Filtering Tolerant Digital Subcarrier Multiplexing System with Flexible Bit and Power Loading

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Abstract: We propose to use adaptive bit and power loading in digital subcarrier-multiplexing (SCM) systems based on time-domain hybrid QAM to increase optical filtering tolerance. 17.5% capacity improvement is achieved in experimental demonstrations.

OCIS codes: (060.1660) Coherent communications; (060.2330) Fiber optics communications

1. Introduction

The ever-increasing capacity demand has led to intensive researches on high-capacity and flexible optical communication systems [1,2]. It is well known that fiber nonlinearities impose a limit on fiber link capacity. In order to increase the nonlinear tolerance, digital subcarrier-multiplexing (SCM) systems have been extensively investigated and sizable improvement has been demonstrated [2-6]. However, compared with single carrier systems, SCM systems are less tolerant to the narrow optical filtering effect caused by cascaded reconfigurable optical add-drop multiplexers (ROADMs) in mesh optical networks [7,8]. In particular, edge subcarriers experience severe filtering penalties in SCM systems, which limit the overall performance. For fixed data rate systems, frequency-domain hybrid QAM (FDHQ) is proposed to increase the filtering tolerance in [4], which demonstrates that the system using QPSK on edge subcarriers and 16QAM on central subcarriers achieves a much higher filtering tolerance than the system using 8QAM on all subcarriers. Furthermore, it is demonstrated that encoding 4D formats across subcarriers or pairwise coding can also increase the filtering tolerance [5,6]. On the other hand, flexible bit rate is essential for future elastic optical networks [2]. Time-domain hybrid QAM (TDHQ) has been proposed in single carrier systems to realize a continuous tradeoff between transmission distance and spectral efficiency [9]. It can be simply extended to SCM systems with all subcarriers modulated by an identical TDHQ format. However, this system is still vulnerable to the optical filtering induced by cascaded ROADMs.

In this work, we propose to use TDHQ based adaptive bit and power loading in order to realize a filtering-tolerant flexible SCM system. In particular, an appropriate TDHQ format is selected for each subcarrier according to the specific signal-to-noise ratio (SNR). In the meantime, the power of each subcarrier is optimized targeting the maximization of the overall data rate. The capacity improvement is experimentally demonstrated in a 4-subcarrier SCM system with an aggregate symbol rate of 34.94 Gbaud. Compared with the system using uniform TDHQ, the proposed system can achieve an average capacity increase of 17.5% over different transmission distances in the experiments.

2. Principle of adaptive bit and power loading based on TDHQ

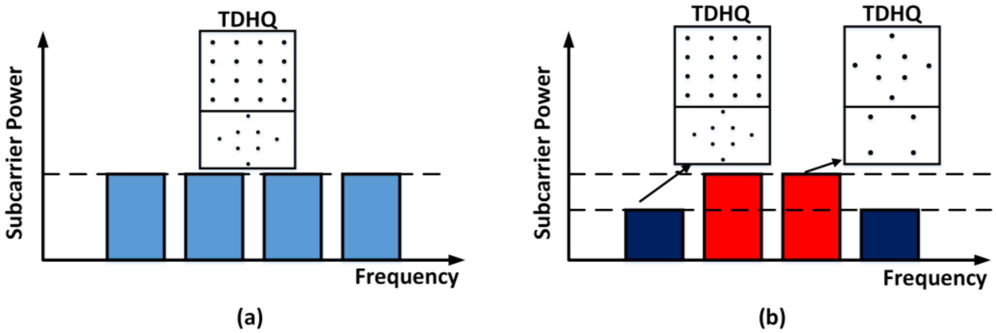

Fig. 1. Schematic illustration of bit and power loading based on TDHQ for flexible SCM systems.

In a conventional SCM system, uniform standard QAM and power are allocated to all subcarriers. In order to realize a flexible bit rate SCM system, uniform TDHQ can be applied to all subcarriers instead of standard QAM as shown in Fig. 1(a). However, the SNRs over subcarriers may vary in the presence of optical filtering induced by cascaded ROADMs, and the overall system performance will be limited by the edge subcarriers which have the lowest SNRs. Meanwhile, the SNR of each subcarrier can be monitored through receiver-side digital signal processing (DSP). Here, for the purpose of both increasing the filtering tolerance and achieving flexible bit rate, we propose to use adaptive bit and power loading based on TDHQ according to the subcarrier SNRs as illustrated in Fig. 1(b). In particular, the modulation format (TDHQ) and power of each subcarrier are co-optimized with the target of maximizing the overall data rate. In principle, this optimization can be achieved by a brute-force search method. However, it will inevitably cause a slow connection starting process and is thus undesired especially in dynamic optical networks.

To realize a fast optimization of bit and power loading, we propose the following process. For simplicity, we take a pair of subcarriers (the mth and $(m+M/2)th$ subcarrier) as an example. Given the individual average powers (P_{S1} , P_{S2}), individual SNRs (SNR_1 , SNR_2), and individual bits-per-subcarrier (BpS_1 , BpS_2), we can calculate the average bit error ratio (BER) of the two subcarriers as

$$\begin{aligned} BER &= \frac{1}{BpS_1+BpS_2}\left[BpS_1\cdot\zeta_1\left(SNR_1\right)+BpS_2\cdot\zeta_2\left(SNR_1\right)\right] \\ &= \frac{1}{BpS_1+BpS_2}\left[BpS_1\cdot\zeta_1\left(\frac{SPR}{SPR+1}\cdot\frac{P_{PS}}{P_{N1}}\right)+BpS_2\cdot\zeta_2\left(\frac{1}{SPR+1}\cdot\frac{P_{PS}}{P_{N2}}\right)\right] \end{aligned} \tag{1}$$

where $\zeta_1(\cdot)$ and $\zeta_2(\cdot)$ are BERs which are functions of SNR according to the modulation format on the first and second subcarriers, respectively [10]. P_{PS} is the total power of the two subcarriers and SPR denotes the subcarrier power ratio between the two subcarriers for the proposed power loading. For the optimization, a maximal BpS_1+BpS_1 is derived according to Eq. (1) at a target BER, which is the soft-decision threshold $BER=2\times10^{-2}$ in this work.

3. Experimental results and discussions

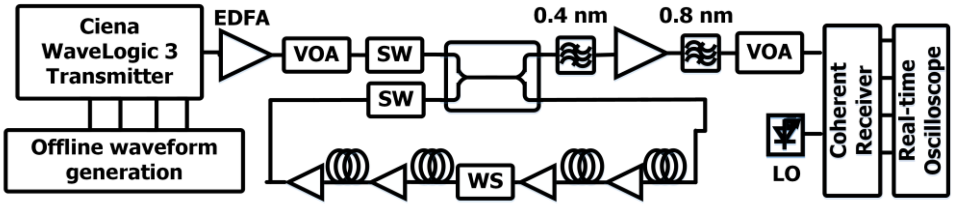

Fig. 2. Experimental setup.

The experimental setup is depicted in Fig. 2. Before being converted into analog signals by four digital-to-analog converters (DACs), the SCM signals are first generated offline in MATLAB. The aggregate symbol rate is 34.94 GBaud for the 4-subcarrier SCM signals. A root raised cosine (RRC) pulse shaping filter with a roll-off factor of 0.1 is used for each subcarrier and no guard band is used. Then, the generated real and imaginary components of the SCM signals are loaded to the transmitter module of a Ciena WaveLogic3 transceiver. A variable optical attenuator (VOA) controls the launch power of the signals entering the re-circulating loop. The loop contains 320 km of standard single mode fiber (SSMF), and the EDFAs are employed after every 80 km fiber to compensate the loss. To emulate cascaded ROADMs, a Finisar WaveShaper (WS) with a variable 3-dB bandwidth is inserted after the second EDFA. At the receiver-side, the optical-to-electrical conversion is achieved by 4 balanced photodiodes, and a four-channel real-time oscilloscope with a sampling rate of 80 GSa/s per channel is used to digitize the waveform. Finally, the captured waveforms are processed offline in MATLAB. The receiver-side DSP includes CD compensation, coarse frequency offset (FO) compensation, subcarrier de-multiplexing, matched filtering, adaptive equalization, phase recovery, and symbol decision. Finally, the BER is calculated by counting the bit errors across all the 4 subcarriers.

First, the received average SNRs for edge and central subcarriers as a function of the WS 3-dB bandwidth after transmitting 7 loops are shown in Fig. 3(a). The launch power is 1 dBm. The received SNR for the central subcarriers remains almost the same as the 3-dB bandwidth varies, whereas the received SNR of the edge subcarriers decreases as WS 3-dB bandwidth reduces because the edge subcarriers are severely filtered. Then in Fig. 3(b), we investigate the achievable capacity of the proposed SCM scheme with bit and power loading as a function of the WS 3-dB bandwidth after transmitting 7 loops. The SCM systems using uniform standard QAM and TDHQ are also evaluated for comparison. For a large WS 3-dB bandwidth, e.g. 46 GHz, the SNR difference between edge and central subcarriers is small. Therefore, the optimal solution is to use the same format, which is 16QAM in the experiment, and uniform power to all subcarriers. In this case, the achievable capacity is the same for all the SCM systems. However, as the bandwidth decreases, the edge subcarriers are severely filtered and the SNR difference becomes large. When the 3-dB bandwidth is small, e.g. 36 GHz, the received SNR of the edge and central subcarriers is 6.6 dB and 13.3 dB, respectively. Compared with the system using uniform standard QAMs on all subcarriers, the system using uniform TDHQ on all subcarriers increases the system flexibility and achieves a capacity improvement of 37.5%. The proposed system with bit and power loading further increases system flexibility and a total capacity improvement of 62.5% is achieved. Furthermore, by averaging the capacity improvement across all WS 3-dB bandwidths, the average capacity improvement is 14.2% and 29.9% for the system using uniform TDHQ and the proposed scheme, respectively.

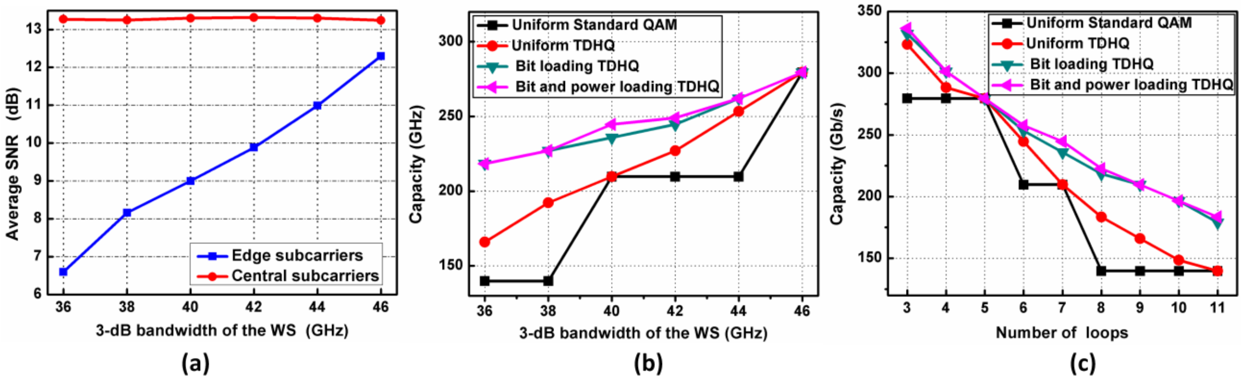

Fig. 3. (a) Received SNR of subcarriers, and (b) Achievable capacity versus WS 3-dB bandwidth after transmitting 7 loops. (c) Achievable capacity versus transmission distance with a WS 3-dB bandwidth of 40 GHz.

Next, we fix the WS 3-dB bandwidth at 40 GHz and investigate the achievable capacity as a function of transmission distance in Fig. 3(c). As expected, using TDHQ can achieve a continuous tradeoff between capacity (data rate) and distance, which enables to convert the available margin into capacity for each specific link. However, using uniform TDHQ over subcarriers is vulnerable to the narrow optical filtering. The proposed system with bit and power loading can significantly increase the capacity especially at longer distances with more cascaded filtering as shown in Fig. 3(c). The maximal and average capacity improvement over distances with respect to the system using uniform standard QAMs are summarized in Table 1. When compared to the system with uniform TDHQ, the average improvement achieved by adaptive bit and power loading is 17.5%. It is observed that power loading has a very small benefit. However, considering the fact that the additional complexity of this technique is negligible it is still attractive for practical applications.

Table 1. Capacity improvement compared with the SCM scheme using uniform standard QAMs.

	Uniform TDHQ	Bit loading TDHQ	Bit and power loading TDHQ
Maximal	31.3%	56.3%	59.4%
Average	10.2%	26.1%	27.7%

4. Conclusion

Adaptive bit and power loading based on time domain hybrid QAM (TDHQ) is proposed for digital subcarrier-multiplexing (SCM) systems to achieve flexible data rate and high filtering tolerance. Its benefit is demonstrated in a 34.94 Gbaud 4-subcarrier SCM transmission experiment and 17.5% increase in capacity is achieved.

This work was supported by, the 863 High Technology Plan (2015AA015502), and NSFC (61575071,61331010), China CSC (201506160024).

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