Comparison of Cap and QAM-DMT Modulation Format for In-Home Network Environment

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***Abstract*—Carrierless amplitude phase (CAP) modulation format has appeared as a potential advanced modulation format candidate for spectrally efficient single-carrier modulation type due to less complexity and has competitive performance. In this paper, the comparison between 2D-CAP-4 and 4-QAM-DMT modulation format over 3 km single mode fiber (SMF) transmission link using 1310 nm vertical cavity surface emitting laser (VCSEL) has been performed for in-home network environment. The net bit rates of 625 Mb/s and 454.6 Mb/s are achieved for 2D-CAP-4 and 4-QAM-DMT, respectively. Spectral efficiencies of 1.89 b/s/Hz for 2D-CAP-4 and 1.43 b/s/Hz for 4-QAM-DMT are reported. It is observed that 2D-CAP-4 outperforms 4-QAM-DMT with 1.14 dB better receiver sensitivity. These results indicate that the privilege properties of CAP modulation format can be an attractive prospect for in-home network environment.**

***Index Terms*— Carrierless amplitude phase (CAP), quadrature amplitude phase (QAM), vertical-cavity surface-emitting laser (VCSEL).**

I. INTRODUCTION

The growing demand for higher data rate applications such as fast internet communication, video-based multimedia and high definition video streaming nowadays has driven the need of higher spectral efficiency to provide intensive capacity at higher speed of optical transmission system network. But a challenge that arises is how to continuously provide spectrally efficient system since the channel spacing in the optical transmission systems will be decreased at higher bit rate and longer transmission distances.

Implementation of multiple wavelengths in optical communication system can be used for implementing transceiver modules in order to enhance system capacity and data rate [1] but it contributes to increment of overall cost and power dissipation as a result of multiple optoelectronic components used. To avoid the escalating cost of multiple optical components, employment of advanced modulation format in optical transmission system nowadays has become a potential approach to further increase spectral efficiency.

Research works have been carried out to investigate various types of advanced modulation formats in order to improve spectral efficiency and the whole transmission system performances. In recent years, 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) has been explored extensively. New advanced multilevel modulation formats has been reported in [2] to show that there are many technical solutions available for the next generation optical communication system. 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 a potentially good choice to build up flexible, less complexity and cost-effective transmission system for next generation access and in-home network.

In similarity to QAM, CAP transmits two parallel input data streams. But contrary to QAM, instead of using sinusoidal carrier, CAP uses transversal filters with orthogonal impulse response to generate orthogonal components I and Q in order to separate respective data streams. CAP does not rely on local oscillator for carrier generation, complex mixers and optical IQ modulator. This makes CAP simpler and provides an advantage over single carrier modulation formats like QAM.

CAP modulation also has been shown to be less complex than DMT [3] because it uses an analogue or digital finite impulse response (FIR) filter with simpler computational method. DMT which is a variation of the OFDM uses bit loading for each sub-channel and applies Hermitian symmetry property to the transmitted signal in order to obtain a real-valued time-domain sequence.

Unlike CAP, 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 means CAP can significantly reduce the complexity of a transmission system and introduces direct real time implementation.

Moreover, CAP can be extended to more than two dimensions with extension number of transversal filters used [4]. This multi-dimensional characteristic of CAP modulation format can be an attractive option to support multiple services via single fiber link architecture for in-home networks environment [5]. High dimensionality 3D-CAP and 4D-CAP with directly modulated vertical cavity surface emitting lasers (DM-VCSELs) over 20 km standard single mode fiber (SSMF) has been experimentally demonstrated for the first time to provide more flexibility in optical fiber systems [6].

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 [7, 8].

Due to its privilege properties and the capability of generating the respective orthogonal waveforms using transversal filters, CAP modulation format has gained increasing attention for various applications of optical communication system in recent days.

A comparison between CAP and other advanced modulation format over polymer optical fiber (POF) link has been carried out to investigate CAP privilege properties. The CAP-64 scheme generally gives a higher system margin than non-return-to-zero (NRZ) modulation over step index polymer optical fiber (SI-POF) link for home networks [9] and CAP-64 outperforms 64-QAM-OFDM which represents 70% improvement in capacity [10]. For high-speed transmission, 16-CAP modulation format achieved highest bit rate of 5 Gb/s over 50-m 1-mm SI-POF link when comparison of NRZ, PAM and CAP modulation techniques has been done experimentally [11].

Meanwhile, LED-based visible light communication (VLC) has attracted considerable interests in recent years as an alternative wireless communication technique in next-generation indoor wireless local area network (WLAN). The performance comparison between OFDM signal and CAP signal over high capacity RGB-LED-based wavelength division multiplexing (WDM) VLC shows that the CAP scheme gives competitive performance and provides an alternative spectrally efficient modulation for next generation optical wireless networks compared to OFDM [12]. On the other hand, 2-level pulse amplitude modulation (PAM) and CAP modulation are proved to exhibit better immunity to nonlinear distortions in VLC link while DMT performance was substantially worse [13].

Besides that, CAP also displays better sensitivity than DMT [14]. For lengths up to 30 km, the CAP-16 scheme without forward error correction (FEC) offers good performance and has half the power consumption of optical orthogonal frequency division multiplexing (OOFDM) schemes [15].

In this paper, we present a performance comparison of 2D-CAP-4 against 4-QAM-DMT signals for in-home network environment. These modulation formats are successfully propagated over 3 km length of SMF. These signals have been employed to directly modulate a 1310 nm VCSEL.
The design and simulation of optical transmission system for this research is using VPI Transmission Maker software. From the simulation, 2D-CAP-4 displays better sensitivity of 1.14 dB than 4-QAM-DMT. The net bit rate of 625 Mb/s is achieved for 2D-CAP-4 and 454.6 Mb/s for 4-QAM-DMT with 312.5 Mbaud modulation rate and 1.25 GHz sampling rate. Therefore, it is believed that the proposed CAP system allows simple implementation than QAM-DMT and has good potential for in-home networks environment.

II. SIMULATION SETUP

The block diagram of CAP transmission system is shown in Figure 1. At the transmitter, a 215-1 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 2D-CAP-4, k is equal to 2.

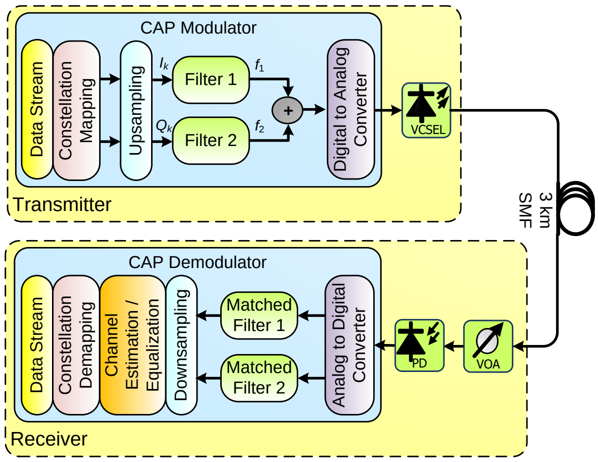

Figure 1: CAP transmission systems

These mapped symbols are split and upsampled to 4 samples per symbol to match the sample rate of shaping filters. The in-phase, Ik and quadrature, Q_k component 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 in order to achieve orthogonality between them.

The output waveform is then moved from baseband to passband. The resultant waveforms of each filter are given by:

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

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

where fc is a frequency suitable for the passband filters. The pair of modulated waveforms f1 and f2 constitutes a Hilbert pair and denotes in-phase and quadrature filter with phase responses 90o apart from each other.

These two orthogonal signals are summed and converted to analog signal using digital to analog converter. Figure 2(a) shows the combined frequency spectrum of CAP with 330 MHz bandwidth of total CAP spectrum.

At the receiver, after direct detection and conversion to digital form, the signals are fed into two matched filters that have time-inversion impulse response of the orthogonal filters at the transmitter. The matched filters separate the I and Q components in order to recover each dimension and the original sequence of symbols.

These symbols are downsampled and 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.

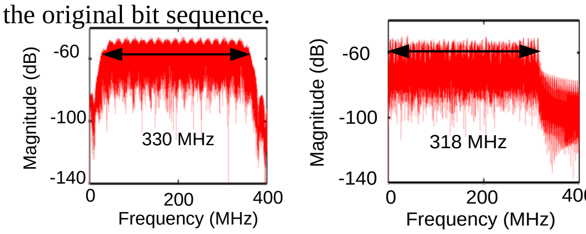

Figure 2: (a) CAP spectrum (b) DMT spectrum

The block diagram of the DMT transmission system is shown in Figure 3. The serial bit sequence of data stream is divided into parallel data streams before it is modulated into 64 subcarriers and mapped using 4-QAM modulation format to form a complex symbol.

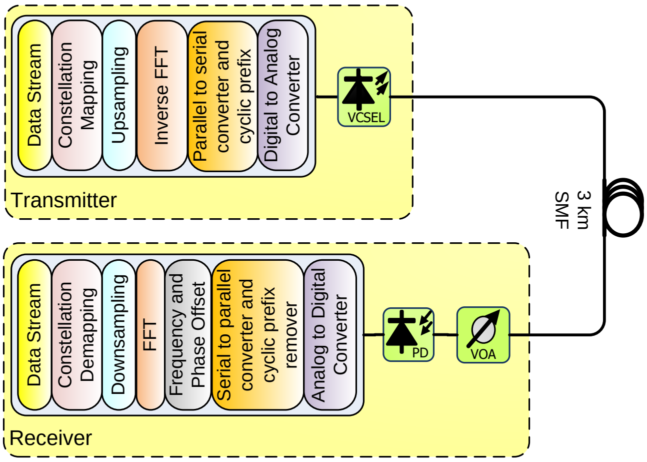

Figure 3: DMT transmission systems

These QAM symbols are upsampled to 4 samples per symbol and modulated using inverse fast Fourier transform (IFFT), which transforms frequency domain parallel data into time domain parallel data. In order to obtain the time domain sequence in real valued, 64 of 4-QAM symbols are duplicated with their conjugate symmetric of the first half and subjected to 128 point IFFT length since 64 subcarriers are used.

In parallel-to-serial block, a 10% cyclic prefix (CP) is inserted to each DMT symbol to avoid inter-symbol interference (ISI). The CP length lengthens the symbol period, making it longer than the channel delay spread which is caused by the time delayed reflections of the original symbol arriving at the receiver.

Then the generated DMT signal is converted to analog signal through a digital to analog converter and subsequently used for optical transmission. The total bandwidth of the DMT signal is 318 MHz as shown in Figure 2(b).

At the receiver, direct detection is employed and the signals are converted back to digital form. The cyclic prefix is discarded and DMT signal goes through a serial-to-parallel conversion. Frequency and phase offset is applied afterwards for synchronization purpose due to common frequency and phase error. It is followed by demodulation process of 128 point fast Fourier transform (FFT) length.

The parallel data is downsampled and demapped to recover the original data bits and converted into a serial bit stream. Only the first half of the 128 points output after FFT is necessary for signal decoding.

CAP is a single-carrier modulation format that operates in time domain while DMT is a multi-carrier modulation format that operates in frequency domain. This two modulation formats were compared using same simulation schematics in VPI transmission Maker as shown in Figure 4.

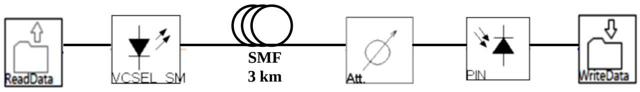

Figure 4: Optical transmission system simulation design

The transmitter is composed of an import module and a vertical-cavity surface-emitting laser (VCSEL). The link is simulated with a 3 km length of SMF while the receiver is modeled with an optical attenuator, a PIN photodetector (PD) and an export module.

A text file generated in MATLAB program consist of CAP signal and QAM-DMT signal is imported as an input in the import module. The electrical signal output of the import module is then converted into optical signal by VCSEL at 1310 nm wavelength with 7.5 mA bias current. The optical signal is transported via 3 km of SMF link with 0.35 dB/km fiber attenuation.

After 3 km optical transmission via SMF, the signal is directly detected by a PIN photodiode which has 1 A/W responsivity value and 10 pA/√Hz thermal noise. The export module is used to export the received signal as a text file for offline demodulation process in MATLAB program.

Since forward error correction (FEC) may be applied to obtain error free transmission when the 7% FEC overhead is taken into account, receiver sensitivity at a BER of 2.8×10^{-3} is used to access transmission quality.

A net bit rate (BR) of 625 Mb/s for 2D-CAP-4 and 454.6 Mb/s for 4-QAM-DMT signals (including the 7% forward error correction (FEC) overhead) are achieved in the system with spectral efficiency (SE) of 1.89 b/s/Hz and 1.43 b/s/Hz, respectively. The summarized parameters value of 2D-CAP-4 and and 4-QAM-DMT modulation formats are listed in Table 1.

Table1
Parameter value of 2D-CAP-4 and 4-QAM-DMT modulation format

Signal	**Bits / Symbol**	**Total levels**	**Upsampling factor**	**Symbol rate (Mbaud)**	**Net bit rate (Mb/s)**	**Bandwidth (MHz)**	**Spectral efficiency (b/s/Hz)**
2D-CAP-4	2	4	4	312.5	625	330	1.89
4-QAM-DMT	2	4	4	312.5	454.6	318	1.43

III. Result And Discussion

Figure 5 presents the bit error rate (BER) against the received optical power (ROP) for 2D-CAP-4 and 4-QAM-DMT signals. The sensitivity of both modulation formats is compared to see their performance.

The solid symbols represent optical back-to-back (B2B) while the hollow symbols represent 3 km of SMF transmission. For B2B, the receiver sensitivity at FEC limit is −25.73 dBm for 2D-CAP-4 and −24.59 dBm for 4-QAM-DMT. After 3 km of SMF transmission, the receiver sensitivity at the FEC limit is −25.78 dBm and −24.64 dBm for 2D-CAP-4 and 4-QAM-DMT, respectively with a 1.14 dB difference is observed between them. The presented comparison of these two modulation format shows that 2D-CAP-4 has approximately a 1.14 dB better performance than 4-QAM-DMT.

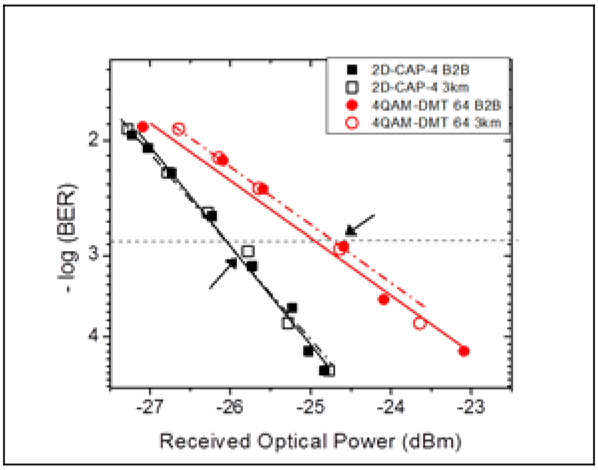

Figure 5: Bit error rate (BER) versus received optical power (ROP) for 2D-CAP-4 and 4-QAM-DMT

Figure 5 shows both signals are successfully demodulated below FEC limit after 3 km of SMF transmission. The constellation diagrams of 2D-CAP-4 and 4-QAM-DMT after transmission are also shown in Figure 5. These are obtained at BER of approximately 1x10-3.

IV. Conclusion

We have compared simulation results between single-carrier modulation format CAP and multi-carrier modulation format QAM-DMT. The 2D-CAP-4 and 4-QAM-DMT signals have been successfully transmitted over 3 km of SMF using 1310 nm VCSELs.

The spectral efficiency of 1.89 b/s/Hz for 2D-CAP-4 and 1.43 b/s/Hz for 4-QAM-DMT are reported at bit rate of 625 Mb/s and 454.6 Mb/s, respectively. Bit error rate (BER) versus received optical power (ROP) measurement shows that 2D-CAP-4 has approximately 1.14 dB better receiver sensitivity and performance than 4-QAM-DMT. The spectral efficiency of DMT is reduced due to the addition of cyclic prefix and training sequence.

Even though DMT has better bandwidth flexibility allocation in dividing the bandwidth into sub-channels, it involves complex system. CAP allows simple implementation and less algorithm complexity due to the absence of sinusoidal carrier generation.

It is believed that CAP can be viewed as an attractive alternative modulation format for in-home networks environment in the future.

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