Optical trellis-coded modulation with multi-parallel MZM

Takahide Sakamoto, Akito Chiba, Isao Morohashi and Tetsuya Kawanishi
National Institute of Information and Communications Technology,
4-2-1 Nukui-Kita, Koganei, Tokyo 184-8795, Japan e-mail: tsaka@nict.go.jp

Abstract *We demonstrated trellis-coded modulation onto 10-Gbaud 16QAM by electro-optic vector digital-to-analogue converter employing multi-parallel MZM and trellis encoder. The signal was demodulated with a digital homodyne employing Viterbi decoder.*

Introduction

Optical quadrature amplitude modulation (QAM) and other high-order multi-level modulation formats are promising for optical fibre transmission with great spectral efficiency [1-6]. Previously, we demonstrated synthesis of 50-Gb/s 16QAM by using electro-optic digital-to-analogue convertor (EO-DAC) that employs a quad-parallel Mach-Zender modulator (QPMZM). This approach is advantageous for high-bit-rate operation because 16QAM signal is directly synthesized from the combination of binary data sequences in an electro-optic manner without using electric DACs.

On the other hand, higher-order QAM signals are less tolerant to inter-symbol interferences (ISI) because distances between the symbols are much shorter. Adaptive equalizing based on FIR filter technology effectively reduces such ISI and other signal distortion [4-6]. Adaptive optimization of thresholds has also been discussed, so far, which effectively moderates distortion of constellation [7]. Recently, trellis-coded modulation (TCM) [8] has been demonstrated in the area of optical communications [9][10]. This technology is a powerful implement to reduce the ISI of the high-order multi-level signals although it requires some redundancy for error correction.

In this report, we demonstrate TCM over 16QAM (TCM-16QAM) by using the EO-DAC. 30-Gb/s data is encoded onto 10-Gbaud 16QAM signal, and the signal is demodulated with a digital coherent receiver employing Viterbi trellis decoder.

Electro-optic synthesis of multi-level Formats

Fig. 1(a) shows principle of EO-DAC based on multi-parallel MZM for synthesis of multi-level coherent signals and TCM signals. The EO-DAC consists of a CW laser, multi-parallel MZM and an electric digital encoder. In the EO-DAC, the CW light is electro-optic modulated with the multi-parallel modulator where MZMs are integrated in parallel. In each arm of the modulator, binary PSK (BPSK) signal is generated by the MZM driven with the signal from the electric encoder. At the output of the modulator, the *n* sets of the BPSK signal are superposed to form 2^n-level coherent signals. An n-PSK, n-QAM or other attractive formats can be synthesized by the combination of the binary encoded data, by giving an appropriate control of optical amplitude and phase offset of the BPSKs [11]. The encoder included in the EO-DAC can be also used for coded modulation as described in this report. In this technique, the pairs of the encoded binary data sequences are directly mapped onto the optical carrier in an electro-optic manner. This is advantageous for synthesis of coherent multi-level signals at high bit rate possibly with clear constellation since electric DACs are not required; in addition, electronic device and components dealing with binary data streams have been matured well. Rectifying characteristics of the transfer function of each MZM are also useful for reshaping the encoded signal that drives the modulator.

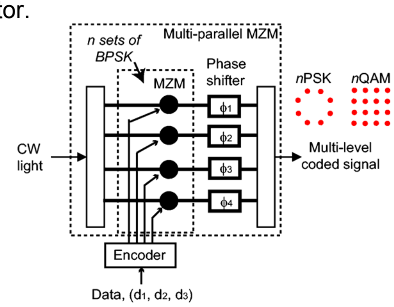

Fig. 1 Electro-optic vector DA converter for synthesis of multi-level formats and trellis-coded modulation

Trellis-coded modulation over 16QAM

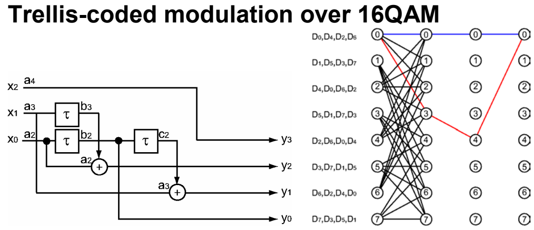

Fig. 2 (a) 8-sate encoder for TCM-16QAM, (b) its trellis diagram; (τ: shift register)

TCM is known to be an effective coding method for multi-level coherent formats like QAM, where forward-error-correction coding and modulation are performed together at one time [8-10]. In the TCM, original data are encoded as temporal sequences of QAM symbols, and the original data can be decoded from the sequence with less error comparing to conventional multi-level signalling ways.

Fig. 2(a) shows the encoder for TCM-16QAM used in this report. The encoder accepts 3-bit data input and it outputs 4-bit encoded data. The encoder has 3-bit shift registers; it can keep 8 different states; each sate is transited to another one according to the incoming data sequences. Fig. 2(b) is the trellis diagram that stands for allowable temporal transition between the states. In the coding, we arrange the branches of transition paths separated with each other as far as possible; we set the length of each branch as long as possible before they are merged back to a particular state (In the case of Fig. 2(b), it takes at least three clocks). In this way, the Euclidian distance between the branches (coded sequences) become larger comparing with conventional multi-level signals without coding. In this report, this trellis encoder is implemented in the encoder section of the EO-DAC.

To decode the TCM signal, in a receiver side, the transition path should be found out among other possible candidates, estimated from the temporal sequence of the received signal. This operation can be achieved with a so-called Viterbi decoder.

Experiments

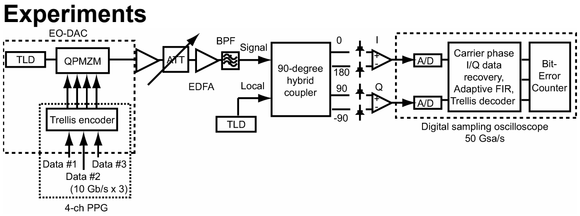

Fig. 3 Experimental setup

Fig. 3 shows experimental setup. In the transmitter side, TCM-16QAM signal was synthesized with the EO-DAC with 4-bit resolution. Therein, a CW light generated from an external cavity laser diode was modulated with a quad-parallel MZM that had a structure of four parallel MZMs and BPSK was generated in each MZM. Four sets of the driving signals for the MZMs were encoded from three sets of 10-Gb/s 2^{15}-1 PRBS with the encoder shown in Fig. 2(a). In this experiments, the functions of PRBS signal sources and encoder were arranged in a 4-ch pulse pattern generator.

The synthesized TCM-16QAM signal was demodulated with a digital coherent receiver based on off-line digital signal processing. In the receiver, the signal was homodyne detected to recover I and Q components of the signal. A Viterbi trellis decoder was implemented to decode the original signal from the recovered I and Q signals together with an adaptive FIR filtering for pre-equalization. The decoder length was set at 16. The order of the FIR filter was 15.

Fig. 4 shows constellation maps of the received signal with different received power, P_r. At P_r = -26.2 dBm, clear constellation was observed, while it was degraded in case of P_r = -35.2 dBm.

Bit error rate (BER) characteristics are shown in Fig. 5. The BERs of TCM-16QAM are plotted as solid squares. Triangles and circles denote the BERs of 16QAM and QPSK, respectively. Error free operation (BER<10^{-6}) was achieved with the received power of -35.2 dBm, which corresponds to the constellation diagram shown in Fig. 4(b). In our former experiments, it had been confirmed that 8PSK had 7.6-dB (theoretically, 5.8-dB) power penalty from QPSK [9]; thus the receiver sensitivity of the 8PSK in this setup can be estimated to be -33.6 dBm (theoretically, -35.4 dBm). It seems that coding gain became positive a little, 1.6 dB, at BER = 1 x 10^{-6}. Further investigation would be required in the smaller error region of BER < 1 x 10^{-6} to strengthen the proof. However, we can deduce that the synthesized TCM-16QAM signal would outperform 8PSK in the region.

(a) (b)

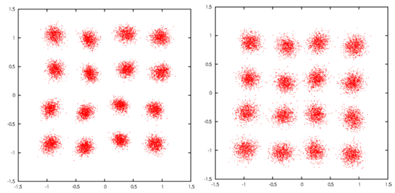

Fig. 4 Constellation maps of 10-Gbaud TCM-16QAM (a) P_r = -26.2 dBm, (b) P_r= -35.2 dBm

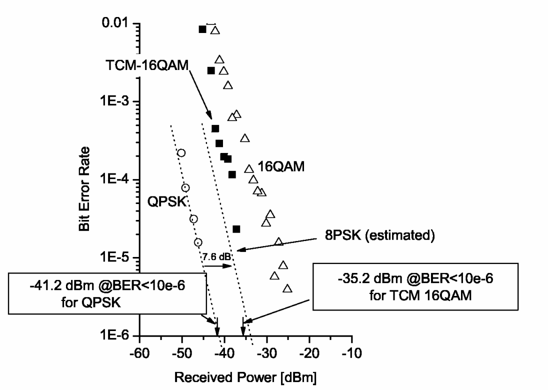

Fig. 5 Bit-error-rate characteristics; solid squares: TCM-16QAM, triangles: 16QAM, circles: QPSK

Conclusions

We demonstrated 10-Gbaud (30-Gb/s) TCM-16QAM synthesized by EO-DAC employing quad-parallel MZM. TCM-16QAM became comparable to 8PSK at BER = 10^{-6}.

References

1 M. Nakazawa, *et al*, OFC'07, PDP26 (2007).
2 A. Chiba, *et al*, OECC'07, 12B3-4 (2007).
3 T. Sakamoto, *et al*, ECOC'07, PD2.8 (2007).
4 Y. Mori et al, ECOC'08, Tu.1.E.4 (2008),
5 M. Nakamura et al, ECOC'08, Tu.1.E.5 (2008)
6 P.J. Winzer et al, ECOC'08, Th.3.E.5 (2008).
7 A. Chiba, *et al*, OFC'08, JWA63 (2008).
8 G. Ungerboeck, *IEEE trans. on Information Theory*, 28 (1982), pp 55-67.
9 H. Bulow, et al., OFC'04, WM5 (2004)
10 H. Zhao et al., ECOC'04, We.3.P.93 (2004),
11 T. Sakamoto, *et al*, OFC'09, OTuG4 (2009)