Dynamic and Flexible OFDM System Based on Joint Coded Modulation

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ABSTRACT An orthogonal frequency division multiplexing (OFDM) interconnected transmission system employing joint modulation of variable-order constellation compression and probabilistic shaping is proposed in this paper. In the proposed system, constant composition distribution matcher (CCDM) is utilized to implement probabilistic shaping, and fixed symbol-level label method is adopted to achieve the constellation compression. The coded modulation schemes can be adjusted dynamically according to the diversified traffic requirement of the users, in a bid to enhance the network utilization and provide effective end-to-end services. So far, to the best of our knowledge, it is the first time that probabilistic shaping and constellation compression modulation have been simultaneously applied to an interconnection system to achieve real-time self-tuning of transmission performances. Moreover, experimental verifications are successfully carried out by setting up a 25 km intensity-modulation/direct-detection interconnection transmission system. The results show lower bit error rate with flexible coding capability, indicating a high-potential transmission solution for the future optical communication.

INDEX TERMS Orthogonal frequency division multiplexing, constant composition distribution matching, probabilistic shaping, constellation compression modulation.

I. INTRODUCTION

The exponential growth of global user data traffic has given tremendous momentum to the new network demands, especially for interconnected transmissions between clusters of data centers. Therefore, it is of great urgency to lay out a reliable transmission system architecture that features high-speed, large-capacity, low-latency, and low-error. The intensity-modulation/direct-detection (IM/DD) passive optical network system is an effective and mature solution suitable for data center interconnection, which is simple and easy to implement [1], [2]. However, in addition to the new requirements for transmission rate and capacity, the data center interconnection transmission systems have higher requirements on the flexibility of receiving end. Multi-rate transmission technology cannot only satisfy the different needs of the user terminals, but also be more suitable for the development and application of future 5G technologies. At present, probabilistic shaping (PS) techniques are able to achieve different information entropy by changing the probability distribution of the transmitted signal. When the Baud rate is constant, the probabilistic shaping technology can bring about flexible multi-rate at the receiver owing to the fact that transmission rate varies with the information entropy. The Alcatel-Lucent Bell Labs experimentally proved that the transmission system employing probabilistic shaping has unprecedented flexibility in terms of transmission rate without increasing the system cost and implementation complexity [3].

Probabilistic shaping in this paper refers specifically to the widely used constant composition distribution matching (CCDM) shaping method, which was elaborated by Patrick Schulte in 2016 [4]. It features higher compatibility,
lower computational complexity, lower bit error rate and lower transmitted power [3], [4]–[7]. For practical application, a transmission system with adjustable data rate based on probabilistic shaping was experimentally demonstrated [3] and 1 Tb/s 4-carriers super-channel transmission, which can achieve either higher spectral efficiency at shortest distance or highest bit rate at the longest distance, was performed in German nationwide backbone network [5]. Besides, this technique is suitable for any high order coded modulation. In particular, the ZTE (TX) Inc. in USA experimentally verified a net data rate of 112 Gb/s/λ truncated PS-16384-quadrature amplitude modulation (QAM) DFT-S orthogonal frequency division multiplexing (OFDM) over 2.4 km single mode fiber (SMF) with a 10-GHz-class direct-detection transceiver, while uniform 1024 QAM could only achieve 94 Gb/s/λ [6]. The impact of bandwidth narrowing due to cascaded wavelength selective switches on the performance of PS-64-QAM constellation was assessed using the generalized mutual information [7]. Although the CCDM probabilistic shaping method can improve the bit error rate performance at the cost of the transmission rate, it is not an ideal implementation method of low-order coded modulation. Variable-order constellation compression modulation (CCM) is a special probabilistic shaping scheme that employs symbol-level labeling and constellation shaping modulation [8], [9]. An experiment demonstrating 33.3 Gb/s 16-to-9 probabilistic shaped mapping carrier-less amplitude and phase (CAP) signals transmission over 25 km SMF in passive optical network was successfully carried out to validate the performance [9]. Meanwhile, we also presented a probabilistic shaped star-CAP-16/32 modulation based on constellation design with honeycomb-like decision regions in [10], which was able to achieve better improvement with regards to constellation figure of merit and bit error rate (BER) performance. It is a simple and easy method to implement low-order modulation, low complexity and low cost. However, it is neither compatible nor easy to achieve probabilistic shaping for high-order signals such as 128 QAM. At present, the variable-order constellation compression modulation technology can only easily realize probabilistic shaping of 64 QAM and lower-order signals.

Orthogonal frequency division multiplexing technology realizes high-speed parallel transmission by allocating data to different orthogonal sub-carriers, which has the advantages of resisting frequency selective fading and narrowband interference [11]–[14]. This technology utilizes inverse fast Fourier transform (IFFT) and fast Fourier transform (FFT) to gain multi-carrier transmission. It is one of the most widely used multi-carrier multiplexing techniques. A hardware architecture of a high-speed OFDM receiver was proposed in [13], which successfully transmitted data over 10 km SMF with a spectral efficiency of 8.38 bit/s/Hz. In addition, the Orange Labs. in France extensively studied the OFDM technique for fiber-based optical transmission in the context of access network [14].

In this paper, we propose to our best knowledge a joint probabilistic shaping modulation based on variable-order CCM and CCDM probabilistic shaping in the OFDM interconnected transmission system. The system can flexibly apply variable-order CCM and CCDM probabilistic shaping method according to the real-time demands of different users. In addition, our proposed system can realize dynamic and flexible data transmission through fine-tuning. The variable-order CCM enables improved performance by changing the compression factor. The CCDM probabilistic shaping enhances the flexibility of the transmission system by setting different probability distribution parameters to allow multiple transmission rates in the system. To better verify the feasibility and transmission performance of our proposed system, we constructed an IM/DD OFDM interconnected transmission system to measure and analyze the transmission superiority.

II. PRINCIPLE AND ARCHITECTURE DESIGN

Figure 1 shows the flow diagram of a dynamically flexible and flexible OFDM interconnected transmission system applying joint coded modulation based on variable-order CCM and CCDM probabilistic shaping. First of all, select an encoder according to user’s requirements, that is, variable-order constellation compression encoder or the CCDM probabilistic shaping encoder. The binary data after serial-to-parallel (S/P) conversion is sent to the selected modulator. The principles for selecting an encoder are: if users need to transmit a large amount of data in the point-to-point transmission system, they would prefer variable-order constellation compression modulation. Give an initial value for the compression factor (f), that is, $f = f_0$. However, if the system needs to fulfill the diverse and flexible needs of various scattered and temporary users, the CCDM probabilistic shaping is given full play. Specifically, the initial value of the probability distribution parameter $v$ is set as $v = v_0$. The OFDM is then performed on the output data to generate the sub-carrier signals for optical fiber transmission. At the receiver, the received signal is sequentially handled by OFDM demodulation, decoder demodulation, and parallel-to-serial (P/S) conversion in order to get binary sequences. Finally, the BER calculation is carried out. If the measured BER is too large, it indicates that the quality of the transmission signal is poor. In other words, it implies that the probability distribution parameter or compression factor should be increased and fed back to the transmitter to modulate and transmit the subsequent data, thereby improving system transmission performance. However, if the system has a very low BER, the probability distribution parameter or compression factor should be appropriately reduced to get transmission rate higher. Hence, the transmission system can achieve self-adjustability for better transmission performance.

The CCDM is one of the mainstream methods for probabilistic shaping. As shown in Fig. 2(a), probabilistic shaping can be achieved by attaching a distribution matcher at...
the transmitter to actualize outer encoding. The set of the constellation symbols is denoted as \( X = \{x_1, x_2, \ldots, x_m\} \).

The probability values of each symbol \( x_i \in X \) after coded modulation obey the Maxwell-Boltzmann distribution [4]:

\[
P_X(x_i) = \frac{e^{-\nu|x_i|^2}}{\sum_{j=1}^{m} e^{-\nu|x_j|^2}},
\]

where \( \nu \) is probability distribution parameter. Moreover, \( \nu \) denotes the degree of probabilistic shaping and its value ranges from 0 to 1. The larger probability distribution parameter, the greater the degree of probabilistic shaping.

Therefore, we can acquire different probability distribution signals by setting different probability distribution parameters. In the process of CCDM probabilistic shaping coding, firstly, an appropriate initial value of probability distribution parameter is set to the distribution matcher according to ONU’s demands. Then QAM modulator and multi-carrier modulator are adopted to encode the output data of the distribution matcher, and finally the waveform data can be get for transmission. At the receiver, the received data should be sequentially demodulated by the multi-carrier demodulator and QAM demodulator. Then the QAM demodulated data is sent to the inverse distribution matcher to recover the original binary data. Generally speaking, in actual optical transmitter, forward error correction (FEC) coding should be used along with CCDM, otherwise the resulting BER calculated after inverse distribution matching will be very high [10]. Due to the powerful error-correcting capability of FEC coding when combined with CCDM, the BER can be reduced to \( 10^{-9} \) or even zero. In this case, the transmitted sequence length should be long enough for the BER performance comparison, and the results may not be obvious as the BER is too small to be clearly compared. Therefore, FEC coding and decoding are not adopted. The modulation process of variable-order constellation compression modulation is illustrated in Fig. 2(c). The first step is to design constellation diagrams of different orders of the signals. Secondly, the original data after serial-to-parallel conversion is labeled and redistributed, respectively. Finally, the redistributed data is mapped onto the well-designed constellation diagram. Hence, the appropriate constellation design combined with symbol-level labeling method can be a favorable approach to get the system performance better. Figure 2(d) gives the demodulation of CCM, including constellation de-mapping and labels removal. It is worth mentioning that the compression factor can be adjusted according to the BER of received binary data, and the modulation order of the constellation can be variable, so that the CCM is more in accord with channel transmission condition.

Figure 3 shows the histogram of the probability distribution at different \( \nu \) from 0.1 to 0.4. As the value of \( \nu \) increases, the probability values of the outer constellation points decrease and that of the inner constellation points become larger. Besides, the information entropy formula is:

\[
H(x) = - \sum_{i=1}^{m} (P_X(x_i) \log_2 P_X(x_i)),
\]

where the unit of information entropy is bits/symbol. With the increasing probability distribution parameter, the information entropy tends to decrease gradually. When the Baud rate is set as 6.25 Gbaud, the trend of transmission rates will be in tune with information entropy, as shown in TABLE 1.

Variable-order constellation compression modulation [8] is a special probabilistic shaping that utilizes a fixed symbol-level label to achieve non-uniform probability distribution. Without distribution matchers, low-order signal modulation method is easy to implement. It greatly helps to improve the BER performance and reduce transmitted
power. The constellation compression modulation can compress high-order signals into low-order signals. In this paper, the first-order CCM is performed on uniformly distributed 32 QAM signals, thereby obtaining 16 QAM non-uniform signals. The BER is calculated at the end of receiver. If the measured BER is too high, the secondary compression is carried out to improve transmission performance, and 9 QAM signals will be obtained. We use the “00”, “01”, and “10” labels to compress and map the points in the outer circle of the constellation to the inner circle, thereby reducing the number of constellation points in the outer circle and increasing the probability values of the constellation points in the inner circle. For instance, we map the constellation “10101” to the constellation point “00101” and mark it with the “10” label, while the original “00101” in the constellation is labeled with “00”. It should be emphasized that the main effect of the label is to identify the constellation information and recover data at the receiver. The constellation mapping rules of conventional uniformly distributed 32 QAM signal are displayed in Fig. 4(a). The first-order and second-order CCM are adopted separately to modulate the conventional 32 QAM signals. Then, we can get the 32-16 CCM signal and 32-16-9 CCM signal in respectively. What is more, the symbol-level label modulation process for 32-16 CCM and 32-16-9 CCM signals has been described in detail in [8], [9]. In the Figure 4, (b) and (c) are the constellation mapping rules for 32-16 CCM signals and 32-16-9 CCM signals, respectively. The histograms of the probability distributions of 32 QAM, 32-16 CCM signals and 32-16-9 CCM signals can be seen in Fig. 4(d-f). The probability distribution of the conventional 32 QAM signal is uniformly distributed, while the signal distribution after CCM is non-uniform. Therefore, different probability distributions can be obtained in accordance to the different constellation compression designs. The probability of constellation points near the center of the constellation is higher than that of the points in the outer circle of the constellation.

The principle diagram of the OFDM multi-carrier system is shown in Fig. 5. The OFDM system can achieve orthogonal multiplexing of multi-carriers to enlarge the transmission capacity. At the transmitter, frequency mapping is applied first, and then IFFT is performed on the input signals to form multiple orthogonal subcarriers. Finally, P/S conversion and cyclic prefix (CP) insertion are employed to modulate the data of subcarriers. And then we can get the final transmitted signals. At the receiver, the OFDM demodulator is used to demodulate the received signal. The demodulation processes include CP remover, S/P conversion, FFT, channel equalization, and P/S conversion, as shown in Fig. 5(b).

### TABLE 1. When Baud rate is 6.25 GBaud, the corresponding information entropy and transmission rate under different $V$.

| $V$ | Information Entropy $H(x)$ (bits/symbol) | Bit Rate (Gbps) |
|-----|--------------------------------------|-----------------|
| 0   | 4.0                                  | 25              |
| 0.1 | 3.7864                               | 23.665          |
| 0.2 | 3.3061                               | 20.663          |
| 0.3 | 2.8265                               | 17.666          |
| 0.4 | 2.4769                               | 15.481          |
III. EXPERIMENTAL SETUP

Figure 6 illustrates the experimental setup of the OFDM interconnected transmission system. The constellation compression modulation and CCDM probabilistic shaping can be flexibly used in our experiments. The MATLAB software is taken to implement offline DSP. At the transmitter, its specific procedures consist of S/P conversion, coded modulation, OFDM modulation, illustrated in Fig. 6(b). The length of raw input bit stream is $2^{15} - 1$. The coded modulation is either CCDM probabilistic shaping or variable-order CCM. What is more, TABLE 2 gives the relevant parameters of the OFDM modulation and demodulation. The output data of DSP was sent into the Mach-Zehnder (MZM) optical modulator through an arbitrary waveform generator (AWG, Tektronix AWG70002A) with a sampling rate of 25 GS/s, thereby loading the information onto the optical carriers. In addition, continuous wave-light (CW) generated by an external cavity laser (ECL) at 1550 nm with an output power of 10 dBm offers the optical input of the MZM for electrical/optical conversion.

![FIGURE 6. (a) Experimental setup, and offline DSP at the (b) transmitter and (c) receiver (AWG: arbitrary waveform generator; ECL: external cavity laser; MZM: Mach-Zehnder modulator; SMF: single-mode fiber; VOA: variable optical attenuator; PD: photo-diode, MSO: mixed signal oscilloscope).](image)

| Table 2: The parameters of OFDM modulation. |
|---------------------------------------------|
| Parameter       | Value  |
| OFDM frames     | 300    |
| FFT size        | 512    |
| Subcarriers     | 256    |
| CP ratio        | 16%    |
| Modulation      | QAM/CCM|

![FIGURE 7. The BER vs. received optical power under different probability distribution parameters $v$.](image)

At the receiver, the optical signals after 25 km SMF is converted into electronic signals by a 40 GHz photodiode (PD). In our experiment, the dispersion and attenuation of the used SMF is $16 \text{ ps/}(\text{nm} \times \text{km})$ and 0.2 dB/km, respectively. The variable optical attenuator (VOA) is used to alter the received optical power to acquire different BER. A mixed signal oscilloscope (MSO, Tektronix MSO73304DX) with a sampling rate of 100 GS/s was utilized to collect data for DSP at the receiver. The DSP demodulation process at the receiver is shown in the Fig. 6(c). The received signals are sequentially subjected to OFDM demodulation, coded demodulation, and P/S conversion in order to recover binary data.

IV. EXPERIMENTAL RESULTS AND ANALYSIS

The OFDM interconnected transmission system was utilized for experimental transmission under different CCDM probabilistic shaping signals. The BER curves are obtained with different received optical powers in Fig. 7. It is well worth noticing that the signal is uniformly distributed when the probability distribution parameter is zero, and other BER curves with non-zero values represent CCDM probabilistic shaped signals. Here, we only give the case where $v$ is 0-0.3 and increments by 0.1. As can be seen from TABLE 1, probability distribution parameters are consistent with transmission rates. The larger probability distribution parameter, the greater the degree of shaping, and the better the shaping gain. But as the value of $v$ increases, the cost of the transmission rate increases. Thus, appropriate probabilistic shaping is
performed on the signal to ensure the error-free transmission. The BER gradually decreases with the increasing received optical power. It can be shown that the BER of OFDM interconnected transmission systems at the same received optical power decreases when the probability distribution parameters increases. At the BER of $3.8 \times 10^{-3}$, the probabilistic shaped signal with $v$ of 0.1, 0.2 and 0.3 outperform the conventional uniform signal by 0.2, 0.3 and 0.5 dB in receiver sensitivity, respectively. Therefore, our proposed system not only has rate flexibility, but also the transmission performances can be enhanced by adjusting probability distribution parameters. Besides, the constellations of CCDM probabilistic shaping modulated signals with different probability distribution parameters are shown in Fig. 8 when the received optical power is $-16$ dBm. The constellation diagrams clearly indicate that the larger the probability distribution parameter, the smaller the number of constellation points in the outer circle of the constellation, and the more the probability distribution of constellation points is concentrated in the center of the constellation.

For the OFDM interconnected transmission system based on CCDM probabilistic shaping, we perform experimental transmission verification on probabilistic shaped signals with single and double probability distribution parameters. The experimental results are exhibited in Fig. 9. Compared with double-parameter uniformly distributed signal, the double-parameter CCDM probabilistic shaped signal has more superior BER performance. It can be observed that CCDM signals and conventional uniform signal under double-parameter has got receiver sensitivity of $-15.6$ dBm and $-15.3$ dBm at the BER of $3.8 \times 10^{-3}$ respectively. However, it should be pointed out that the BER of the double probability distribution parameter signal is little higher than that of single parameter signals. The flexibility of transmission system can be effectively ameliorated by setting double probability distribution parameters. Thus, multiple user’s information can be simultaneously transmitted by assigning different probability distribution parameters to different users, which can also save the cost of the transmission system.

Furthermore, we make fully use of the OFDM interconnected transmission system to transmit variable-order constellation compressed signals. Figure 10 illustrates the BER versus received optical power for different compression factors, where $f=0, 1, 2$ represent conventional 32 QAM signals, first- and second-order constellation compressed signals, respectively. At the BER of $3.8 \times 10^{-3}$, the receiver sensitivity of first-order CCM is $-15.9$ dBm, which upgrades by 0.2 dB compared with $-15.7$ dBm of the conventional one. The decreasing number of rings with different amplitudes in
CCM is a key factor for this phenomenon, which enhances the performance of CCM in present of average power reduction. As a result, the BER performance of the second-order constellation compressed signals are obviously better than that of the first-order signals. The receiver sensitivity of second-order CCM is also 0.2 dB better than first-order one at the BER of \(3.8 \times 10^{-3}\). Figure 11 also explains the constellation diagrams of signals with or without CCM when the received optical power is \(-16\) dBm. As can be seen from the constellation diagrams, the clearness of the constellation diagrams indicates the better BER performance can be acquired by employing variable-order constellation compression modulation.

Finally, we analyzed the OFDM interconnected transmission system with variable-order constellation compression modulation and CCDM probabilistic shaping modulation. Figure 12 illustrates the measured BER as a function of received optical power in different coding and modulation, where the sub-figure (b) is a partial enlarged view of the sub-figure (a). As can be seen from the two BER curves, when the received optical power is less than \(-17.35\) dBm, the BER performances of CCDM probabilistic shaping modulation are superior to the corresponding order in constellation compression modulation, and this trend is more favorable as the two corresponding curves (\(v=0.1, f=1\)) deviate further from each other when the received optical power decreases. The BER performances of variable-order CCM are better than that of probabilistic shaping when the received optical power is greater than \(-16.35\) dBm. Moreover, we find that the received optical power of the variable-order CCM signals are lower than that of CCDM probabilistic shaping signals at the BER of \(3.8 \times 10^{-3}\).

V. CONCLUSION

In this paper, we have proposed a dynamical and flexible OFDM interconnected transmission system applying variable-order constellation compression modulation and CCDM probabilistic shaping. So as to satisfy the flexible and diverse needs of multiple users. In addition, we also used OFDM technique for orthogonal modulation to increase the capacity of the transmission system. The feasibility and superiority of the OFDM interconnected transmission system have been verified by an IM/DD experimental platform. Therefore, while meeting the diversified needs of different users in the network, we are also able to adjust the probability distribution parameters and compression factors to achieve flexible data transmission.

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