VOL. 11, NO. 8, APRIL 2016 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

# 1.25 GBPS AND 2.5 GBPS DATA RATE TRANSMISSION OF 2D-CAP MODULATION FOR ACCESS NETWORK

M. B. Jaafar , M. B. Othman, N. M. Ridzuan , and M. F. L. Abdullah
Optical Fiber and Communication Network, Research Group, Communication Engineering Department, Faculty of Electrical & Electronic Engineering, Universiti Tun Hussein Onn Malaysia, Batu Pahat, Johor, Malaysia
E-Mail: nana91marliana@gmail.com

## ABSTRACT
We have investigated the carrierless amplitude phase (CAP) modulation format at different data streams for access network and simulated by using VPI software. The CAP signals with 1.25 Gbps and 2.5 Gbps are successfully transmitted over 20 km of single-mode fiber (SMF) with 1550 nm SM-VCSELs. The 3.79 b/s/Hz and 7.58 b/s/Hz of spectral efficiency are reported for 2D-CAP of 1.25 Gb/s and 2.5 Gb/s. The receiver sensitivity at FEC limit for B2B of both 1.25 Gbps and 2.5 Gbps is -18.3 dBm and -16.2 dBm, with the difference of 2.1 dB have been observed. After 20 km of transmission, a 2.5 dB difference was detected at the forward error correction (FEC) limit with receiver sensitivity of -18.3 dBm and -15.8 dBm respectively. The result shows that the CAP modulation format has feasibility and potential to deliver high data rate by employing simple baseband electronic design.

**Keywords:** carrierless amplitude phase, data rate.

## INTRODUCTION
In the today's reality, higher data speed surpassing one gigabit per second must be offered in future wireless system to support current bandwidth-hungry applications, like High-Definition (HD) video and high speed internet. To achieve much faster wireless communication, it will be compulsory to develop higher carrier frequencies in the future. This is due to the congestion that affected by the large number of end-users sharing the similar frequency spectra and the limited frequency spectra at low frequencies (A. Ng'oma *et al.* 2009). In addition, the increasing number of users will impose limitation to the data communication.

Carrierless amplitude phase (CAP) modulation can be described as a multidimensional and multilevel modulation scheme,that employed orthogonal waveforms, one for each dimension. With the absence of carrier at the both transmitter and receiver, it makes CAP different with quadrature amplitude phase (QAM) while achieving the same performance and spectral efficiency (SE) (M. I. Olmedo *et al.* 2013).

The origin of making the CAP become more increased interest is its well-known SE, which makes it very competitive with OFDM. Recently, due to its potentially high SE, CAP has gained increasing attention for optical communication (J. D. Ingham *et al.* 2011), (M. Wieckowski *et al.* 2011).

CAP can be generated at high speed with the use of readily available low-cost transversal filter and becoming a simpler scheme than orthogonal frequency division multiplexing (OFDM) (J. D. Ingham *et al.* 2011). Differing to OFDM, CAP is a single-carrier scheme that can lead to higher bit rates, and it is not as highly effected by the primary issue of OFDM, which is high peak to average power ratio (PAPR) (J. L. Wei *et al.* 2012a). Additionally, by comparing the power dissipation, CAP system is significantly lower than in an OFDM system (J. L. Wei *et al.* 2012b).

Due to the flexibility of the CAP system, a software-controlled change in the tap coefficients of an electronic filters can be used to achieved the generation of passband channels, without the necessity for upconversion using a mixer and local oscillator (J. D. Ingham *et al.* 2011). It apparently shows that CAP modulation gives an outstanding development in producing efficient and compact optoelectronic devices that makes the optical communication system networks much simpler and has lower power signal processing with high data rate at a low cost.

In this paper, we have programmed the CAP modulation format at different data streams and simulated by using VPI software for optical transmission. The CAP signals with 1.25 Gbps and 2.5 Gbps have been transmitted over 20 km of singlemode fiber (SMF) with 1550 nm SM-VCSELs.

## MOTIVATION
Carrierless amplitude phase (CAP) modulation, or originally called carrierless amplitude modulation /phase modulation (AM/PM) has been proposed by the Bell Labs as a viable modulation technique for high-speed communication links over copper wires in mid 1975s (D. D. Falconer, 1975). CAP modulation can be considered as a bandpass pulse amplitude modulation (PAM) in digital communication system (E. A. Lee *et al.* 1994), in which the carrier frequency is near baseband. However, compare to pulse amplitude modulation (PAM), CAP has zero direct current (dc) power, where make it well suited to ac coupled channels.

On the other hand, CAP has similarities to QAM modulation in its ability to support multiple levels in more than one dimension. However, CAP modulation viewed differ to QAM in the absence of carrier, whereas CAP uses filters with orthogonal waveforms to separate the different data streams. This makes CAP transceiver simpler compared to QAM while achieving the same

ARPN Journal of Engineering and Applied Sciences



performance and spectral efficiency. The quality that have shown by CAP make it very popular for digital subscriber lines (DSLs) during mid and end of 1990s (A. F. Shalash *et al.* 1999 & G. H. Im *et al.* 1995) and were aimed for private consumers ADSL (J. J. Werner, 1992 & 1993).

As high speed electronics became more affordable and demands of bandwidth raised, there were strong efforts to put into exploiting the available bandwidth of deployed copper cables (J. Gao, 2002). However, CAP was proven to be very sensitive to non-flat spectral channels and required very complex equalizers (J. Gao *et al.* 1999), sacrificing the simplicity of CAP. Since then, CAP was pushed aside in favour of DMT modulation and was compared by (A. F. Shalash *et al.* 1996) for line equalization.

The interesting feature of CAP is the possibility to extend its signal basis to higher dimension, which were discussed by (I. Thng *et al.* 1999) and (A. F. Shalash *et al.* 1999) for DSLs application. Unfortunately, (X. Tang *et al.* 2003) was called for a question based on the unclear result that have been achieved by (I. Thng *et al.* 1999) in terms of spectral efficiency (SE). Not only that, published work on high dimensional CAP up to year 2007 (T. Collins et al., 2008), just focused on simulation results rather than realistic practical experiments. Thus, (M. B. Othman *et al.* 2012) was successfully proved it by demonstrating the multi-dimensional CAP modulation, while (G. Stepniak, 2014) had compared the efficiency of N-Dimensional CAP modulation.

In recent times, the idea for using CAP modulation has been refreshed in the field of optical networks (R. Rodes *et al.* 2011a) due to the possibility of generating the required orthogonal pulses by means of transversal filters and the potential high spectrum efficiency. The (M. Wieckowski *et al.* 2011) was demonstrated 2D-CAP 8-level per dimension (L/D) over 50 m long polymer optical fiber (POF) by using resonance cavity light emitting diode (RC-LED) with a spectral efficiency 4.6 bit/s/Hz. In the same year, (J. D. Ingham *et al.* 2011) was investigated 40 Gbps 2D-CAP 4-L/D with analogue transversal filter over standard single-mode fiber (SSMF) and compared with the NRZ modulation in terms of dispersion and power budget.

Additionally, in 2011, (R. Rodes *et al.* 2011a & 2011b) were introduced WDM system using directly modulated vertical cavity surface emitting lasers (DM-VCSELs) with 2D-CAP 4-L/D over 26 km of SSMF with a 4 bit/s/Hz of spectral efficiency. It was followed by (A. Caballero *et al.* 2011) which has proposed the use of 2D-CAP 2-L/D with the transmission of 8 Gbps over 1 km of MMF by using VCSEL as a light source.

## PRINCIPLE OF CAP MODULATION

Basically, the use of different signals as signature waveforms is a basic idea of the CAP system in order to modulate different data streams. The signature waveforms are generated by orthogonal shaping filters at the transmitter. While at the receiver, the matched filtering is used to reconstruct the individual data streams. The match filter used in the receiver has an impulse response which is the time domain inversion of the impulse response of the transmitter filter.

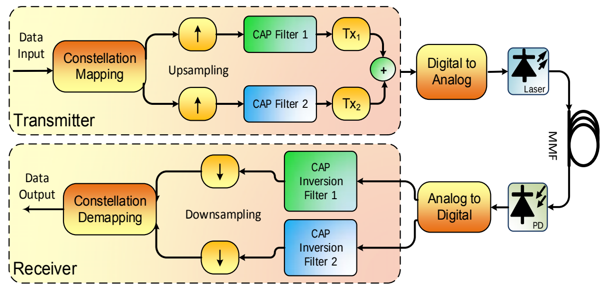


**Figure-1.** Block diagram of 2D-CAP transmitter and receiver.

A block diagram of 2D-CAP transmitter and receiver can be seen in Figure-1. According to the given constellation, data in the transmitter has to be mapped (encoded) by converting a number of raw data bits into a number of multi-level symbols. In order to achieve the desired waveform, these symbols are up-sampled and shaped by the CAP filters, at which forcing required transmission properties on the signals. Those properties include the limited bandwidth, zero cross channel interference (CCI), and zero inter-symbol interference (ISI), allowing for the perfect reconstruction (PR) at the receiver side.

For the 2-dimensional of the CAP modulation (2D-CAP), shaping filters use the properties of a well-known square-root raised cosine (SRRC) filter with zero-ISI, merged with the orthogonal properties of sine and cosine waveforms that has zero-CCI. Before components can be filtered, symbols have to be up-sampled in order to meet the sampling rate criterion. The sampling rate has to be at least two times higher than the highest frequency component of the generated signal. The usual up-sampling factors are 3 or 4, depending on the roll-off factor of the raised cosine (RC) filter used to design shaping filters. It has to be chosen properly in order to avoid any aliasing effects.

The most important part of the CAP system is a proper shaping filters. As mentioned before, basic CAP modulation format which is 2D-CAP employs a product of a SRRC with sine and cosine waveforms in order to achieve the PR in the receiver. SRRC filters are widely used for matched filtering. A combined response of two SRRC filters, which is transmitting and receiving filter, is the one of a RC filter. The raised cosine waveform can be expressed as in equation (1) and the SRRC waveform can be expressed as in equation (2), where T is a symbol period and α is the roll-off factor influencing the amount of the excess bandwidth.

$$h_{RC}(t) = \frac{\sin c\left(\frac{t}{T}\right)\cos\left(\frac{\pi\alpha t}{T}\right)}{1-4\left(\frac{\alpha t}{T}\right)^2} \quad (1)$$

VOL. 11, NO. 8, APRIL 2016 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

$$h_{SRRC}(t)=\frac{4\alpha}{\pi\sqrt{T}}\,\frac{\cos\left(\frac{(1+\alpha)\pi t}{T}\right)+\frac{T}{4\alpha t}\sin\left(\frac{(1-\alpha)\pi t}{T}\right)}{1-\left(\frac{4\alpha t}{T}\right)^{2}} \tag{2}$$

The roll-off factor for baseband systems can be expressed as in equation (3), where $W$ is a bandwidth used by the signal and $1/2T$ is a minimum bandwidth required for the baseband signal with the symbol rate of $T$. for the passband modulations, this formula is different, where $1/2T$ is changed into $1/T$ in order to allocate frequency space for positive as well as negative sideband of the signal.

$$\alpha=\frac{W-\frac{1}{2T}}{\frac{1}{2T}} \tag{3}$$

RC and SRRC are baseband filters, at which suitable for shaping baseband signals such as PAM. With little alteration, those filters can be relocated into the passband and that is exactly what is done in the CAP systems. Continuous-time impulse responses of the CAP filters can be expressed as in equation (4) and (5), where $f_c$ is a frequency suitable for the passband filters. Filter $f_1$ is represents as the in-phase filter and filter $f_2$ is represents as the quadrature filter.

$$f_1=h_{SRRC}(t)\cos(2\pi f_c t) \tag{4}$$

$$f_2=h_{SRRC}(t)\sin(2\pi f_c t) \tag{5}$$

A pair of waveforms $f_1$ and $f_2$ constitute a Hilbert pair. Hilbert pair represents the two signals of the same magnitude response and a phase response shifted by $90^o$. Figure-2 presents the both impulse and the frequency response of the typical CAP filters with an up-sampling factor of 4. The resultant of two orthogonal signals are added and converted from digital to analog form. The combined frequency spectrum of 2D-CAP and added pulse shape in time domain are shown in Figure-3.

At the receiver side, the signals are converted back to digital form. The matched filter are created by reversing the order of coefficients in the filter to recover the original sequence of symbols. The symbols are then down-sampled and de-mapped (decoded), so that the original data can be recovered.

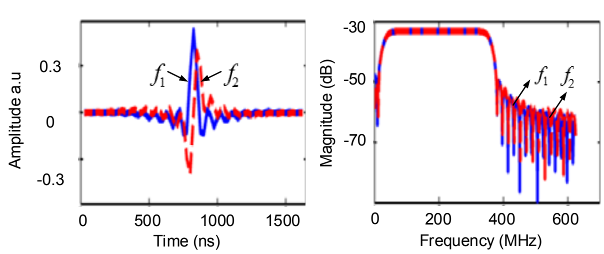


**Figure-2.** Impulse response and frequency response of 2D-CAP filter (M. B. Othman *et al.* 2012).

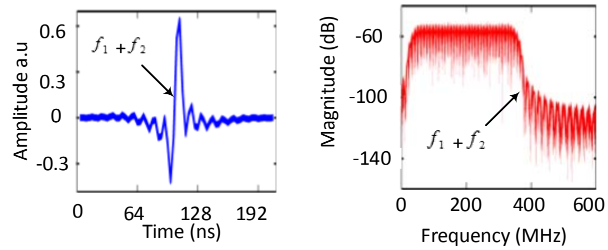


**Figure-3.** 2D-CAP added pulse response and combined frequency spectrum (M. B. Othman *et al.* 2012).

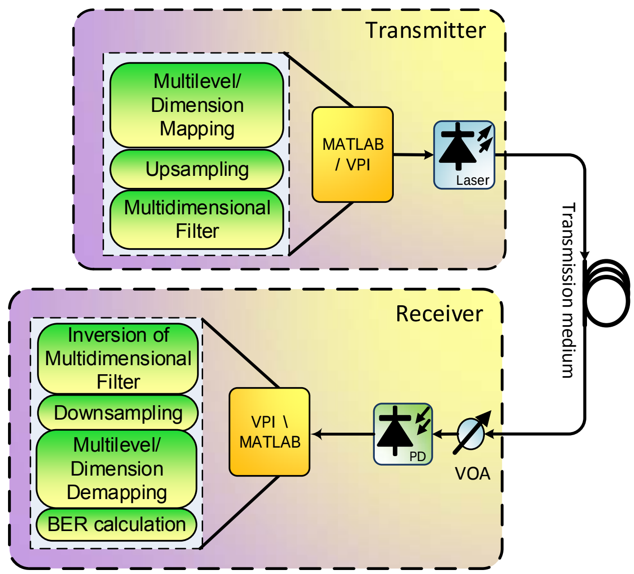


**Figure-4**. Simulation setup of 2D-CAP modulation.

## SIMULATION SETUP

The waveforms of the CAP modulation format has been programmed with the sampling rate of 5 GSa/s and 10 GSa/s. Figure-4 illustrated a simple network configuration of the CAP transmitter and receiver. The offline generated test signal is based on the pseudo random binary sequence (PRBS) with the length of $2^{15}–1$ in order to construct the CAP signal. According to the QAM constellation, data in the transmitter is mapped by converting a 1.25 Gbps and 2.5 Gbps of data bits into a number of multi-level symbols.

These symbols are up-sampled to 4 samples per symbol and use the CAP filters to shape it 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 from baseband to passband. All of this step will be performed in MATLAB and integrated with VPI software for the optical network design.

The 1550 nm single-mode vertical-cavity surface emitting laser (SM-VCSEL) are directly modulated with the CAP signal. The signal is then propagated through 20 km of singlemode fibre (SMF). For bit error rate (BER) measurements, a variable optical attenuator (VOA) is used

ARPN Journal of Engineering and Applied Sciences



and placed after the fibre. At the receiver, the photodetector (PD) is used to detect the signals directly. After that, the signals are stored for demodulation.

All the data that have been stored will be processed in MATLAB software. To retrieve the original sequence of symbols, the time inversions of the transmission filters are implemented. The symbols are down-sampled and de-mapped before the data can be recovered. Since the 7% forward error correction (FEC) overhead is taken into account, the transmission quality can be assessed using receiver sensitivity at a BER of 2.8 x $10^{-3}$.

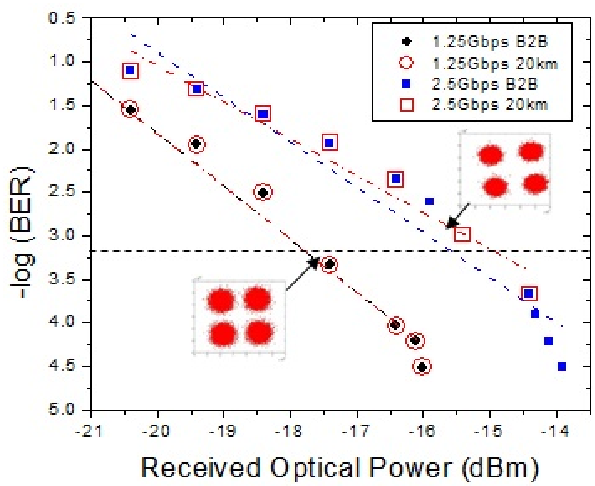


**Figure-5.** BER against received optical power (ROP) of D-CAP for 1.25 Gbps and 2.5 Gbps.

## RESULT

Data rate of 1.25 Gbps with 5 GSa/s sampling rate has been compared with 2.5 Gbps for sampling rate up to 10 GSa/s, as shown in Figure-5. The bit error rate (BER) against received optical power (ROP) was measured in order to compare the sensitivity. The solid symbols describe the optical back-to-back (B2B), while the hollow symbols describe the 20 km of SMF transmission.

The receiver sensitivity at FEC limit for B2B of both 1.25 Gbps and 2.5 Gbps is -18.3 dBm and -16.2 dBm, with the difference of 2.1 dB have been observed. After 20 km of transmission, a 2.5 dB difference was detected at the FEC limit with receiver sensitivity of -18.3 dBm and -15.8 dBm respectively.

All of the signals are successfully demodulated below FEC limit after transmission. This can be clearly seen in Figure-5, where the constellation diagram with a BER is approximately 1 x $10^{-3}$ after 20 km of SMF transmission.

## CONCLUSIONS

In this paper, we have programmed the CAP modulation format at different data streams and have been simulated by using VPI software for optical transmission. The CAP signals with 1.25 Gbps and 2.5 Gbps are successfully transmitted over 20 km of SMF with 1550 nm SM-VCSELs. 3.79 b/s/Hz and 7.58 b/s/Hz of spectral efficiency are reported for 2D-CAP of 1.25 Gbps and 2.5 Gbps respectively. The result shows that the feasibility and potential of CAP modulation format to deliver high data rate by employing simple baseband electronic design. In order to increase the spectral efficiency with the higher data rate, CAP signal requires excess bandwidth due to the higher up-sampling factor. All of these factors need to be considered in system design. However, CAP modulation format has higher possibility to increase the number of level as well as number of dimension with the absence of carrier.

## ACKNOWLEDGEMENTS

This work was fully supported by Fundamental Research Grant Scheme (Vot No.: 1416) and Universiti Tun Hussein Onn Malaysia (UTHM).

## REFERENCES

[1] F. Shalash and K. K. Parhi (1996). Comparison of discrete multitone and carrierless AM/PM techniques for line equalization. IEEE International Symposium on Circuits and Systems, pp. 560–563.

[2] F. Shalash and K. Parhi (1999). Multidimensional Carrierless AM/PM Systems for Digital Subscriber Loops. IEEE Trans. On Comm., vol. 47, no. 11, pp. 1655-1667.

[3] Anthony Ng'oma and Mike Sauer (2009). Radio-over-Fiber Systems for Multi-Gbps Wireless Communication. Proc. of SPIE-OSA-IEEE Asia Communications and Photonic, SPIE vol. 7632 76321I-1.

[4] Antonio Caballero, Tien Thang Pham, J. B. Jensen and Idelfonso Tafur Monroy (2011). Carrierless N-Dimensional Modulation Format for Multiple Service Differentiation in Optical In-home Networks. Proc. IPC, pp. 300-301, paper TuM4.

[5] D. D. Falcooner (1975). Carrierless AM/PM. in Bell Laboratories Technical Memorandum.

[6] E. A. Lee and D. G. Messerschmitt (1994). Digital Communication. Kluwer Academic Publishers, Norwell, Mass.

[7] G. H. Im, D. Harman, G. Huang, A. Mandzik, M. H. Nguyen, and J. J. Werner (1995). 51.84 Mbps 16-CAP ATM LAN Standard. J. Sel. Areas Comm., vol. 13, no. 4, pp. 620-632.

[8] Grzegorz Stepniak (2014). Comparison of Efficiency of N-Dimensional CAP Modulations. Journal of

Lightwave Technology, vol. 32, no. 14, pp. 2516-2523.

[9] I. Thang, X. Li, and C. Ko (1999). A New 3D CAP System. in Proc. IEEE TENCON, pp. 309-312.

[10] J. D. Ingham, R. V. Penty, I. H. White, and D. G. Cunningham (2011). 40 Gbps Carrierless Amplitude and Phase Modulation for Low-cost Optical Data Communication Links. Optical Fiber Comm. Conference and Exposition (OFC/NFOEC), p. OThZ3.

[11] J. Gao (2002). Equalisation for Carrierless Amplitude and Phase Modulation. Ph.D, Curtin University of Technology.

[12] J. Gao and Y. Leung (1999). A New Adaptive Equalizer for Carrierless Amplitude and Phase (CAP) Receiver. in ISCAS'99, Proceeding of the 1999 IEEE International Symposium on Circuit and Systems VLSI (Cat. No. 99CH36349), vol. 3, pp. 90-93.

[13] J. J. Werner (1992). Tutorial on Carrierless AM/PM-Part I: Fundamentals of digital CAP transmitter. AT&T Contribution to ANSI X3T9.5 TP/PMD.

[14] J. J. Werner (1993). Tutorial on Carrierless AM/PM-Part II: Performance of bandwidth efficient line codes. AT&T Contribution to ANSI X3T9.5 TP/PMD.

[15] J. L. Wei, L. Geng, D. G. Cunningham, R. V. Penty, and I. H. White (2012a). Comparisons between Gigabis NRZ, CAP and Optical OFDM Systems over FEC Enhanced POF Links Using LEDs. $14^{th}$ Int. Conf. Transparent Optical Netw., p. Tu.P.17.

[16] J. L. Wei, L. Geng, D. G. Cunningham, R. V. Penty, and I. H. White (2012b). Gigabit NRZ, CAP and Optical OFDM Systems over POF Links using LEDs. Opt. Exp., vol. 20, no. 20, pp. 22284-22289.

[17] M. B. Othman, X. Zhang, L. Deng, M. Wieckowski, J. B. Jensen, and I.T. Monroy (2012). Experimental Investigations of 3D/4D-CAP Modulation with DM-VCSELs. IEEE Photonics Technology Letters, vol. 24, no. 22, pp. 2009-2012.

[18] M. Wieckowski, J. B. Jensen, I. Tafur Monroy, J. Siuzdak, and J. P. Turkiewicz (2011). 300 Mbps Transmission with 4.6 bit/s/Hz Spectral Efficiency over 50m PMMA POF Link using RC-LED and Multilevel Carrierless Amplitude Phase Modulation. Optical Fiber Comm. Conference and Exposition (OFC/NFOEC), p. NTuB8.

[19] Miguel Iglesias Olmedo, Tianjian Zuo, Jesper Bevensee Jensen, Qiwen Zhong, Xiaogeng Xu, Sergei Popov, and Idelfonso Tafur Monroy (2013). Multiband Carrierless Amplitude Phase Modulation for High Capacity Optical Data Links. Journal of Lightwave technology, vol. 9, no. 9, pp. 1-8.

[20] Roberto Rodes, Marcin Wieckowski, Thang Tien Pham, Jesper Bevensee Jensen, Jarek Turkiewicz, Jerzy Siuzdak and Idelfonso Tafur Monroy (2011a). Carrierless Amplitude Phase Modulation of VCSEL with 4bit/s/Hz Spectral Efficiency for Use in WDM-PON. Optics Express, Vol.19, No.27.

[21] Roberto Rodes, Marcin Wieckowski, Thang Tien Pham, J. B. Jensen and Idelfonso Tafur Monroy (2011b). VCSEL-based DWDM PON with 4 bit/s/Hz Spectral Efficiency using Carrierless Amplitude Phase Modulation. ECOC Technical Digest, Optical Society of America, 978-55752-932-9.

[22] T. Collins (2008). Carrierless Amplitude Phase Modulation. Handbook of Computer Networks: Key Concepts, Data Transmission, and Digital and Optical Networks, John Wiley and Sons.

[23] Xiaosong Tang, Ian Li-Jin Thng, and Xinrong Li (2003). A New Digital Approach to Design 3D CAP Waveforms. IEEE Transactions on Communications, vol. 51, no. 1.