# A Carrierless Amplitude Phase (CAP) Modulation Format: Perspective and Prospect in Optical Transmission System

**N. M. Ridzuan, M. F. L. Abdullah, M. B. Othman, M. B. Jaafar**
Department of Communication Engineering, Faculty of Electrical and Electronic Engineering,
Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Batu Pahat, Johor, Malaysia

## ABSTRACT

The explosive demand of broadband services nowadays requires data communication systems to have intensive capacity which subsequently increases the need for higher data rate as well. Although implementation of multiple wavelengths channels can be used (e.g. $4 \times 25.8$ Gb/s for 100 Gb/s connection) for such desired system, it usually leads to cost increment issue which is caused by employment of multiple optical components. Therefore, implementation of advanced modulation format using a single wavelength channel has become a preference to increase spectral efficiency by increasing the data rate for a given transmission system bandwidth. Conventional advanced modulation format however, involves a degree of complexity and costly transmission system. Hence, carrierless amplitude phase (CAP) modulation format has emerged as a promising advanced modulation format candidate due to spectral efficiency improvement ability with reduction of optical transceiver complexity and cost. The intriguing properties of CAP modulation format are reviewed as an attractive prospect in optical transmission system applications.

*Corresponding Author:*

N. M. Ridzuan,
Department of Communication Engineering,
Faculty of Electrical and Electronic Engineering,
Universiti Tun Hussein Onn Malaysia,
86400 Parit Raja, Batu Pahat, Johor, Malaysia.
Email: noridah.mohdridzuan@gmail.com

## 1. INTRODUCTION

Today's information transmission process relies on data communication system that can provide larger bandwidth at high-speed access due to rapid expansion of communication services such as fast internet communication, video-based multimedia, on-line gaming, etc. Multiple wavelength channels in optically routed network can be used for implementing transceiver modules in order to enhance system capacity and data rate [1]. Mixed modulation format has been implemented for wavelength division multiplexing (WDM) system but there are critical issues to conquer such as nonlinear crosstalk from adjacent channels and the cost increment of the mixed WDM signal control [2].

The demand for cost-effective system through reduction of the optical components used in the system requires the minimal number of wavelengths. Hence, implementing advanced modulation format can be a potential option to avoid complexity and significant costs of optoelectronic devices while further increase spectral efficiency.

Advanced modulation schemes such as *M*-ary phase shift keying (*M*-PSK), *M*-ary quadrature amplitude modulation (*M*-QAM), discrete multitone (DMT) and orthogonal frequency division multiplexing (OFDM) [3] has been explored extensively. New advanced multilevel modulation formats has been reported to show that there are many technical solutions available for the next generation optical communication

system [4]. But apparently, all these advanced modulation formats involve complicated and costly transmission system. The optical transmission system will be more feasible and efficient if the employment of advanced modulation formats can reduce the complex portion of the system while simultaneously achieve higher bit rates and spectral efficiency using relatively reduced optoelectronic components count.

Therefore, carrierless amplitude phase (CAP) modulation format can be highlighted as a potentially good choice to build up flexible, less complexity and cost-effective transmission system for optical access and in-home network system. CAP modulation is a multilevel and multidimensional modulation scheme that resembles quadrature amplitude modulation (QAM) at a point where it transmits concurrently two input data streams. But the significant difference between them is CAP uses transversal filters with orthogonal impulse response to generate in-phase and quadrature filters to separate that respective data streams instead of using carrier in order to do so.

This means CAP does not rely on local oscillator for carrier generation, complex mixers and optical IQ modulator. The absence of carrier leads to less expensive digital transceiver implementation as the computation intensive multiplication operations needed for carrier modulation and demodulation becomes unnecessary. Consequently, it makes CAP simpler than single carrier modulation format such as QAM while achieving similar spectral characteristic and performance. Multi carrier modulation format like DMT and OFDM are practically much more complex because inverse fast Fourier transform (IFFT) and fast Fourier transform (FFT) are required at the transmitter and receiver part for modulation and demodulation process.

This paper reviews the privilege properties of CAP that has open up a growing interest of researches to choose and implement CAP modulation format in optical communication link applications. Comparison between CAP and other modulation formats has been carried out substantially in previous work to prove the competitive performance of CAP. Its convincing potential performance can be a good prospect for next generation access and in-home network environment.

## 2. PRINCIPLE OF CAP MODULATION FORMAT
### 2.1. 2D-CAP

The block diagram of CAP transmission system is shown in Figure 1. At the transmitter part, an original bits sequence length of data stream which is based on the pseudo random binary sequence (PRBS) is transmitted. This bits sequence are encoded and mapped according to the given constellation by converting it into a number of multi-level symbols of $M$-QAM with $M = 2k$ where $k$ is the number of bits/symbol. For example, $k$ is equal to 2 for 2D-CAP-4.

These mapped symbols are split and upsampled to 4 samples per symbol to match the sample rate of shaping filters. The in-phase, $I_k$ and quadrature, $Q_k$ component which are extracted from the upsampled sequence are shaped by the digital shaping filters in order to achieve square-root raised cosine (SRRC) waveforms. The impulse responses of the filters are given by multiplying these SRRC waveforms with sine or cosine waveforms to achieve orthogonality between them. The waveforms of each filter which is then moved from baseband to passband are given by:

$$f_1(t) = g_{SRRC}(t)\cos 2\pi f_c t \tag{1}$$
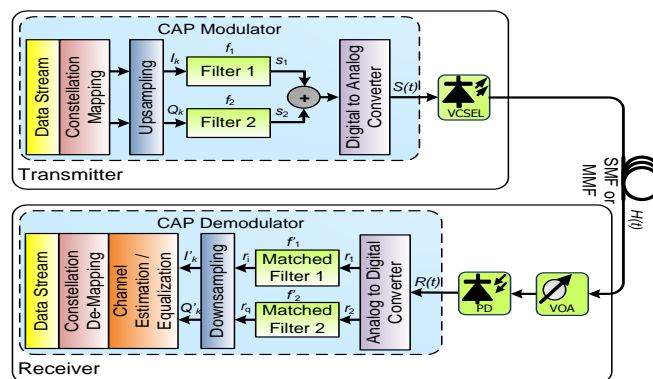
$$f_2(t) = g_{SRRC}(t)\sin 2\pi f_c t \tag{2}$$



Figure 1. CAP systems

$f_c$ is a frequency suitable for the passband filters. The pair of modulated waveforms $f_1$ and $f_2$ constitutes a Hilbert pair and denotes in-phase and quadrature filter with phase responses $90°$ apart from each other. Figure 2(a) and 2(b) present the impulse response of the CAP filters in time domain. The resultant signals after the in-phase, $I_k$ and quadrature, $Q_k$ component being shaped by CAP filter are:

$$s_1 = I_k \otimes f_1(t) \tag{3}$$

$$s_2 = Q_k \otimes f_2(t) \tag{4}$$

These two orthogonal signals are summed and converted to analog signal using digital to analog converter. The output CAP signal transmitted can be represented as:

$$S(t) = \sum_{k=-\infty}^{\infty} [I_k \otimes f_1(t-kT)] - [Q_k \otimes f_2(t-kT)] \tag{5}$$

where $T$ indicates the symbol duration and $\otimes$ denotes convolution. Figure 2(c) shows the combined frequency spectrum of CAP.
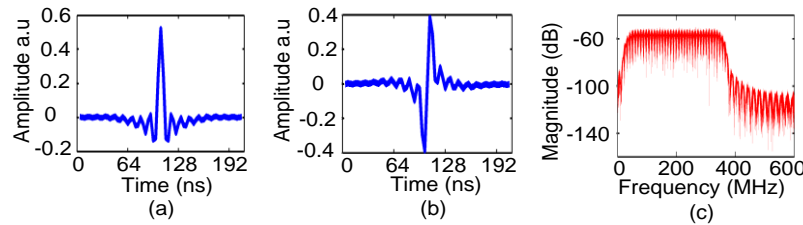


Figure 2. (a) Impulse response of Filter 1, $f_1$ (b) Impulse response of Filter 2, $f_2$ (c) Combined frequency spectrum, $S(t)$

After direct detection at the receiver part, the convolution process between CAP signal $S(t)$ and $H(t)$ as channel responses (without considering noises) produces the received signal $R(t)$:

$$R(t) = S(t) \otimes H(t) \tag{6}$$

The received signal, $R(t)$ is then converted from analog to digital signal. This signal is separated to two signals, $r_1$ and $r_2$ before being fed into two matched filters, $f'_1$ and $f'_2$ that have time-inversion impulse response of the orthogonal filters at the transmitter side. The output signals of both matched filters can be written as:

$$r_i = r_1 \otimes f'_1(t) \tag{7}$$

$$r_q = r_2 \otimes f'_2(t) \tag{8}$$

where $f'_1(t) = f_1(-t)$ and $f'_2(t) = f_2(-t)$. The matched filters recover each dimension and the original sequence of symbols. These symbols are downsampled to form $I'_k$ and $Q'_k$ component. A linear equalizer is employed afterwards to ensure synchronization in CAP demodulation part due to the serious intersymbol interference (ISI) caused by matched FIR filters with timing error. Then, a decoder is utilized and demapped to retrieve the original bit sequence.

## 2.2. High Dimensionality CAP

High dimensionality CAP employs more than two filter responses where the numbers of orthogonal filters used indicates the numbers of dimensions. The numbers of dimensions correspond to different users and services. According to dimensionality theorem [5], with the symbol interval $T$, minimum bandwidth $W$ and modulation dimensionality $N$:

$$2WT = N \tag{9}$$

If $N = 1$, the bandwidth $W = 1/2T$ as Nyquist theorem. However, for 2-D and 3-D case, the minimum bandwidth required are $W = 1/T$ and $W = 3/2T$ respectively.

This shows that increment of dimensionality will increase the occupied signal bandwidth. On the other hand, the required sample/symbol ratio is linearly proportional to the number of dimensions [6]. This means the up-sampling factor must be increased to support an increased number of dimensions.

Therefore, it is impossible to improve spectral efficiency (SE) by just simply increase the dimensionality because the symbol rate must be decreased if wish to maintain the signal bandwidth or to increase the up-sampling factor. The unavoidable increase of signal bandwidth accompanying the increase of dimension number compensates the higher number of symbols in the alphabet and leads to the same SE of CAP modulations irrespective of the dimensionality [7]. However, the advantage of additional dimensions lies in the possibility to flexibly allocate different services to different users [6].

As mentioned in previous sub section, 2D-CAP uses Hilbert pair modulated waveforms in order to achieve two orthogonal filters at the transmitter and its inversion or matched filters at the receiver. However, this Hilbert pair modulated waveform cannot be applied for higher dimensionality CAP. Hence, other method is required to develop a new set of filters for higher dimensionality CAP system.

The method which is formerly known as minimax optimization procedure was first introduced for high dimensionality CAP [6]. This method was later improved and modified to overcome design flaws in previous work [8]. This new method is also a straightforward way to extend this approach to design 4D or higher dimensional CAP systems.

The shaping filter at the transmitter and its matched filter at receiver must satisfy perfect reconstruction (PR) condition to avoid inter-dimensional crosstalk. To assure the PR of the filters, the new optimization algorithm (OA) has been applied to extend the conventional 2D-CAP scheme to higher dimensionality. The new optimization algorithm (OA) is described as follows [8]:

$$\min_{f1,f2,f3,...fN} \max\left(\left|F_{1,HP}\right|, \left|F_{2,HP}\right|, \left|F_{3,HP}\right|,..\left|F_{N,HP}\right|\right) \tag{10}$$

where $F_i$ is a discrete Fourier transform (DFT) of vector $f_i$. The high pass (HP) subscript denotes the out-of-band portion of the transmitter response above the boundary frequency, $f_B$ to ensure the transmitters and receiver's frequency magnitude response will be matched to each other. (10) subject to perfect reconstruction (PR) condition:

$$P(f_i)f'_i = \tilde{\delta} \qquad\qquad i \in \{1,2,3,...N\} \tag{11}$$

$$P(f_i)f'_j = \tilde{0} \qquad\qquad i,j \in \{1,2,3,...N\} \tag{12}$$

where

$$f'_i = \text{inverse}[f_i] \qquad\qquad i \in \{1,2,3,...N\} \tag{13}$$

The variables $f_i$ and $f'_j$ are the vector form represents the CAP transmitter and receiver finite impulse response (FIR) filters respectively. $P(f_i)$ is a shift matrix operating on vector $f_i$, where the shift is by the upsampling factor. $\tilde{\delta}$ is a vector with one unity element and zeroes elsewhere while $\tilde{0}$ is a vector of all zeroes. The constraint in (13) requires the receiver to be the matched filter of the transmitter.

There is some minimum bandwidth, $f_{B,min}$ value that will allow the PR condition. Any value smaller than $f_{B,\,min}$ will not result in any PR solution. For a 3D-CAP system, the minimum bandwidth required is $3/2T$ which resulting from (9) in order to achieve PR condition. Therefore, the boundary frequency, $f_B$ must be at least equal to or bigger than $3/2T$.

Figure 3 shows the 3D-CAP or 4D-CAP system. Data in the transmitter is mapped according to the given constellation by converting a number of raw data bits into a number of multi-level symbols. These symbols are upsampled and shaped by the digital finite impulse response (FIR) shaping filters to achieve the

desired waveforms. After optimization algorithm (OA) to ensure the PR condition of the filters, these signals are added and converted to analog signal before transmitted as a CAP signal:

$$S(t) = \sum_{i=1}^{N} x_i \otimes f_i$$

(14)

where $x_i$ denotes the signal after upsampling process with subscript i denotes the dimension.
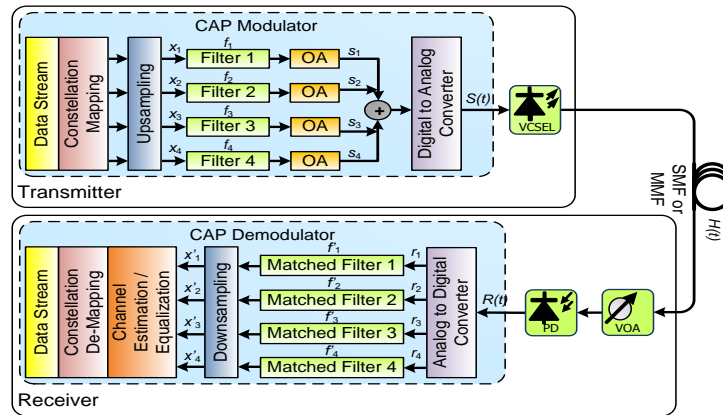


Figure 3. 3D or 4D-CAP systems

After conversion to digital signal at the receiver, the dimension of the signal is recovered by filters that matched to the shaping filters at transmitter. The signal from the filters is downsampled to form $x'_i$ where then equalized and decoded to retrieve original data stream.

### 2.3. Multiband CAP (MultiCAP)

The basic concept of Mutiband CAP (MultiCAP) counts on dividing the signal into independent smaller sub-bands that represent different frequency bands. This means that the signal power and modulation order can be assigned freely to the SNR in each sub-band while increasing the flexibility of the total throughput in comparison to conventional CAP.

In MultiCAP systems, each sub-band are assigned for each users using distinct shaping filter pairs at the transmitter, and the users can retrieve their original data back using the matched filter pair at the receiver. In this way, N sub-bands can be assigned to N users without any interference. As illustrated in Figure 4, MultiCAP employs more than one filter pair for each data stream. The individual data stream in MultiCAP complies with 2D-CAP modulation operation principle as stated in previous sub section.
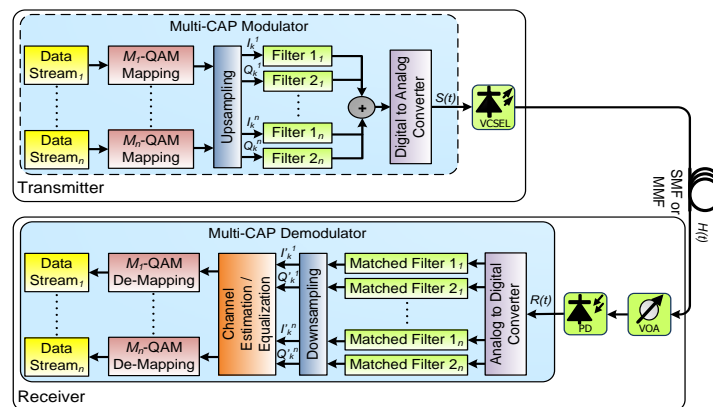


Figure 4. MultiCAP systems

*A Carrierless Amplitude Phase (CAP) Modulation Format: Perspective and Prospect in .... (N. M. Ridzuan)*

Each data stream is separately mapped into the multilevel symbols of *M*-QAM. The signal is upsampled before being split into the real and imaginary parts, $I_k$ and $Q_k$ before filtering. The pair of modulated signal waveform (1) and (2) form a Hilbert pair that denotes in-phase and quadrature filters. The impulse response of the filters are given as the product of a square root raised cosine (SRRC) filter and a cosine (real) or sine (imaginary) wave with frequency at least twice that of the pulse width of the SRRC filter. The output of each filter is real-valued and summed to form the time domain signal for transmission. The output signal *S(t)* is given by:

$$S(t) = \sum_{i=1}^{n} \left[ I_k^i \otimes f_1^i(t - kT) \right] - \left[ Q_k^i \otimes f_2^i(t - kT) \right]$$

(15)

where $T$ indicates the symbol duration and $\otimes$ denotes convolution. $I_k^i$ and $Q_k^i$ are the in-phase and quadrature *M*-QAM mapped symbols from the upsampled sequence on the *i*-th subcarrier while $f_1^i$ and $f_2^i$ are the in-phase filter and quadrature filter of the *i*-th subcarrier respectively.

The received signal will pass through the time-inversed in-phase and quadrature receiver filters which are matched to the corresponding transmitter filter. The signal is then downsampled, equalized and de-mapped to obtain the transmitted signal.

## 3.    CAP MOTIVATION

Carrierless amplitude phase (CAP) modulation format or formerly known as carrierless AM/PM was proposed in mid-1975 by the Bell Labs as a viable modulation technique for high-speed communication links over copper wires [9]. CAP is merely getting attention and become popular during early and mid-1990s with the dawn of the digital subscriber loop (DSL) techniques that were aimed for private consumers asymmetric digital subscriber line (ADSL) [10], [11].

The quality shown by CAP has put an interest to be implemented in asynchronous transfer mode (ATM) local area networks (LAN) standard application [12]. Consequently, CAP has been adopted primarily and widely used for ADSL and ATM LANs because of its high bandwidth efficiency and low implementation costs. CAP was proven to be very sensitive to non-flat spectral channels and required very complex equalizers [13], sacrificing the simplicity of CAP. Since then, CAP was pushed aside in favor of DMT modulation by international telecommunications union (ITU) [14].

However, for high speed transmission, CAP modulation has been demonstrated to be simpler and has better performance than discrete multitone (DMT) [15]. Multi carrier modulation format like DMT is much more complex compared to CAP where inverse fast Fourier transform (IFFT) and fast Fourier transform (FFT) are needed in modulation and demodulation process while on the other hand, CAP uses a filter or digital convolution with less computational complexity.

The interesting feature of CAP is the possibility to extend its signal basis to higher dimension for DSL application [6], [16]. It shows that CAP supports modulation in more than two dimensions whereas orthogonal pulse shapes can be identified to provide multiple services application. For high dimensionality CAP, the optimization algorithm (OA) has been used to extend the conventional 2D-CAP scheme to higher dimensionality and to assure perfect filter reconstruction [8].

High dimensionality 3D-CAP and 4D-CAP with directly modulated vertical cavity surface emitting lasers (DM-VCSELs) over 20 km SSMF has been experimentally demonstrated for the first time to provide more flexibility in optical fiber systems [17]. However, it requires excessive bandwidth due to the higher upsampling factor that resulting to decreased spectral efficiency performance. This tradeoff between the flexibility and spectral efficiency needs to be considered in the system design. Nevertheless, CAP modulation with higher dimension is useful and highly beneficial for service and user allocation in WDM optical access [18]. The results indicate the prospects of combining the orthogonal division multiple access (ODMA) in WDM network for service and user allocation.

In order to extend the bandwidth of each channel for high speed data transmission, multi-level multi-band CAP (MultiCAP) or m-CAP modulation format (where m is the number of subcarriers or sub-bands) has been introduced by dividing the CAP signal into smaller sub-bands [19], [20]. The use of carrierless amplitude phase (CAP) in a novel multiband approach (MultiCAP) for high capacity optical data links manage to extend the system capacity to 102.4 Gb/s over 15 km of SSMF. The result achieves record spectral efficiency, increases tolerance towards dispersion and bandwidth limitations, and reduces the complexity of the transceiver.

The transmission distance for high speed CAP is limited due to spectrum fading effect caused by chromatic dispersion. Optical single-side band (OSSB) technology is a good solution against spectrum fading effect. Therefore, the first demonstration of MultiCAP in WDM-CAP-PON based on OSSB for multi-users access network has been reported [21]. The experiment successfully transmits 11 channels, 55 sub-bands for 55 users at 10 Gbps downstream data rate per user over 40 km SMF.

## 4.    CAP PROSPECT IN OPTICAL COMMUNICATION SYSTEM

In recent years, there is growing interest to implement CAP modulation format in various optical communication system application. Numerous comparisons between CAP and other modulation scheme also have been reported to show how CAP modulation format manage to outperforms others.

For the first time, high speed of 40 Gb/s 2D-CAP-16 modulation over 10 km standard single mode fiber (SSMF) has been shown to provide significant dispersion advantages compared to non-return-to-zero (NRZ) modulation [22]. It proves the feasibility of generating and decoding 40 Gb/s CAP channels using current low-cost transversal filters. The comparison of CAP and DMT modulation using DM-VCSELs has been carried out experimentally over MMF. As shown in Figure 5 [23], CAP displays 0.7-1.1 dB better sensitivity and performance than DMT. Spectral efficiencies of 3.79 b/s/Hz and 2.91 b/s/Hz are reported for CAP-16 at 1.25 Gb/s and 16-QAM-DMT at 909.2 Mb/s respectively. Spectral efficiency for DMT is reduced due to the addition of the cyclic prefix and training sequence. From this comparison, it is believed that CAP can be viewed as an attractive alternative modulation format for optical in-home networks.



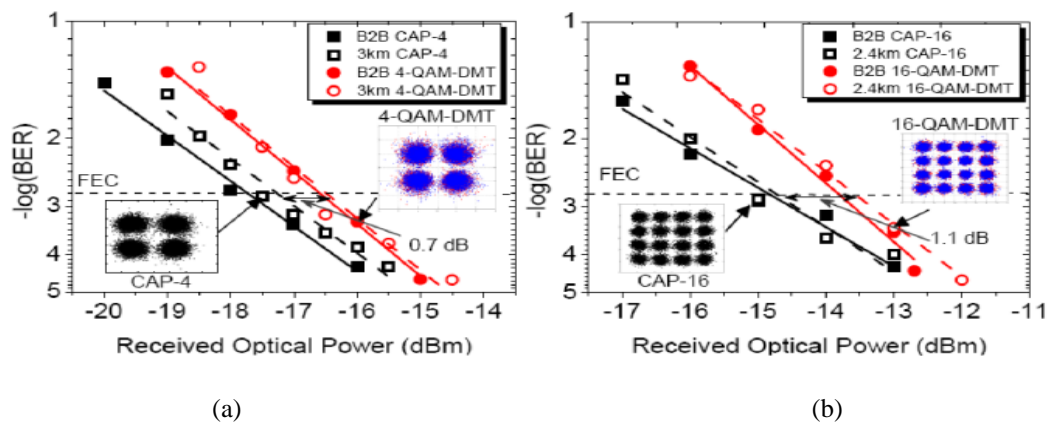(a)                                                                (b)

Figure 5. BER vs received optical power (ROP) (a) CAP-4 and 4-QAM-DMT (b) CAP-16 and 16-QAM-DMT

Theoretical investigations have been intensively analyzed to compare the link power budget and power dissipation of non-return-to-zero (NRZ), PAM-4, CAP-16 and 16-QAM-OFDM systems for data communication applications [24], [25]. The results show that for lengths up to 30 km of SMF, the 2D-CAP-16 scheme without forward error correction (FEC) offer good performance and have half the power consumption of optical orthogonal frequency division multiplexing (OOFDM) schemes at 28 Gb/s data rate.

Then the comparison of link power budget and power dissipation has been extended between 100Gb/s CAP-16/64 and 16/64-QAM-OFDM systems over 2 km FEC enhanced SMF links using directly modulated lasers (DML) [26], [27]. Simulation results showed that these schemes, incorporating FEC and decision feedback equalisation (DFE), single channel CAP-16 and 16-QAM-OFDM can support transmission over >5 km of SMF, with transceiver power dissipation of about 2 times that of the 4x25 Gb/s NRZ version of 100 Gigabit Ethernet. But CAP schemes which do not require DAC/ADCs have great potential for cost-effectiveness and power efficiency.

Step-index polymer optical fibers (SI-POF) are particularly an attractive transmission medium for high speed in-home optical network system application due to easy installation and low cost properties [28]. POF links use light emitting diode (LED) as an optical source to continuously sustain the system cost-effectiveness, ease system installation and maintenance. The main challenge arises in the LED-based SI-POF link is to further increase the system capacity due to limited bandwidth of LED and SI-POF itself.

A straightforward way to increase system capacity is to improve system spectral efficiency by allowing the same bit rate to be transmitted using a reduced bandwidth. In this case, employing simple

implementation of CAP modulation format in SI-POF link can be an appealing approach to increase bandwidth efficiency while maintaining an overall low complexity and relatively low energy cost system.

For this reason, a record high error free transmission without feed forward error correction (FEC) over 50 m SI-POF link at 1.5 Gbps is experimentally demonstrated where the 2D-CAP-64 scheme is shown to generally gives a higher system margin than NRZ modulation using a low-cost commercially resonant cavity light emitting diode (RC-LED) [29].

Comparisons between gigabit NRZ, CAP and Optical OFDM systems over FEC enhanced 50 m POF links at 2.1 Gbps using LEDs has been performed. Figure 6 [30], [31] shows a plot of the maximum bit rate versus POF length for NRZ, CAP and Optical OFDM systems. For all the modulation schemes, the bit rate decreases with increasing POF length, simply due to increased fiber dispersion. However, the results show that CAP-64 outperforms both NRZ and 64-QAM-OFDM scheme for all POF lengths and supports record high 3.5 Gb/s bidirectional and 2.1 Gb/s unidirectional transmission over 50 m POF link. The unidirectional 2.1 Gb/s transmission over 50 m POF achieved by CAP-64 represents an improvement of 70% in capacity compared with the published best performance of 1.25 Gb/s NRZ signal over 50 m POF unidirectional transmission [32].

CAP-64 modulation also consumes similar transceiver power compared with NRZ modulation whilst 64-QAM-OFDM consumes double that. This indicates that CAP-64 modulation offers great potential in terms of signal capacity and power efficiency for LED based POF links.
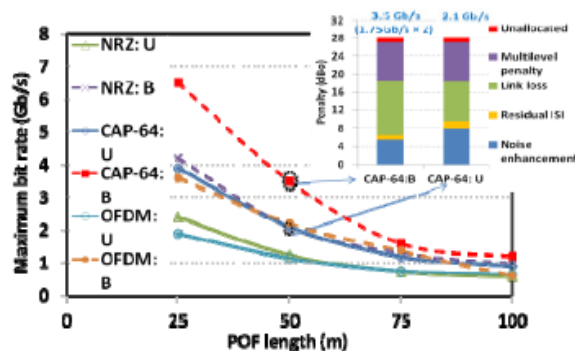


Figure 6. Maximum bit rates versus POF length. U: Unidirectional; B: Bidirectional

On the other hand, comparison between CAP and PAM modulation schemes for data transmission over SI-POF has been carried out [33]. Using 2D-CAP-16 over 50 m SI-POF link at 5 Gbps, the measurement results show that $M$-CAP offering potentially the same spectral efficiency as a corresponding $M$-PAM modulation format and provides a slightly better performance when the signal-to-noise ratio (SNR) is high enough.

LED-based visible light communication (VLC) has attracted considerable interests in recent years as an alternative wireless communication technique in next-generation indoor wireless LAN in regards with LED capability to simultaneously provide illumination and communication. VLC using white LEDs offers many advantages for home area networking and next-generation short-range wireless access, such as worldwide availability, high security, immunity to radio frequency interference, and spatial reuse of the modulation bandwidth in adjacent communication cells [34]. High spectrally efficient modulation format like CAP can be a direct method to increase the capacity due to severe bandwidth limitation caused by LED in VLC system.

Performance comparison between CAP signal and OFDM signal over high capacity RGB-LED-based WDM visible light communication (VLC) on 25 cm air-transmission has been made [35]. The maximum aggregate data rates of CAP and OFDM are 3.22 and 2.93 Gb/s, respectively, shows the CAP scheme gives competitive performance and provides an alternative spectrally efficient modulation for next generation optical wireless networks compared to OFDM.

Comparison of PAM, CAP and DMT modulation in a VLC link using white phosphorescent light-emitting diode (LED) has been reported [36]. At data rates of 450 Gbps on 30 cm air-transmission, 2-level PAM and CAP modulations exhibit better immunity to nonlinear distortions and allow for lower BER than their 4-level counterparts. DMT performance, however, was substantially worse than the performance of 2-level modulations.

## 5.    CONCLUSION

This paper reviews the employment of CAP modulation format in various optical communications applications. Recently, CAP modulation format has gained serious interest in the research community due to its intriguing properties such as high spectral efficiency, scalability to higher order modulation, potentially low cost implementation and simplicity compare to modulation formats with carrier. The flexibility to extend the number of CAP orthogonal filters for higher dimensional CAP can potentially be utilized to allocate different services to different users.

Numerous papers have investigated the employment of CAP modulation format in new Ethernet standards, visible light communications (VLC), single mode fiber (SMF), multimode fiber (MMF) and polymer optical fiber (POF) link. Comparison of CAP against other modulation format also has been demonstrated and the results show that CAP can be an alternative modulation format candidate with competitive performance in optical transmission system applications.

However, the significant drawback of CAP system is that it requires a flat channel frequency response. The non-flat frequency response of the transmission system will significantly degrade the system performance. Therefore, further research need to be carried out to implement more advance equalization techniques in order to mitigate such impairments.

Other drawback of CAP is difficulties to further improve system spectral efficiency. The utilization of high dimensional CAP requires high upsampling factor thus limits the overall achievable spectral efficiency. Continuous effort also must be taken into account to improve CAP receiver which is highly sensitive to timing errors, high susceptibility to symbol timing offset and jitter. With further improvement of the CAP system, it is worth mentioning that CAP deserves further attention for next generation optical access, in-home and wireless network.

## REFERENCES

[1]    L. Tao, Y. Ji, J. Liu, A. P. T. Lau, N. Chi, and C. Lu, "Advanced modulation formats for short reach optical communication systems," *IEEE Netw.*, vol. 27, no. 6, pp. 6–13, 2013.
[2]    L. Li, W. Jian-yi, Z. Xiu-tai, and L. Hong-an, "Research on Mixed Data Rate and Format Transmission in WDM Networks," vol. 11, no. 1, 2013.
[3]    B. U. Rindhe, J. Digge, and S. K. Narayankhedkar, *"Implementation of optical OFDM based system for optical networks,"* 2014 Int. Conf. Adv. Commun. Comput. Technol. (ICACACT 2014), vol. 4, no. Cd, pp. 1–9, 2014.
[4]    T. Tokle, M. Serbay, J. B. Jensen, W. Rosenkranz, and P. Jeppesen, *"Advanced modulation formats for transmission systems,"* Opt. Fiber Commun. Fiber Opt. Eng. Conf., p. OMI1, 2008.
[5]    J. G. Proakis, Digital Communications, 4th ed. New York, NY, USA: McGraw-Hill, 2000.
[6]    A. F. Shalash and K. K. Parhi, "Multidimensional carrierless AM/PM systems for digital subscriber loops," *IEEE Trans. Commun.*, vol. 47, no. 11, pp. 1655–1667, 1999.
[7]    G. Stepniak, "Comparison of Efficiency of N -Dimensional," vol. 32, no. 14, pp. 2516–2523, 2014.
[8]    X. Tang, I. L. J. Thng, and X. Li, "A new digital approach to design 3-D CAP waveforms," *IEEE Trans. Commun.,* vol. 51, no. 1, pp. 12–16, 2003.
[9]    D.D. Falconer, "Carrierless AM/PM," Bell Lab. Tech. Memo., 1975.
[10]    J. J. Werner, *"Tutorial on Carrierless AM/PM-Part I: Fundamentals of digital CAP transmitter,"* AT&T Contrib. to ANSI X3T9.5 TP/PMD, 1992.
[11]    J. J. Werner, *"Tutorial on Carrierless AM/PM-Part II: Performance of bandwidth efficient line codes,"* AT&T Contrib. to ANSI X3T9.5 TP/PMD, 1993.
[12]    G. H. Im, D. D. Harman, G. Huang, A. V. Mandzik, M. H. Nguyen, and J. J. Werner, "51.84 Mb/s 16-CAP ATM LAN standard," *IEEE J. Sel. Areas Commun.,* vol. 13, no. 4, pp. 620–632, 1995.
[13]    J. Gao and Y. H. Leung, *"A new adaptive equalizer for carrierless amplitude and phase (CAP) receivers,"* ISCAS'99. Proc. 1999 IEEE Int. Symp. Circuits Syst. VLSI (Cat. No.99CH36349), vol. 3, pp. 90–93, 1999.
[14]    I. T. U. Itu-T, "G.992.1 - Asymmetric digital subscriber line (ADSL) transceivers," 1999.
[15]    A. Shalash and K. K. Parhi, *"Comparison of discrete multitone and carrierless AM/PM techniques for line equalization,"* IEEE Int. Symp. Circuits Syst. Circuits Syst. Connect. World. ISCAS 96, vol. 2, pp. 560–563, 1996.
[16]    I. Thng, X. Li, and C. C. Ko, "A New 3D CAP System," no. 1, pp. 309–312, 1999.
[17]    M. B. Othman, X. Zhang, L. Deng, M. Wieckowski, J. B. Jensen, and I. T. Monroy, "Experimental investigations of 3-D-/4-D-CAP modulation with directly modulated VCSELs," *IEEE Photonics Technol. Lett.,* vol. 24, no. 22, pp. 2009–2012, 2012.
[18]    M. B. Othman, X. Zhang, J. B. Jensen, and I. T. Monroy, "Using CAP Dimensionality for Service and User Allocation for Optical Access Networks," vol. 1, pp. 5–7, 2012.
[19]    M. I. Olmedo, Z. Tianjian, J. B. Jensen, Z. Qiwen, and X. Xiaogeng, *"Towards 400GBASE 4-lane Solution Using Direct Detection of MultiCAP Signal in 14 GHz Bandwidth per Lane,"* Opt. Fiber Commun. Fiber Opt. Eng. Conf., p. PDP5C.10, 2013.
[20]    M. I. Olmedo, T. Zuo, J. B. Jensen, Q. Zhong, X. Xu, S. Popov, and I. T. Monroy, "Multiband carrierless amplitude phase modulation for high capacity optical data links," *J. Light. Technol.*, vol. 32, no. 4, pp. 798–804, 2014.

[21] J. Zhang, J. Yu, F. Li, H. C. Chien, X. Li, and Z. Dong, *"11x5x10Gb/s WDM-CAP-PON Based on Optical Single-side Band Multi-level Multi-band Carrier-less Amplitude and Phase Modulation with Direct Detection,"* Eur. Conf. Exhib. Opt. Commun., p. Th.1.F.4, 2013.

[22] J. D. Ingham, R. V. Penty, I. H. White, and D. G. Cunningham, *"40 Gb/s carrierless amplitude and phase modulation for low-cost optical datacommunication links,"* Opt. Fiber Commun. Conf. Expo. Natl. Fiber Opt. Eng. Conf., p. OThZ3, 2011.

[23] M. B. Othman, T. T. Pham, X. Zhang, L. Deng, J. B. Jensen, and I. T. Monroy, *"Comparison of Carrierless Amplitude-Phase (CAP) and Discrete Multitone (DMT) Modulation,"* IEEE 5th Int. Conf. Photonics, pp. 214–216, 2014.

[24] J. L. Wei, J. D. Ingham, D. G. Cunningham, R. V Penty, and I. H. White, "Performance and Power Dissipation Comparisons Between 28 Gb/s NRZ , PAM , CAP and Communication Applications," *J. Light. Technol.,* vol. 30, no. 20, pp. 3273–3280, 2012.

[25] J. L. Wei, J. D. Ingham, D. G. Cunningham, R. V Penty, and I. H. White, "Comparisons between 28 Gb / s NRZ , PAM , CAP and optical OFDM systems for Datacommunication Applications," vol. 2, pp. 28–29, 2012.

[26] J. L. Wei, D. G. Cunningham, and R. V Penty, "Feasibility of 100G Ethernet enabled by Carrierless Amplitude / Phase Modulation and Optical OFDM," *ECOC*, p. P6.05, 2012.

[27] J. L. Wei, D. G. Cunningham, R. V Penty, S. Member, and I. H. White, "Study of 100 Gigabit Ethernet Using Carrierless Amplitude / Phase Modulation and Optical OFDM," *J. Light. Technol.*, vol. 31, no. 9, pp. 1367–1373, 2013.

[28] A. Nespola, S. Abrate, R. Gaudino, C. Zerna, B. Offenbeck, and N. Weber, "High-speed communications over polymer optical fibers for in-building cabling and home networking," *IEEE Photonics J.*, vol. 2, no. 3, pp. 347–358, 2010.

[29] L. Geng, R. V. Penty, I. H. White, and D. G. Cunningham, *"FEC-Free 50 m 1.5 Gb/s Plastic Optical Fibre Link Using CAP Modulation for Home Networks,"* Eur. Conf. Exhib. Opt. Commun., p. Th.1.B.4, 2012.

[30] J. L. Wei, L. Geng, D. G. Cunningham, R. V. Penty, and I. H. White, *"Comparisons between gigabit NRZ, CAP and optical OFDM systems over FEC enhanced POF links using LEDs,"* Int. Conf. Transparent Opt. Networks, p. Tu.P.17, 2012.

[31] J. L. Wei, L. Geng, D. G. Cunningham, R. V. Penty, and I. H. White, "Gigabit NRZ, CAP and optical OFDM systems over POF links using LEDs," *Opt. Express*, vol. 20, no. 20, pp. 22284–22289, 2012.

[32] C. Zerna, J. Sundermeyer, A. Fiederer, N. Verwaal, B. Offenbeck, and N. Weber, *"Integrated PAM2 Decision Feedback Equalizer for Gigabit Ethernet over Standard SI-POF using red LED,"* in European Conference on Optical Communication, ECOC, 2010, p. We.6.B.4.

[33] R. Kruglov, S. Loquai, C. Bunge, M. Schueppert, J. Vinogradov, and O. Ziemann, "Comparison of PAM and CAP Modulation Schemes for Data Transmission Over SI-POF," *IEEE Photonics Technol*. Lett., vol. 25, no. 23, pp. 2293–2296, 2013.

[34] Y. Wang, Y. Wang, N. Chi, J. Yu, and H. Shang, "Demonstration of 575-Mb/s downlink and 225-Mb/s uplink bi-directional SCM-WDM visible light communication using RGB LED and phosphor-based LED," *Opt. Express,* vol. 21, no. 1, pp. 1203–1208, 2013.

[35] F. M. Wu, C. T. Lin, C. C. Wei, C. W. Chen, Z. Y. Chen, H. T. Huang, and S. Chi, "Performance comparison of OFDM signal and CAP signal over high capacity RGB-LED-based WDM visible light communication," *IEEE Photonics J.*, vol. 5, no. 4, 2013.

[36] G. Stepniak, L. Maksymiuk, and J. Siuzdak, "Experimental Comparison of PAM, CAP, and DMT Modulations in Phosphorescent White LED Transmission Link," *IEEE Photonics J.*, vol. 7, no. 3, pp. 1–8, 2015.

## BIOGRAPHIES OF AUTHORS

**Noridah Mohd Ridzuan** received the B.Eng.(Hons.) degree in electrical-telecommunication engineering from Universiti Teknologi Malaysia in 2007 and M.Eng. degree in electrical engineering from Universiti Tun Hussein Onn Malaysia in 2013. She is currently working toward her Ph.D. degree in electrical engineering at Universiti Tun Hussein Onn Malaysia. Her research interests include optical fiber communication, modulation format and radio over fiber (RoF) system.

**Mohammad Faiz Liew Abdullah** received B.Sc.(Hons.) degree in electrical (communication) engineering in 1997, Dip Education in 1999 and M.Eng. degree by research in optical fiber communication in 2000 from Universiti Teknologi Malaysia. He completed his Ph.D. degree in August 2007 from the University of Warwick, United Kingdom in wireless optical communication engineering. He started his career as a lecturer at Polytechnic Seberang Prai in 1999 and joined Universiti Tun Hussein Onn Malaysia as a lecturer in 2000. At present, he is a Professor at Faculty of Electrical & Electronic Engineering, Universiti Tun Hussein Onn Malaysia. His research areas of interest are wireless optical communication, photonics system and solar cell design. He was a senior

member of IEEE and member of IET.

**Maisara Binti Othman** received the B.Eng.(Hons.) degree in computer system and communication engineering and M.Sc. degree in communication network engineering from Universiti Putra Malaysia in 2001 and 2005, respectively. She received her Ph.D. degree in metro-access and short range system from DTU Fotonik, Technical University of Denmark in 2012. Currently, she is a Senior Lecturer and the Deputy Dean (Student Affairs and Alumni) at Faculty of Electrical & Electronic Engineering, Universiti Tun Hussein Onn Malaysia. She is a member of IEEE. Her research interests include advanced modulation formats, photonic wireless integration and access and in-home network technologies.

**Marliana Jaafar** received the B.Eng.(Hons.) degree in electronic engineering and M.Eng. degree in electrical engineering in 2014 and 2017 respectively from Universiti Tun Hussein Onn Malaysia. Her research interests include photonics system, modulation format and radio over fiber (RoF) system.