Non-Orthogonal Variable Multi-Band Carrier-less Amplitude and Phase Modulation with Reduced Subcarriers

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Abstract— In this paper, we theoretically investigate the impact of power allocation for subcarriers on the bit error rate (BER) performance of a non-orthogonal variable multi-band carrier-less amplitude and phase modulation (m-CAP) scheme within the contest of visible light communications. We consider subcarriers with different bandwidth as well as sub-carrier with overlapping in order to efficiently utilize the passband region of the system frequency response for data transmission. We show that, for the proposed scheme the average BER performance is improved by up to 20% compared to the conventional m-CAP system.

Keywords— Carrier-less amplitude and phase modulation, visible light communications

I. Introduction

The extremely high demand for high-speed data traffic, which is expected to increase eightfold by 2020 in comparison to 2015 [1], is putting enormous pressure on the spectrum usage of the existing radio frequency (RF) wireless technologies, thus leading to the bandwidth bottleneck that needs addressing. There are a number of potential solutions such as the move to the higher carrier frequencies (i.e., millimeter wave of 20-80 GHz), parallel transmission, multi-level and multi-carrier modulation schemes, spectrum hoping, sharing and borrowing, advanced modulation and coding schemes, interference elimination, massive multiple input multiple outputs, etc. [2]. Alternatively, one could adopt optical wireless communication (OWC) technologies as a complementary to RF in certain applications [3]. The OWC technologies covering the main three bands of ultra violet, infrared and visible bands offer a number of advantageous such as a very high unregulated spectrum (i.e., ~400 THz of bandwidth), very high data rates, inherent security at the physical layer, no RF induced electromagnetic interference, etc., which can be used in both indoor and outdoor environments [2],[3],[4]. In the visible band, we have seen growing research interests in the emerging field of visible light communications (VLC), which effectively utilizes the light emitting diodes (LEDs) based lighting fixtures to provide high-speed connections mostly in indoor environments [5].

The VLC technology offers unique key features of simultaneous data transmission and illumination at homes, offices, train and bus station, manufacturing, etc. In addition, VLC can be used to provide indoor localization and sensing in areas where RF-based systems cannot be adopted. However, one of the most important challenges the VLC facing is the limited bandwidth of the LEDs (i.e., a few MHz with standard LEDs for illumination), which results in limited data transmission rate depending on the environment and the transmission range [6].

One of the most widely used methods adopted in VLC in order to increase the transmission data rate is the use of modulation schemes with higher spectrum efficiencies such as orthogonal frequency division multiplexing (OFDM), multi-level modulations and carrier-less amplitude and phase modulation (CAP) and its variant [7]. OFDM, which is adopted from the RF domain and widely reported in the literature for use in VLC systems, is based on fast Fourier transforms (FFTs) and inverse FFTs (IFFTs) and offers very high data rate with much reduced intersymbol interference (ISI) [8],[9]. However, the need for a high peak to average ratio (PAPR) in OFDM is a major problem in VLC systems where LEDs introduce some nonlinearity in the power-current characteristic, thus leading to reduced signal to noise ratio

(SNR) (i.e., higher BER) [10]. On the other hand, the CAP scheme, which is much simpler than OFDM requiring no FFT and IFFT and using orthogonal filters only, is seen as a potential alternative to OFDM in VLC systems. In [11], experimental results were reported for the CAP VLC system offering higher transmission data rates of 3.22 Gbps and 2.93 Gbps based on wavelength division multiplexing in comparison to the OFDM VLC system. The structure of CAP receivers is much simpler than that of OFDM. This is because there is no carrier requirement while both of them could have the same spectral efficiency and performance [12]. Note that, in multi-carrier modulation schemes including CAP having, a wide-band and a flat frequency response is desirable in order to achieve a high data rate with the optimal link performance. However, LEDs have 1st order filter type frequency response, which limits the achievable data rates. To overcome this this problems, a number of solutions have been proposed including (i) splitting the signal bandwidth into m-subcarrier within the pass-band region to overcome the flat band requirement [13]; (ii) increasing the number of subcarriers with reduced bandwidth, which reduces the potential of fading induced attenuation [14]; and (iii) transmitting sub-carrier with lower SNR levels in the stop-band. Note that, the bandwidth available within one decade of frequency in the stop-band is much higher than the pass-band. In addition, not all system will require the same SNR level.

In this paper, we theoretically investigate m-CAP VLC by considering the impact of power allocation for subcarriers on the BER performance. We consider subcarriers with different bandwidth allocations as well as sub-carrier with overlapping in order to efficiently utilize the passband region of the system frequency response for data transmission. We show that for the proposed scheme the average BER performance is improved by up to 20% compared to the conventional m-CAP system.

The rest of the paper is organized as follow. Section II outlines the system model of the m-CAP system and what has been proposed. Results and simulations are shown in Section III and finally, the conclusion is given in Section IV.

II. SYSTEM MODEL

The schematic block diagram of the m-CAP system is shown in Fig. 1.

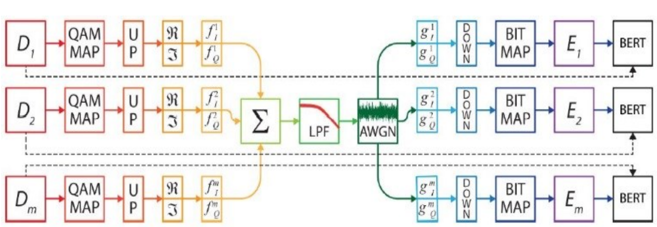

Fig. 1: Schematic system block diagram of m-CAP.

At the transmitter, m independent data streams D ∈ {0, 1} are generated then mapped into M-QAM (i.e. quadrature amplitude) modulation before being up-sampled based on the number of n_{sa}, which is given by [15]:

$$n_{sa} = \lceil 2m \cdot (1+\beta) \rceil \tag{1}$$

where ⌈.⌉ is the ceiling function, β is the roll-off factor of a square root raised cosine filter (SRRCF) and m is number of CAPs. Following up-sampling, the data stream is split into real and imaginary parts prior to being passed through real and imaginary pulse shaping transmit filters. Note, the in-phase (I) and quadrature (Q) transmit filters f_I^m and f_Q^m are finite impulse response (FIR) filters, which form a Hilbert pair thus are orthogonal in the time domain and their outputs are real-valued. The filter impulse response is generated as a product of the cosine and sine waves with the impulse response of the SRRCF for the I and Q filters, respectively, see Fig. 1.

The I and Q transmit filter impulse responses are given by [15]:

$$f_I^m(t) = \left[\frac{\sin\left(\frac{\pi t}{T_S}(1-\beta)\right)+4\beta\frac{t}{T_S}\cos\left(\frac{\pi t}{T_S}(1+\beta)\right)}{\frac{\pi t}{T_S}\left(1-\left(4\beta\frac{t}{T_S}\right)^2\right)}\right].\cos\left(2\pi f_{c,i} t\right) \tag{2}$$

$$f_Q^m(t) = \left[\frac{\sin\left(\frac{\pi t}{T_S}(1-\beta)\right)+4\beta\frac{t}{T_S}\cos\left(\frac{\pi t}{T_S}(1+\beta)\right)}{\frac{\pi t}{T_S}\left(1-\left(4\beta\frac{t}{T_S}\right)^2\right)}\right].\sin\left(2\pi f_{c,i} t\right) \tag{3}$$

where T_s is the symbol duration. $0 \le \beta \le 1$ determines the bandwidth requirement. In [12] it was shown that lower values of β result in higher spectral efficiency. Based on [15], the carrier frequency of i^{th} subcarrier in conventional m-CAP is given by:

$$f_{c,i} = \frac{(2i-1)\mathbf{B}_{\text{sig}}}{2m} \tag{4}$$

where the signal bandwidth is given as:

$$\mathrm{B}_{\text{sig}} = \frac{1}{T_S}(1+\beta)m \tag{5}$$

In m-CAP, the last subcarriers may not carry the same data rate because of the low-pass filter response of LED, which will reduce the SNR level thus leading to higher BER. In this work, we carry out a number of analyses in order to improve the BER performance and increase the data rates. First, we transmit no data in the last subcarriers and instead of it, we share the power allocated to last subcarriers between other subcarriers. By doing so, the BER performance of data carrying subcarriers is reduced, thus trading-off data for performance. Secondly, we allocate higher transmission bandwidth by about 1.2 to the 1st subcarrier, which is in the pass-band region, compared to the others. Thirdly, we have introduced an overlap between subcarriers in line with the work reported in [16] in order to increase the transmission data rate at the cost of increased ISI. Note that, by overlapping of subcarrier, the orthogonality is no longer valid in m-CAP. This (i.e., non-orthogonality between subcarriers) is fine for indoor VLC systems where the channel is rather static with not much deep fading as is the case in highly dynamic outdoor channels. Therefore, the subcarrier frequency is defined as:

$$f_{c,i} = \frac{(2i-1)B_{\mathrm{sig}}}{2m}\alpha \tag{6}$$

where the compression factor is 1< α <2. For example in conventional m-CAP α =1. In such case, we simply shift the subcarriers (i.e., compressing) and therefore intentionally overlapping the subcarriers, which results in non-orthogonality between the subcarriers. Note that, (i) for the first subcarrier α is different and larger than the other subcarriers; and (ii) the frequency sampling is defined as:

$$f_s = R_s\, n_{sa} \tag{7}$$

where the symbol rate $R_s = T_s^{-1}$. The final m-CAP signal is given by [12]:

$$s(t) = \sum_{n=1}^{m}\left[C_I^n(t)\otimes f_I^n(t) - C_Q^n(t)\otimes f_Q^n(t)\right] \tag{8}$$

where ⊗ represents time-domain convolution and C_I and C_Q are M-QAM I and Q components for the n^{th} subcarrier, respectively.

The received electrical signal is given by:

$$y(t) = x(t) \otimes h(t) + n(t) \tag{9}$$

where $x(t)$ is the intensity modulated transmitted optical signal, h(t) is the channel impulse response, and $n(t)$ is the additive white Gaussian noise (AWGN) (i.e., representing background, dark current, thermal and signal shot noise sources) with zero mean and variance of $N_0/2$ (where N_0 is the noise spectral density).

Following detection and regeneration of the m-CAP signal, demodulation, which is the inverse of modulation, is carried out in order to recover the transmitted data streams. For more details on the operation of the demodulator, the readers are referred to [14,17]. Note, the main parts of demodulator are the matched filters given by $g_I^m(t) = f_I^m(-t)$, $g_Q^m(t) = f_Q^m(-t)$

III. RESULTS AND SIMULATIONS

As we stated earlier, we have made the bandwidth of subcarriers wider and overlapping with each other in order to increase the data throughput at the cost of BER performance deterioration at the first and last subcarriers. We have carried out a number of simulation using the parameters given in Table 1 and for a range of α in order to obtain the optimum results (i.e., higher bit rates at lower BER). Figure 2 shows the BER against the E_b/N_0 for a 5-CAP system with the first three subcarriers. Also shown is the 7% forward error correction (FEC) limit of 3.8×10^{-3} for comparison. In 5-CAP the first subcarrier is allocated with α of 1.2155, whereas the remaining two subcarriers we have used α of 1.0285. By doing so, we could achieve (i) a spectral efficiency (i.e., data transmission) of 12 bit/s/Hz, which is lower 15 bits/s/Hz for the conventional 5-CAP; (ii) improvement in the BER performance by 22% compared to the conventional 5-CAP as show in Fig. 3.

Table. 1. System parameters

Parameter	Value
β	0.36
Ts	1.8
α	1.2155 for 1st sub-band 1.0285 for others sub-bands

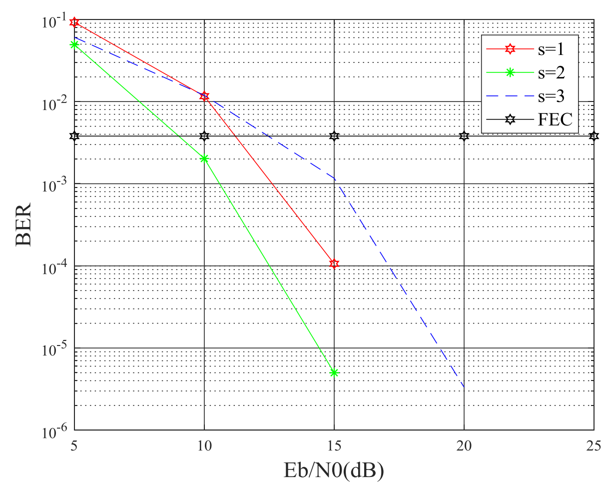

Fig. 2: The BER against the E_b/N_0 for a 5-CAP system with the first three subcarriers.

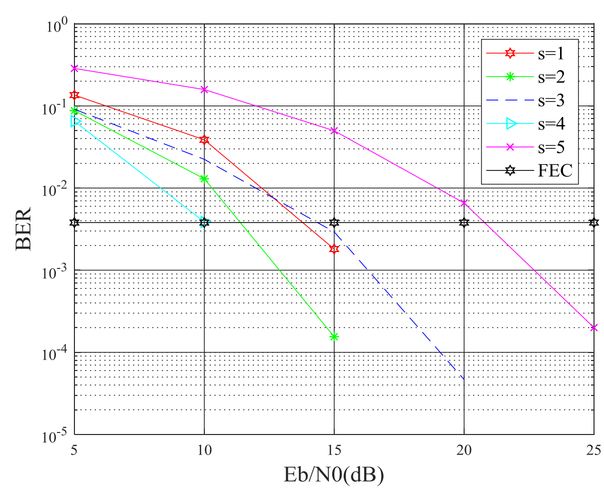

Fig. 3: The BER against the E_b/N_0 for a conventional 5-CAP system.

Figure 4 depicts the BER against the E_b/N_0 for a 7-CAP system with the first five subcarriers. In 7-CAP with the first five subcarriers having the same α as in 5-CAP system, the spectral efficiency is 21 bit/sec/Hz, which is lower than the conventional 7-CAP with an efficiency of 24 bits/s/Hz, but is much higher than 5-CAP. In addition, the proposed scheme shows improved BER performance compared to conventional 7-CAP, see Figs. 4 and 5. E.g., for s of 4 and at a E_b/N_0 of 15 dB, the BER for the proposed scheme and the conventional 7-CAP are < 10^{-5} and 10^{-3}, respectively that are below the FEC limit.

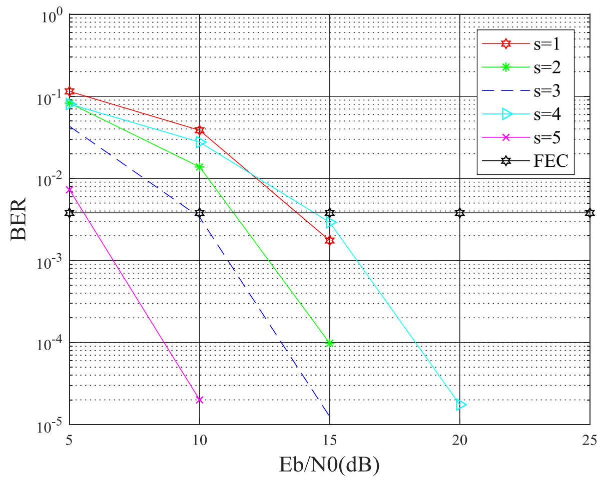

Fig. 4: The BER against the E_b/N_0 for a 7-CAP system with the first five subcarriers.

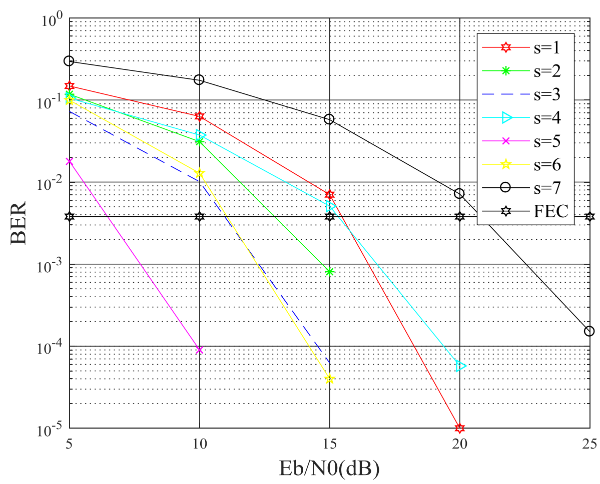

Fig. 5: The BER against the E_b/N_0 for a conventional7-CAP system.

Figure 6 displays the BER against the E_b/N_0 for a 10-CAP system with the first seven subcarriers. In 10–CAP the first seven subcarriers have the same α as in 5-CAP system and the spectral efficiency is 28 bit/sec/Hz compared to 32 bits/s/Hz for the conventional 10-CAP system, and 12 bit/s/Hz and 21 bits/s/Hz for the 5-CAP and 7-CAP systems, respectively. Note that, 10-CAP shows improved BER performance compared to the conventional 10-CAP, see Figs. 6 and 7. Note, in Fig. 6 we have only shown the plots for the first 5 subcarriers whereas for 6 and 7 subcarriers the performance is almost error free.

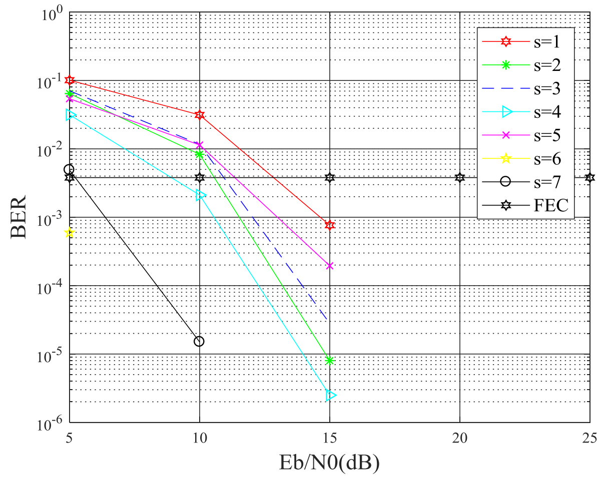

Fig. 6: The BER against the E_b/N_0 for a 10-CAP system with the first seven subcarriers

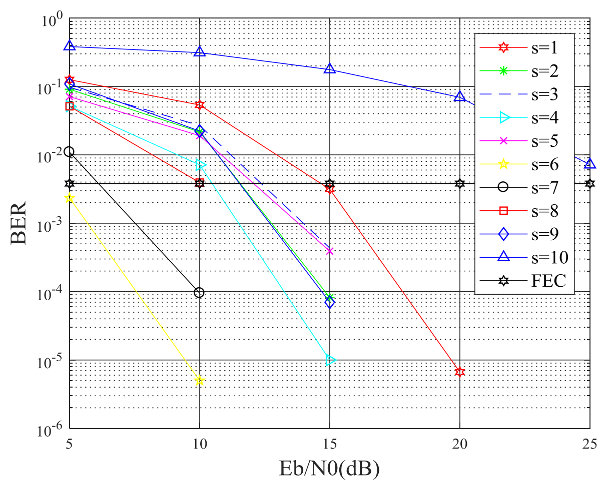

Fig. 7: The BER against the E_b/N_0 for a conventional 10-CAP system.

Of course, the BER results will be different depending on the data rates, transmit power, transmission span, the number of used subcarriers and α.

IV. CONCLUSION

In this paper the non-orthogonal subcarriers based m-CAP system, where the last subcarriers were not used because of the unfavorable channel condition, was investigated by means of simulation. We showed that, the proposed scheme can offer higher data rates with lower BERs compared to the conventional m-CAP systems.

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