Faster-Than-Nyquist Subcarrier Modulation Utilizing Digital Brick-Wall Filter-Based THP for Band-Limited DML-DD Systems

Yixiao Zhu, Qi Wu, Longjie Yin, and Weisheng Hu

State Key Laboratory of Advanced Optical Communication System and Networks, Shanghai Jiao Tong University, 800 Dongchuan Rd, Shanghai, 200240, China, yixiaozhu@sjtu.edu.cn wshu@sjtu.edu.cn

Abstract *With digital brick-wall filter-based coefficients estimation and Tomlinson-Harashima precoding, we experimentally demonstrate faster-than-Nyquist subcarrier modulation using a 20GHz O-band DML. At the 20% SD-FEC threshold, up to 105%, 45.5%, and 18.2% FTN rates are achieved for QPSK, 16-QAM and 32-QAM formats, respectively.*

Introduction

Cost-effective direct-detection (DD) solutions with bitrate of 100Gb/s and beyond has attracted wide attentions for short-reach applications[1]. Compared with electro-absorption modulated laser (EML) and Mach-Zehnder modulator (MZM), directly-modulated laser (DML) exhibits the lowest cost with small footprint and high power efficiency[2]. Remarkably, based on detuned-loading and photon-photon resonance (PPR) effect, 54GHz distributed Bragg reflector (DBR) laser is reported[3], supporting 100GBaud 4-level pulse amplitude modulation (PAM-4) and 80GBaud PAM-8 signal transmission. However, most commercial available DMLs still have a limited bandwidth around 25GHz.

So far, PAM-N[4], carrier-less amplitude and phase modulation (CAP)[5], subcarrier modulation (SCM)[6], discrete multi-tone (DMT)[7] and other digital modulation schemes have been adopted to realize ~100Gb/s DML-DD links. To further overcome the bandwidth limitation and increase the data rate, faster-than-Nyquist (FTN) signaling provides a promising approach. Theoretically, equalizer with feedback structure has the capability of handling severe inter-symbol interference (ISI) induced by spectral nulls in the frequency-domain. Unfortunately, the error propagation (EP) effect would severely deteriorate the performance of receiver-side decision feedback equalizer (DFE). Therefore, Tomlinson-Harashima precoding (THP) is proposed[8,9], which avoids EP effect by operating with original data symbols at the transmitter. With 80GSa/s analog-to-digital convertor (ADC) and 33GHz sharp-edged bandwidth limitation, up to 94Gbaud PAM-4 signal is successfully detected at a record FTN rate ($=\frac{Nyquist\ bandwidth}{system\ bandwidth}-1$) of 41.4%[10]. Based on a THP - multi-input-multi-output (MIMO) - feedforward equalizer (FFE) scheme[11], 28GBaud optical carrier-assisted 16-QAM signal can be squeezed within 24GHz bandwidth, and 80km standard single-mode fiber (SSMF) transmission is demonstrated at FTN rate of 16.7%. For practical implementation, another issue is that additional test with un-coded data transmission is usually required to precisely estimate the THP coefficients, which increases the complexity of operations.

In this work, by utilizing digital brick-wall filter (BWF)-based coefficients estimation and THP, FTN SCM signal transmission with direct detection is experimentally demonstrated with a 20GHz DML in O-band. To avoid the bandwidth limitation of DML, a manually designed digital BWF and its corresponding THP taps are applied on the SCM signals for bandwidth compression before modulation. At both back-to-back (BTB) and 10km SSMF transmission scenarios, 105%, 45%, and 18.2% FTN rates are achieved for QPSK, 16-QAM, and 32-QAM formats at the 20% soft-decision forward error correction (SD-FEC) threshold of 2.4×10^{-2}, respectively.

Principle

Fig.1 illustrates the principle of BWF-based THP for band-limited DML-DD system. For conventional SCM with target baud rate of B_s, root raised cosine (RRC) filter with roll-off factor approching zero is applied on the QAM symbols to obtain rectangular spectral shape. Then the baseband waveform is digitally up-converted to the intermediate frequency (IF), which is slightly larger than half of the signal bandwidth to reduce the guard band without introducing spectral overlap. Hermite symmetry is exploited for intensity modulation with DML transmitter. In this case, the Nyquist electrical bandwidth for ISI-free SCM transmission is B_s. After modulation, the optical signal is low-pass filtered by DML bandwidth (dashed red line). As a consequence, the bit-error rate (BER) performance would be severely degraded due to the spectral loss.

In comparison, the FTN transmission scheme is shown in the bottom line of Fig.1. Firstly, the data sequence is processed with THP, leading to almost uniform distribution in the constellation with boundary determined by modulo operation.

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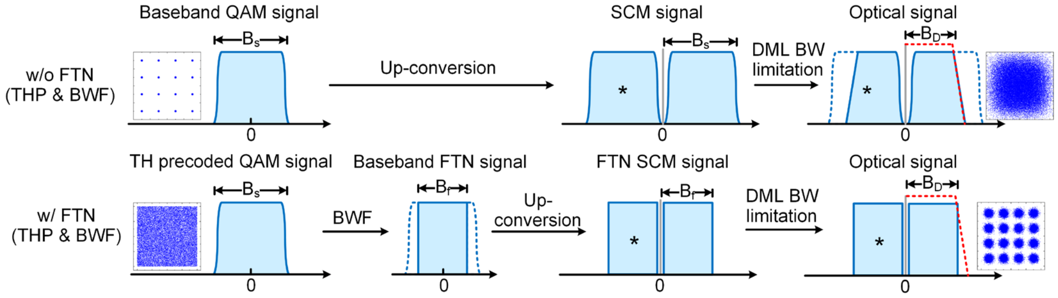

Fig. 1: Principle of brick-wall filter-based THP for band-limited DML-DD system.

Then digital BWF is employed to strictly narrow the signal bandwidth to B_f. Once the THP coefficients match the BWF, the penalty from spectral compression can be greatly suppressed. Afterwards, the FTN signal is up-converted, occupying approximately B_f bandwidth. If $B_D \approx B_f$, the influence of device bandwidth impairment is alleviated. Note that in this scheme, the THP tap estimation can be done numerically without additional accurate experimental measurement.

Experimental setup and DSP stack

Fig.2(a) shows the experimental setup of FTN SCM DML-DD system. At the transmitter, an arbitrary waveform generator (AWG, Keysight M8195A) operating at 64GSa/s generates electrical waveform. An electrical amplifier (EA, SHF 804M) is employed to enlarge the modulation depth. Then the electrical signal is fed into an O-band DML (Xeston 9016E) for modulation. The output optical power of DML is adjusted as 8.5dBm, in order to suppress the transient chirp. After 10km SSMF transmission, a variable optical attenuator (VOA) is placed to control the received optical power as 3dBm. Finally, the optical signal is detected by a 40GHz photodiode (PD, Picometrix PT-40A) and sampled by a digital storage oscilloscope (DSO, Tektronix DPO75902SX) with 100GSa/s sampling rate and 33GHz bandwidth.

The transmitter- and receiver-side DSP stacks are plotted in Fig.2(b)-(c). After QPSK/16-QAM/32-QAM symbol mapping, THP is performed on the sequence without up-sampling. Note that the THP coefficients are calculated numerically at baseband through the combination of BWF, additive white Gaussian noise (AWGN) channel and DFE. The bandwidth of BWF is set as 22GHz and optical signal-to-noise (OSNR) is fixed at 25dB to emulate the practical condition and avoid noise accumulation. Since the BWF symmetrically narrows the signal spectrum, only the real part of the DFE taps is used for THP, which can also reduce the computational complexity. Afterwards, the pre-coded sequence is up-sampled, and spectrally shaped by BWF or RRC filter, and up-converted. Before sending to the AWG, down-sampling is applied to obtain the desired signal baud rate. At the receiver, the captured waveform is re-sampled to 4 samples per symbol (SPSs), down-converted, synchronized. After sparse Volterra equalization (161 1st-order taps, 9 3rd-order taps) and modulo operation, BER is obtained by counting over >6×10^5 bits.

Fig.2(d) shows the measured optical spectra at 0.02nm resolution. The wavelength is centered at 1311nm with red shift due to adiabatic chirp after modulation. The S21 response of DML is depicted in Fig.2(e), ~20GHz 3-dB bandwidth is observed and the frequency response drops rapidly after that.

Experimental results and Discussions

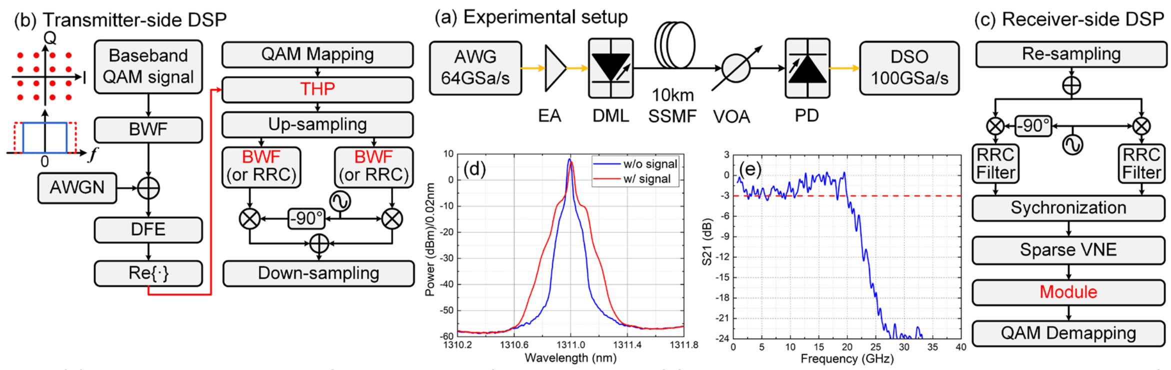

Fig. 2: (a) Experimental setup. AWG: arbitrary waveform generator; DSO: digital storage oscilloscope; EA: electrical amplifier; DML: directly-modulated laser; SSMF: standard single-mode fiber; VOA: variable optical attenuator; PD: photodiode. (b) Transmitter- and (c) Receiver-side DSP stack. THP: Tomlinson-Harashima precoding; BWF: brick-wall filter; RRC: root raised cosine; AWGN: additive white Gaussian noise; DFE: decision feedback equalizer. (d) Measured optical spectra of DML without/with signal modulation. (e) Measured S21 response of DML.

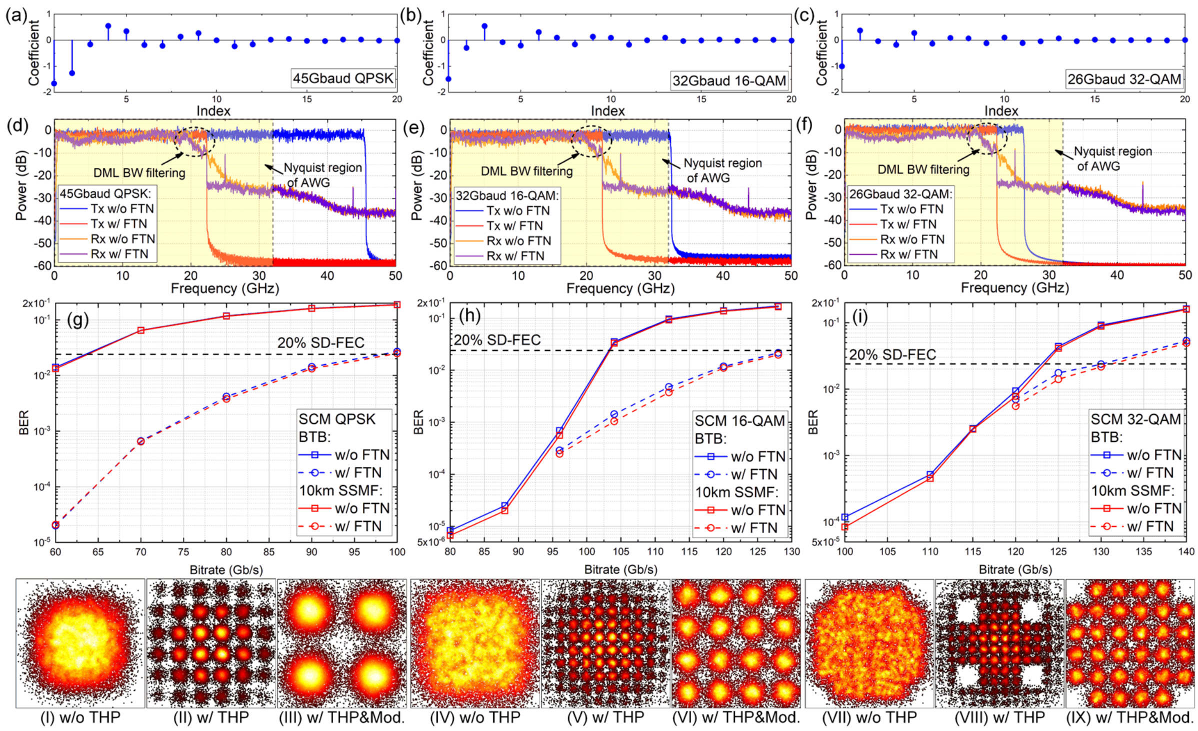

Fig. 3: Calculated THP coefficients for (a) QPSK, (b) 16-QAM, (c) 32-QAM. Electrical signal spectra of (d) QPSK, (e) 16-QAM, (f) 32-QAM format. Measured BER versus bitrate for (g) QPSK, (h) 16-QAM, and (i) 32-QAM formats at BTB and after 10km SSMF transmission, respectively. (I)~(IX) Typical constellations without/with THP for QPSK/16-QAM/32-QAM formats.

Fig.3(a)-(c) provide the calculated THP coefficients for QPSK, 16- and 32-QAM. Fig.3(d)-(f) display the transmitted and received electrical spectra of FTN SCM signals. For QPSK format, 45Gbaud occupies ~45GHz bandwidth without FTN (blue curve), which is severely filtered after transmission (orange curve). Thanks to BWF, the transmitted signal bandwidth can be effectively decreased to ~22GHz (red curve), correspoding to bandwidth compesssion ratio (BCR) of 48.9%. Although DML bandwidth filtering still distorts the corner around 20GHz, most of the spectrum is remained (purple curve). For 32Gbaud 16-QAM and 26Gbaud 32-QAM, 68.8% and 84.6% BCR is realized for 22GHz brick-wall-shaped narrowing, respectively. In addition, it is worth noting that since the Nyquist frequency of 64GSa/s AWG is 32GHz, the FTN scheme also helps for SCM QPSK and 16-QAM sub-sampling generation.

Fig.3(g)-(i) presents the measured BER versus bitrate for QPSK, 16-QAM, and 32-QAM format at BTB and after 10-km SSMF transmission, respectively. For conventional SCM signal without FTN, the BER rises rapidly to larger than 0.1, leading to indistinguishable constellations as Fig.3 (I), (IV) and (VII). Thanks to BWF and THP-based FTN scheme, an order of magnitude improvement in BER can be observed in the bandwidth-limited case. At the 20% SD-FEC threshold of 2.4×10^{-2}, 90Gb/s QPSK, 128Gb/s 16-QAM and 130Gb/s 32-QAM is successfully transmitted, resulting in 50%, 33.3% and 8.2% increase in bitrate, respectively. Moreover, the BER after 10km SSMF transmission becomes slightly better because of the DML chirp.

Fig.3(II), (V) and (VII) display the constellations of FTN SCM 45Gbaud QPSK, 32Gbaud 16-QAM, and 26Gbaud 32-QAM after equalization, whose levels are increased due to pre-coding. Nevertheless, after modulo operation M (M=4,8 and 12 for QPSK, 16- and 32-QAM), the constellations turn back to the conventional pattern with separated clusters in Fig.3(III), (VI) and (IX) of Fig.3.

Conclusions

In this work, we experimentally demonstrate FTN SCM signal transmission based on 20GHz band-limited DML. The signal bandwidth is narrowed by digital BWF before modulation, and the induced ISI is eliminated using numerically estimated THP coefficients. At the 20% SD-FEC threshold, 50%, 33.3% and 8.2% bitrate increase is benefited both at BTB and after 10km SSMF transmission, respectively. Correspondingly, record 105%, 45% and 18.2% FTN rates (or 48.9%, 68.8% and 84.6% bandwidth compression ratios) are achieved for QPSK, 16-QAM, and 32-QAM formats The results indicate the feasibility of FTN with high-order modulation formats for high-speed short-reach applications.

Acknowledgements

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