasing of the received power, the BER curve of turbo code 16QAM declines slowly, especially at the point of BER = 5e-5 (marked by dashed ellipse) the error floor appears.

In the experiment, we also compared the performance of trellis coded modulation with 16QAM signal, the results in Fig. 6 show that trellis code 32 QAM can provide 5 dB code gain at BER =

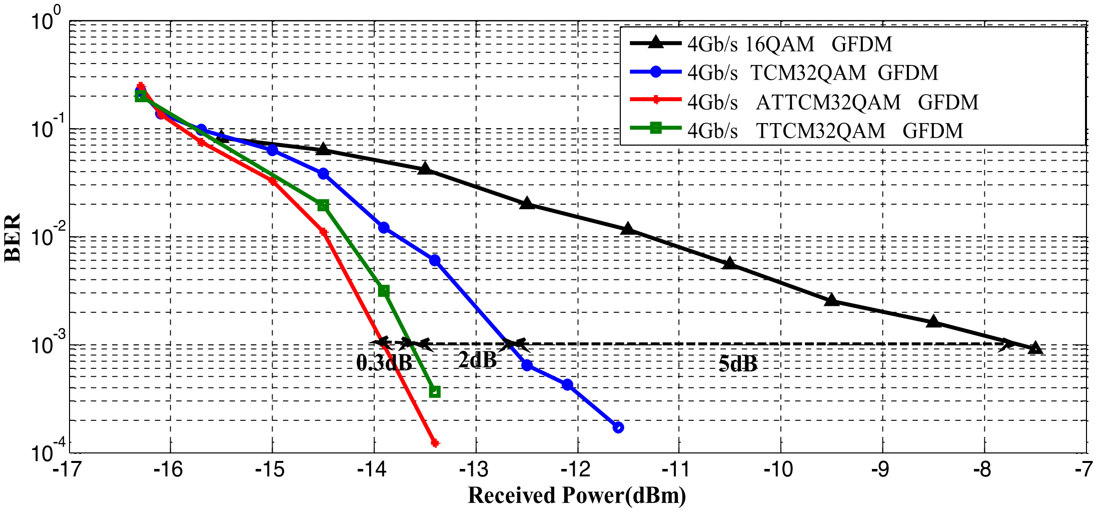

Fig. 7. BER performance for novel concatenated coded modulation GFDM.

1e-3 than 16 QAM signal. The sensitivity of TCM32QAM is improved by using convolution code, which proves that the trellis code has powerful error correcting ability.

Based on the results in Figs. 5 and 6, we propose the scheme of novel concatenated coded modulation (ATTCM32QAM), which used Log-MAP algorithm for decoding. From Fig. 7, we observe that the ATTCM32QAM provides 7.3 dB (BER = 1e-3) coding gain than uncoded 16 QAM signal, and the improvement of performance gain for concatenated coding modulation is 2.3 dB (BER = 1e-3) compared with TCM32QAM. The error floor problem was avoided. The results indicates that the designed novel concatenated coded modulation achieved high spectrum efficiency and significant coding gain, the complexity is also reduced by integrating turbo code with trellis code modulation together.

4. Conclusion

In this paper, we have proposed a novel concatenated coded modulation based on GFDM for optical access system. The performance of the scheme combining the adaptive turbo code with trellis coded modulation (ATTCM) was successfully demonstrated in the experiment. The experimental results showed the concatenated coded modulation (ATTCM32QAM) can solve the error floor problem, it provides 7.3 dB(BER = 1e-3) coding gain than uncoded 16QAM signal and achieves 2.3 dB(BER = 1e-3) performance improvement than that of trellis coded modulation 32QAM (TCM32QAM) after 1 km transmission. The results indicates that the designed novel concatenated coded modulation achieved high spectrum efficiency and significant coding gain, the complexity is also reduced by integrating turbo code with trellis code modulation together. This work shows that the proposed method will be a promising solution for future 5G access system.

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