



OPTICAL TRANSMISSION SYSTEM EMPLOYING CARRIERLESS AMPLITUDE PHASE (CAP) MODULATION FORMAT

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ABSTRACT

Multiple wavelength channels can be used for implementing transceiver modules in optical transmission system network in order to increase spectral efficiency. However, it leads to cost increment which is caused by employment of multiple optical components. Therefore, implementation of advanced modulation format has become an option to further increase spectral efficiency. But apparently, it involves complicated and costly transmission system. Carrierless amplitude and phase (CAP) modulation has emerged as promising advanced modulation format candidate in optical transmission system due to spectral efficiency improvement ability with reduction of optical transceiver complexity and cost. In this paper, we propose a transmission of 2.5 Gb/s CAP-4 and CAP-16 modulation formats over single mode fiber (SMF) link using 1550 nm vertical cavity surface emitting laser (VCSEL) with 2.5 Gbaud modulation rate. The signal is successfully recovered after 35 km of SMF in system of 10 GHz sample rate.

Keywords: carrierless amplitude phase, vertical-cavity surface-emitting laser.

INTRODUCTION

The revolution in the telecommunication habits lead to the demand for increasing bandwidth capacity and bit-rate per user in transmission system due to rapid expansion of communication services in the last decades. To ensure continuity of outstanding information transmission process, telecommunication network systems that can support higher data rate and intensive capacity at low cost are necessary. Optical transmission systems are enhancing from simple modulation scheme known as on-off keying (OOK), to M-ary pulse amplitude modulation (M-PAM), to M-ary phase shift keying (M-PSK), to M-ary quadrature amplitude modulation (M-QAM) and towards advanced modulation techniques such as discrete multitone (DMT) (Kalet, 1989).

However, optical transmission systems has to deal with the channel spacing decrement issue as the transmission distances and the bit rate per channel increases. In order to mitigate nonlinear transmission impairments, to improve receiver sensitivity and facilitate a per channel bit rate increase beyond the limits of binary systems, more advanced modulation formats that upgrading differential quadrature phase shift keying (DQPSK) modulation scheme has been proposed (Tokle *et al.*, 2008). But it is preferable if the use of more advanced modulation formats can help to make the system more feasible and efficient for optical transmission system by putting the complexity raise of the system at the minimum level while supporting higher capacity link and increasing bit-rate per user demand.

Therefore multilevel and multidimensional modulation scheme carrierless amplitude phase (CAP) has been proposed by the Bell Labs (Werner, 1992) and merely getting attention and become popular for digital subscriber lines (DSLs) during the 90s (Im *et al.*, 1995). CAP modulation is a multilevel and multidimensional modulation scheme which is quite similar to quadrature amplitude modulation (QAM) in term of transmitting two

streams of data in parallel. But contrary to QAM, CAP does not require a sinusoidal carrier, but employing filters with orthogonal impulse response to generate orthogonal waveforms that used to separate the different data streams. This makes CAP receivers simpler than QAM receivers while achieving the same spectral efficiency and performance.

CAP modulation has been demonstrated to be simpler than DMT (Shalash and Parhi, 1996). Multi carrier modulation format like DMT is much more complex compared to CAP where IFFT and FFT are needed in modulation and demodulation process while on the other hand, CAP uses a filter or digital convolution with less computational complexity. Additionally, CAP supports modulation in more than two dimensions, provided that orthogonal pulse shapes can be identified (Shalash and Parhi, 1999). This privilege characteristic of multi-dimensional modulation has bring CAP modulation format as an attractive option in supporting multiple services for next generation access networks and in-home networks as well (Caballero *et al.*, 2011). The usability of CAP modulation with higher dimensions for service and user allocation in WDM optical access has been experimentally demonstrated in (Othman *et al.*, 2012a).

Nowadays, the development of a transmission system that can avoid complexity and significant cost of optoelectronic devices is highly required. Compared to QAM and orthogonal frequency division multiplexing (OFDM), complex mixers and radio frequency (RF) sources or optical IQ modulator is not necessary for CAP (Tao *et al.*, 2013). This makes CAP a good candidate for next generation optical transmission network system where cost is the main consideration. In fact, cost effectiveness is always be a key issue and will be decisive for the network topology choices.

Recently, there is growing interest of CAP modulation format implementation in the optical communication system (Geng *et al.*, 2012), (Othman *et al.*,



2012b), (Wu *et al.*, 2013) due to its high spectral efficiency prospect and the capability of generating the respective orthogonal waveforms using transversal filters instead of using sinusoidal carrier. In (Geng *et al.*, 2012), CAP-64 modulation scheme has been experimentally demonstrated to give higher system margin and error free transmission compared to non-return-to-zero (NRZ) modulation using a low-cost commercially available resonant cavity light emitting diode (RC-LED) for home networks. High dimensionality CAP with directly modulated vertical cavity surface emitting lasers (DM-VCSELs) has been proposed to provide more flexibility in optical fiber systems in (Othman *et al.*, 2012b) and CAP scheme has shown competitive performance compared to OFDM in providing an alternative spectrally efficient modulation for next generation optical wireless networks as reported in (Wu *et al.*, 2013).

The experimental study has shown that the hybrid adaptive equalization technique that consists of decision-directed least mean square (DD-LMS) and modified cascaded multi-modulus algorithm (CMMA) allows the realization of 30 Gb/s and 40 Gb/s CAP-32 transmission over 40 km SSMF (Tao *et al.*, 2013). While in (Olmedo *et al.*, 2014), multi-level multi-band CAP (MultiCAP) that has been proposed to extend the bandwidth of each channel for high capacity data transmission achieves record spectral efficiency, increases tolerance towards dispersion and bandwidth limitations with less complexity of the transceiver. This multi-band CAP modulation is then has been proposed as an approach for multi-user access in wavelength division multiplexing visible light communication (WDM-VLC) system using a single RGB LED (Wang *et al.*, 2014).

In this paper, we present an optical transmission of 2D-CAP-4 and 2D-CAP-16 signals using VCSEL. In optical transmission system, vertical cavity surface emitting lasers (VCSELs) have emerged to be a potential light source due to low modulation voltage and cost effective production (M.B. Othman *et al.*, 2012). The CAP modulated signals are successfully propagated over 35 km length of SMF. Design and simulation of optical transmission system using Optisystem 13 software is integrated with MATLAB program for CAP modulation coding that represents CAP modulator and CAP demodulator.

CAP MODULATION FORMAT IN OPTICAL TRANSMISSION ARCHITECTURE

Optical transmission system is designed and simulated using Optisystem 13 software while CAP modulation coding is constructed using MATLAB program. OptiSystem is a comprehensive software design suite that enables users to plan, test, and simulate optical links in the transmission layer of modern optical networks. On the other hand, MATLAB is a good software tool to develop coding or modeling. Integration between Optisystem 13 software and MATLAB program is performed in order to ensure the CAP signal from MATLAB is transmitted directly and successfully in the optical transmission system design.

The schematic of the simulation design in Optisystem 13 software is shown in Figure-1. The transmitter is composed of an import module and vertical-cavity surface-emitting laser (VCSEL). The link is simulated with a 35 km length of SMF while the receiver is modeled with a photo-diode (PD) and an export module.

Data stream sequence lengths of 2^{15} bits are sampled up to 4 samples per bit with 10 GHz sample rate and 2.5 Gbaud symbol rate at 2.5 Gbps. For CAP modulation part, the text file generated offline in MATLAB program is put into the MATLAB component which acts as CAP modulator in order to generate the CAP signal through the link. The output signal is then used to directly modulate 1550 nm VCSEL with 65 mA bias current. The signal is transported via 35 km of SMF link. The optical fiber attenuation is 0.2 dB/km while dispersion value is 16.75 ps/nm/km. After transmission over SMF, the signal is directly detected by a PD which is modeled with a responsivity value of 1 A/W. Finally, the signal is then recovered using another MATLAB component that represents CAP demodulator.

The signal is automatically exported as a text file and processed by calling the MATLAB program from Optisystem software itself. This method can avoid the need to manually export and process the signals for offline demodulation in MATLAB program.



Figure-1. Optical transmission system simulation design.

A block diagram of the CAP transmitter and receiver is shown in Figure-2. The original bit sequence of data stream in the transmitter which is based on the pseudo random binary sequence (PRBS) with sequence length of 2^{15} bits is first mapped according to the given constellation by converting it into a number of multi-level symbols. These mapped symbols are then upsampled to 4 samples per symbol and shaped by the CAP filters in order to achieve square-root raised cosine (SRRC) waveforms. These waveforms are multiplied by sine or cosine waveforms to achieve orthogonality between them and move them from baseband to passband. The resultant waveforms are given by:

$$f_1(t) = h_{SRRC}(t) \cos 2\pi f_c t \quad (1)$$

$$f_2(t) = h_{SRRC}(t) \sin 2\pi f_c t \quad (2)$$

where f_c is a frequency suitable for the passband filters. The pair of modulated waveforms f_1 and f_2 constitute a Hilbert pair. A Hilbert pair is two signals of the same magnitude response but with phase responses shifted by 90° .

Figure-2(a) and (b) presents the impulse response of the CAP filters in time domain. The two orthogonal signals are added and converted from digital to analog



form. The combined frequency spectrum of CAP is shown in Figure-2(c).

At the receiver, the signals are converted back to digital form and fed into two matched filters. The matched filter used has an impulse response which is the time-inversion of the orthogonal filters at the transmitter in order to recover each dimension and to retrieve the original sequence of symbols. These symbols are then downsampled and demapped to obtain original data.

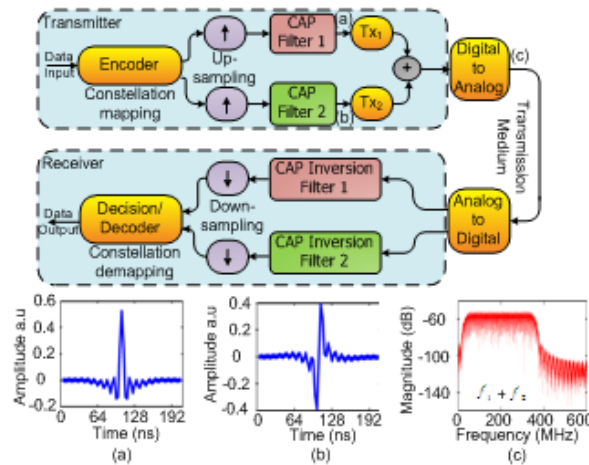


Figure-2. 2D CAP transmitter and receiver (a) Impulse response CAP filter 1 (b) Impulse response CAP filter 2 (c) Combined frequency response(Othman, 2012c).

Figure-3 shows the schematic diagram of CAP transmitter and receiver in optical transmission system using integrated software. In Optisystem software, transmitter MATLAB component block represents CAP modulator while the receiver MATLAB component block represents CAP demodulator.

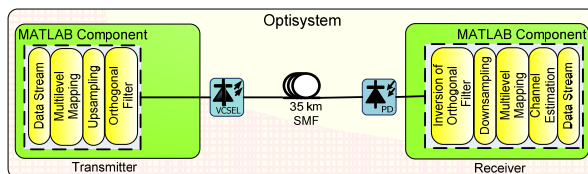


Figure-3. Schematic diagram of CAP transmitter and receiver in optical transmission system using integrated software.

SIMULATION RESULTS

Figure-4 and Figure-5 show the constellation diagrams for optical back to back (B2B) and after SMF transmission for CAP-4 and CAP-16. The signals are successfully transmitted from 5 to 35 km of SMF with 1550 nm VCSEL at 2.5Gbps.

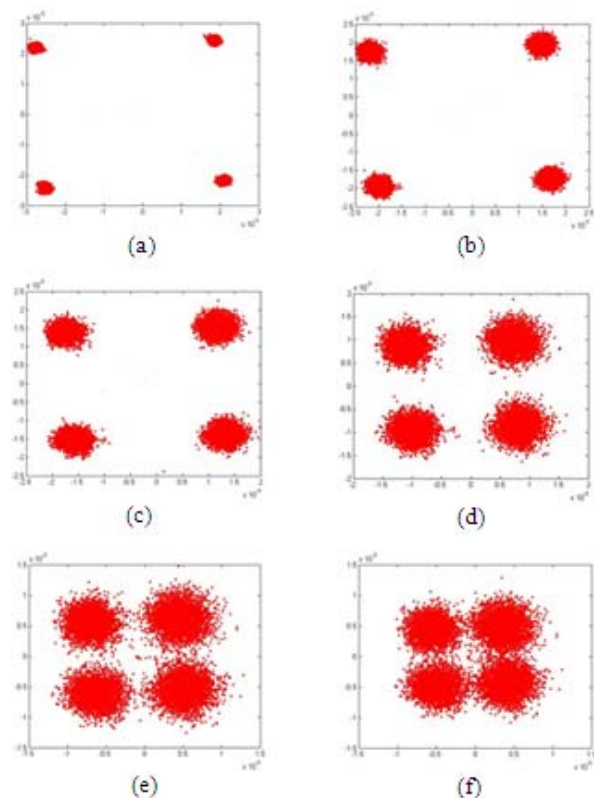


Figure-4. Constellation diagram for 2D CAP-4 (a) optical back to back (B2B) (b) after 5 km transmission (c) after 10 km transmission (d) after 20 km transmission (e) after 30 km transmission (f) after 35 km transmission.

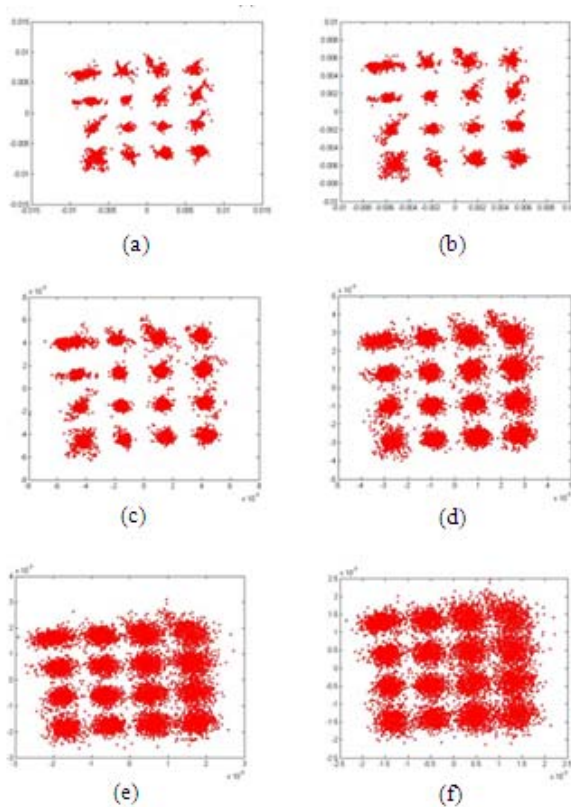


Figure-5. Constellation diagram for 2D CAP-16 (a) optical back to back (B2B) (b) after 5 km transmission (c) after 10 km transmission (d) after 20 km transmission (e) after 30 km transmission (f) after 35 km transmission.

As can be clearly seen in Figure-4 and Figure-5, all of the signals are successfully demodulated after 35 km of SMF transmission. The received signals may be affected by the attenuation, distortion, phase noise or interference at the transmission channel as the distance increases. These have caused the constellation points to rotationally spreading, getting closer to one another and move towards the center at higher length. However, the results show that constellation diagrams of CAP-4 and CAP-16 signals able to preserve until 35 km at 2.5 Gbps data rate with 2.5 Gbaud modulation rate.

The results obtained prove that the integration process between Optisystem software (where the simulation design is performed) and MATLAB program (where CAP signal is generated) are successfully carried out.

CONCLUSIONS

We have demonstrated simulation results of single carrier modulation format carrierless amplitude and phase (CAP). The CAP-4 and CAP-16 signals have been successfully transmitted over 35 km of SMF with 1550 nm VCSEL at bit rate of 2.5Gbps. The constellation diagram results show that the integration process is established and implementation of CAP modulation format can be a good option in optical transmission system. Integration

establishment between Optisystem and MATLAB allow a direct demodulation process without requiring manually offline demodulation stage.

In conclusion, CAP has the advantage of not rely on the generation of sinusoidal carriers at the transmitter and receiver part. CAP modulation drives a remarkable development in producing efficient and compact optoelectronic devices whereas make the optical communication system network much simpler and cost effective. We believe CAP can be viewed as an attractive alternative modulation format for optical access networks such as WDM access network with higher data rates.

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