Rate-Adaptive OFDM MIMO VLC System

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Abstract

In this paper, we investigate link adaptation for an orthogonal frequency division multiplexing (OFDM)-based multiple-input multiple-output (MIMO) visible light communication (VLC) system. The MIMO system under consideration employs repetition coding, therefore all the transmitters emit the same information. We propose a rate adaptation algorithm where the modulation size is selected among the available constellation sets. The receiver first calculates the instantaneous signal-to-noise ratio per subcarrier, then determines the maximum constellation size on each subcarrier that can be supported while satisfying a predefined target bit error rate. Our numerical results reveal that a peak data rate of more than 1.14 Gbits/sec can be achieved using LEDs with cut-off frequency of 10 MHz in typical office spaces.

1. Introduction

Light emitting diodes (LEDs) have been rapidly gaining in value and preference over traditional lighting sources due to steady cost reductions and superior lighting performance. The fact that LEDs can be pulsed at very high speeds without any adverse effect on lighting output also prompts their use as wireless access points. Visible light communication (VLC), also known as LiFi, has therefore emerged as a powerful complementary wireless technology to radio frequency (RF) counterparts [1].

In earlier works on VLC, simple modulation techniques such as on-off keying (OOK) and pulse position modulation (PPM) were employed [2]. To enable high data rates over VLC channels with frequency-selective characteristics, orthogonal frequency-division multiplexing (OFDM) was investigated in more recent works [3, 4, 5, 6, 7] and also adopted in the upcoming VLC standard IEEE 802.15.7r1 [8]. This standard targets peak data rates on the order of Gbits/sec. To achieve such high data rates, the use of link adaptation and multiple input multiple output (MIMO) techniques in conjunction with OFDM was proposed in the standard draft [9].

Link adaptation involves the selection of transmission parameters, e.g., modulation size, transmit power etc. based on the channel conditions. Adaptive OFDM for single-input single-output (SISO) VLC systems was proposed in [10, 11, 12] where variants of bit/power loading were studied. Link adaptation for a coded OFDM VLC system was studied in [13] where code rate and modulation order were selected as adaptive transmission parameters. Link adaptation was further explored for MIMO VLC systems [14, 15]. In [14], a joint power control and modulation selection scheme was proposed for a MIMO system with spatial multiplexing. In [15], a transmitter/receiver selection algorithm was proposed for a MIMO VLC system employing spatial modulation. It should be noted that these works [14, 15] are mainly limited to single-carrier systems. The combination of OFDM and MIMO in a VLC system was only recently considered in [16] where spatial multiplexing was employed and performance improvements through bit and power loading were presented.

In a MIMO system, the deployment of spatial multiplexing makes it possible to extract the multiplexing gains and improves the achievable data rate. On the other hand, a MIMO system can be also used to enhance the link reliability through diversity gains. Coded streams are sent through MIMO channels for this purpose. While sophisticated space-time codes are used in RF systems, simple repetition coding (RC) has been shown to be an effective solution for optical channels [17] and proposed also for the IEEE standard [18]. In this paper, we consider an adaptive OFDM MIMO VLC system with RC and propose a bit loading scheme that adapts the data rate according to channel conditions. We aim to maximize the spectral efficiency while satisfying a given bit-error-rate (BER) target. Our results reveal that a peak data rate of more than 1.14 Gbits/sec can be achieved under realistic indoor channel conditions.

Notation: $(.)^*$, $[.]^{\mathrm{T}}$ and $||.||^2$ denote complex conjugate, transpose and Euclidean distance operations. $F\{.\}$ represents the continuous Fourier transform. Vectors are denoted by bold face regular letters, e.g., **X**. $X[k]$ denotes the k^{th} element of **X**.

2. System Model

As illustrated in Fig. 1, we consider an office space with dimensions of $5\ \mathrm{m} \times 5\ \mathrm{m} \times 3\ \mathrm{m}$. 16 LED ceiling light sources act as transmitters (see Fig. 2). The destination terminal is in the form of a laptop computer placed on the desk. As illustrated in Fig. 3, it is connected to four USB hubs each of which is

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equipped with 4 photodetectors (PDs). This effectively creates an 16x16 MIMO system with $L = 16$ LEDs and $P = 16$ PDs[1]. The separation between PDs, each with a surface area of $1\ \mathrm{cm}^2$, is $5\ \mathrm{cm}$. The distance between two adjacent USB hubs are 12 cm. The other specifications can be found in Table 4 of [8].

Fig. 1. Office space under consideration.

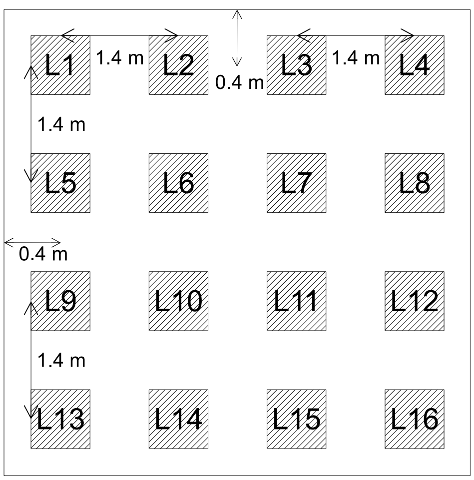

Fig. 2. Arrangement of luminaries on the ceiling (figure not to scale).

Let $h_{p,l}^{opt}(t)$, $l \in \{1, 2...L\}$, $p \in \{1, 2...P\}$ denote optical channel impulse response (CIR) for the link from the l^{th} LED to the p^{th} PD. In addition to the multipath propagation environment, the low-pass filter nature of the LEDs should be further taken into account [20]. The "effective" channel frequency response can be then expressed as $H_{p,l}^{eff}(f) = H_{LED}(f)H_{p,l}^{opt}(f)$ where $H_{p,l}^{opt}(f) = F\{h_{p,l}^{opt}(t)\}$.

The system architecture is built upon direct current biased optical OFDM (DCO-OFDM) and illustrated in Fig. 4. In DCO-OFDM, binary information is first mapped to complex symbols using either $M-$ary phase-shift keying (PSK) or quadrature amplitude modulation (QAM) with the average symbol energy of E. Assume that N is the number of subcarriers. Let $s_{l,1}\ \ s_{l,2}\ \ ...\ \ s_{l,N/2-1}$ denote the complex-valued modulated symbol sequence to be transmitted from the l^{th} LED. To ensure that the output of inverse discrete Fourier transform (IDFT) is real valued, Hermitian symmetry is imposed resulting in the transmitted sequence of $\mathbf{X}_l = \left[0\ s_1\ s_2\ ...\ s_{N/2-1}\ 0\ s_{N/2-1}^*\ ...\ s_2^*\ s_1^*\right]^{\mathrm{T}}$. The IDFT output is $\mathbf{x}_l$ whose n^{th} element is given by

$$x_l[n] = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_l[k] e^{j\frac{2\pi nk}{N}},\ \ n \in \{0, 1, ..., N-1\}\,. \tag{1}$$

The imposed Hermitian symmetry ensures that $x_l[n]$ is real valued. A cyclic prefix with the length of N_{CP} is appended to $\mathbf{x}_l$ in order to compensate the intersymbol interference (ISI). Finally, a DC bias (B_{DC}) is applied to shift the amplitude values to the dynamic range of the LEDs. The resulting signal propagates through the optical channel.

The received signal by each PD is first sampled at a rate of T_S and then discrete Fourier transform (DFT) is performed to obtain the frequency domain signal. The output of DFT at the p^{th} PD on the k^{th} subcarrier can be written as

$$Y_p[k] = \sqrt{\frac{E}{L}} R \sum_{l=1}^{L} X_l[k] H_{p,l}[k] + V_p[k] \tag{2}$$

where R is optical to electrical conversion coefficient (A/W) and $V_p[k]$ is additive white Gaussian noise (AWGN) term with zero mean and N_0W variance. Here, N_0 denotes power spectral density (PSD) and $W = 1/2T_S$ is system bandwidth under the consideration of Nyquist rate. In (2), $H_{p,l}[k]$ is the DFT response of the band-limited electrical CIR between the l^{th} LED and the p^{th} PD, i.e., $H_{p,l}(f) = G_T(f)H_{p,l}^{eff}(f)G_R(f)$ where $G_T(f) = F\{g_T(t)\}$ and $G_R(f) = F\{g_R(t)\}$ respectively denote transmit and receive filter frequency responses.

The MIMO system under consideration employs RC, therefore all the LEDs emit the same information, i.e., $X_1[k] = X_2[k] = ... = X_L[k] = X[k]$. Under the assumption of perfect channel state information at the receiver side, the Maximum Likelihood (ML) decision rule is given by

$$\hat{X}[k] = \underset{X[k]\in\Omega_k}{\arg\min} \left[\sum_{p=1}^{P} \left\| Y_p[k] - X[k] R \sum_{l=1}^{L} H_{p,l}[k] \right\|^2 \right] \tag{3}$$

where Ω_k is the set of constellation points on the k^{th} subcarrier.

Adaptive transmission controller at the receiver side selects modulation order per subcarrier based on channel condition to

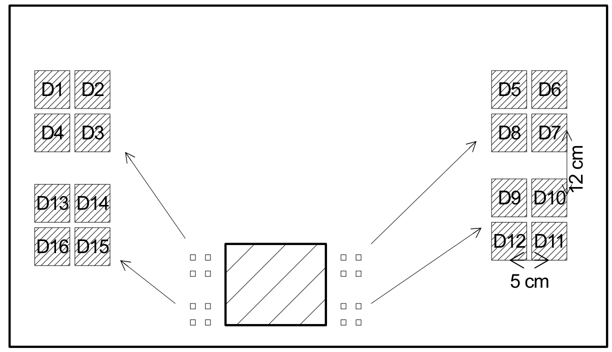

Fig. 3. Top view of the desk with laptop computer and PDs labeled from 1 to 16 (figure not to scale).

[1]We assume an optical power of 17 W for each LED. For the indoor space under consideration, this achieves illumination levels in the range of $365 - 612$ lux complying with Illuminating Engineering Society of North America (IES) Standard [19].

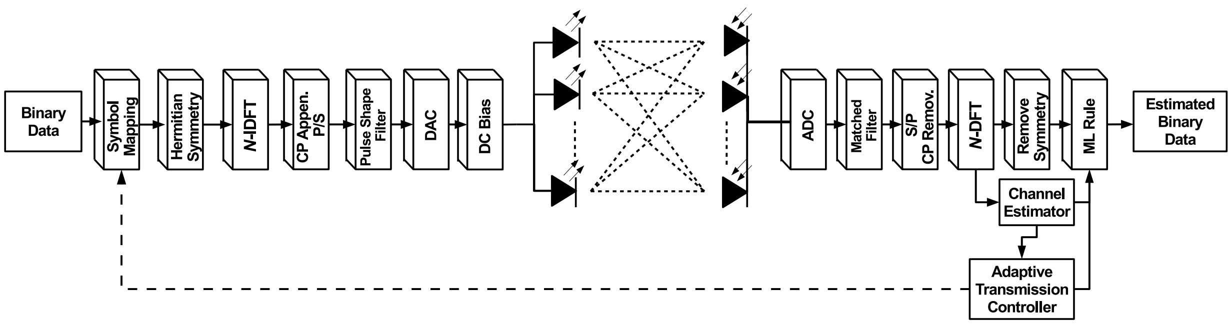

Fig. 4. Block diagram of adaptive MIMO DCO-OFDM VLC system using RC.

yield the highest spectral efficiency. Related bit loading information (i.e., constellation size for each subcarrier) is sent to the transmitter through a feedback link. It should be noted that signal-to-noise ratio (SNR) level may not be sufficient for the target BER even with the lowest modulation order. In this case, power increment signal is transmitted through feedback link and the process of modulation order selection per subcarrier is repeated. Further details of adaptation algorithm are presented in the following section.

3. Rate Adaptation Algorithm

We propose a rate adaptation algorithm where the modulation size is selected among the available constellation sets. The system supports binary PSK ($\mathrm{B-PSK}$), square QAM and rectangular QAM. The receiver first calculates the instantaneous SNR per subcarrier, then determines the maximum constellation size on each subcarrier that can be supported while satisfying a predefined target BER.

Subcarrier-based BER for different constellations can be calculated as Eq. (10) of [21] where $\mathrm{SNR}[k]$ denotes the instantaneous SNR for the k^{th} subcarrier and is given by

$$\mathrm{SNR}[k] = \frac{ER^2}{LN_0W} \sum_{p=1}^{P} \left| \sum_{l=1}^{L} H_{p,l}[k] \right|^2 . \tag{4}$$

Required SNR levels to achieve a predefined BER target can be obtained by taking the inverse of (6) and storing in a look-up table (LUT). As an example, LUT is provided in Table 1 for $\mathrm{B-PSK}$ and $M-$QAM where $M = 4, 8...4096$ assuming target BER of 10^{-3}. Based on the available SNR in the system, the highest modulation size that can be supported is selected. Let $D[k]$ denote the maximum constellation size on the k^{th} subcarrier. The spectral efficiency (SE) is then calculated as

$$\mathrm{SE} = \frac{1}{N + N_{CP}} \sum_{k=1}^{N/2-1} \log_2 D[k] \text{ bits/sec/Hz}. \tag{5}$$

The corresponding data rate is equal to SE/T_S expressed in bits/sec.

4. Numerical Results

In this section, we present the performance of our proposed adaptive MIMO OFDM system. System parameters are summarized in Table 2. Optical CIRs for each link are obtained using ray tracing simulations similar to those in [22]. In our simulation study, we consider 16x16 MIMO system as well as various 1x1, 4x4, 4x16 and 16x4 MIMO scenarios (see Table 3) where a subset of LEDs/PDs are selected. It should be emphasized that in all scenarios under consideration, all LEDs are always on and used for illumination. The scenarios in Table 3 describe only which LEDs and PDs are used for data transmission/reception.

Table 1. LUT for target BER of 10^{-3}.

Modulation	Required receive SNR [dB]
B−PSK	6.79
4−QAM	9.80
8−QAM	14.42
16−QAM	16.54
32−QAM	20.57
64−QAM	22.55
128−QAM	26.46
256−QAM	28.42
512−QAM	32.31
1024−QAM	34.26
2048−QAM	38.15
4096−QAM	40.12

Table 2. Simulation parameters.

Number of subcarriers (N)	1024
Cyclic prefix length (N_{CP})	48
Pulse shape filter ($g_T(t), g_R(t)$)	Sinc filter
Sampling interval (T_S)	5 nsec
Responsivity (R)	1.0 A/W
LED cut-off frequency ($f_{\mathrm{cutt-off}}$)	10 MHz
Bandwidth (W)	100 MHz
Noise PSD (N_0)	10^{-22} W/Hz
Target BER	10^{-3}

In Fig. 5, we present the spectral efficiency and corresponding data rate of the proposed adaptive MIMO OFDM VLC system for 4x4 scenarios, i.e., Scenarios 5, 6, 7 and 8. The results are given with respect to transmit SNR defined as E/N_0W. As benchmarks, we present the performance of non-adaptive MIMO system (i.e., without bit loading) for the same scenarios. It can be observed that in Scenario-5, non-adaptive transmission satisfies targeted BER of 10^{-3} at SNR$=$ 137 dB; on the other hand, the required SNR decreases to 110 dB with adaptive transmission. In Scenarios 6, 7 and 8, these further reduce

Table 3. Different MIMO scenarios under consideration.

	MIMO Configuration	LEDs	PDs
Scenario-1	1x1	6	2
Scenario-2	1x1	7	2
Scenario-3	1x1	10	2
Scenario-4	1x1	11	2
Scenario-5	4x4	1 4 13 16	1 5 11 16
Scenario-6	4x4	1 4 13 16	1 2 3 4
Scenario-7	4x4	6 7 10 11	1 5 11 16
Scenario-8	4x4	6 7 10 11	1 2 3 4
Scenario-9	4x16	1 4 13 16	all
Scenario-10	4x16	6 7 10 11	all
Scenario-11	16x4	all	1 5 11 16
Scenario-12	16x4	all	1 2 3 4
Scenario-13	16x16	all	all

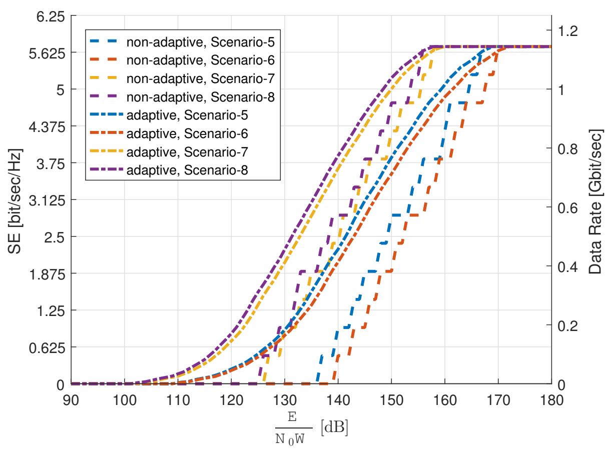

Fig. 5. Spectral efficiency and data rate of RC based MIMO OFDM VLC system with 4x4 scenarios.

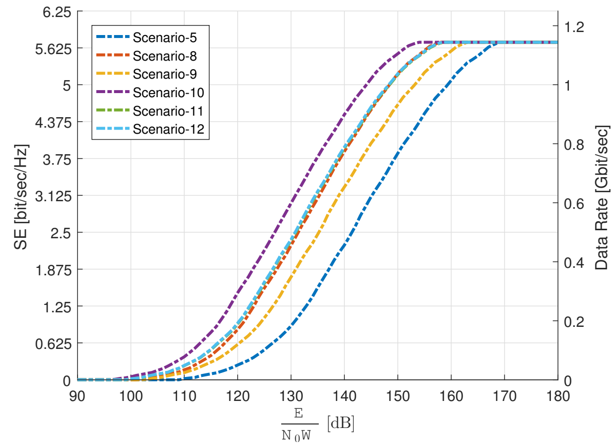

Fig. 6. Spectral efficiency and data rate of adaptive OFDM VLC system in 4x16 and 4x16 MIMO scenarios.

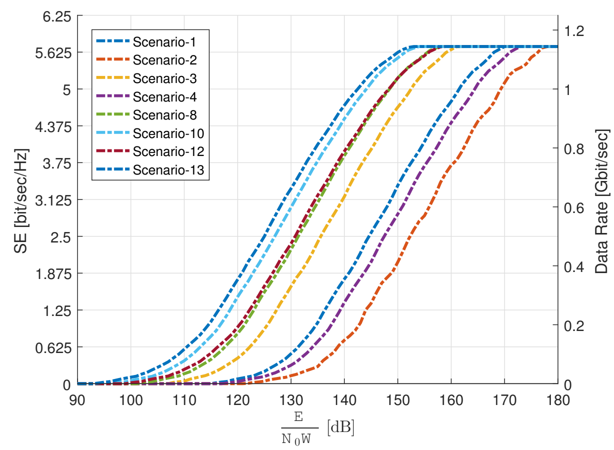

Fig. 7. Spectral efficiency and data rate of adaptive OFDM VLC system in 1x1, 4x4, 4x16, 16x4 and 16x16 MIMO scenarios.

to respectively 110 dB, 102 dB and 102 dB. It is also observed that adaptive 4x4 MIMO systems are able to achieve a spectral efficiency of 5.72, corresponding to 1.14 Gbits/sec for sufficiently high SNRs. It should be noted that channel gain (inversely proportional to LED−PD distance) is the main factor affecting diversity gain. This can be clearly observed through the performance comparisons of Scenarios 5 and 6 (where LEDs are placed at the corners) with Scenarios 7 and 8 (where LEDs are placed at the middle of the ceiling). Since the LED−PD intra-distances in Scenarios 7 and 8 are shorter (i.e., higher channel gain) than those in Scenarios 5 and 6, the system yields a higher diversity gain in Scenarios 7 and 8.

In Fig. 6, we present the spectral efficiency and data rate of the proposed adaptive MIMO OFDM VLC for 4x16 and 16x4 scenarios, i.e., Scenarios 9, 10, 11 and 12. As benchmarks, we include the performances of 4x4 MIMO systems, specifically Scenario−5 (where LEDs are placed at the corners) and Scenario−8 (where LEDs are placed at the middle of the ceiling). It can be noted that the same LEDs are used as transmitters in Scenarios 5 and 9. It is observed that 16x4 MIMO system in Scenario−9 outperforms 4x4 MIMO system in Scenario−5 by 7 dB due to receive diversity. Similarly, a performance difference of 5 dB is observed between Scenarios 8 and 10. Similar observations can be made for transmit diversity. Particularly, 16x4 MIMO system in Scenario−11 has a 10 dB gain over 4x4 MIMO system in Scenario−5 while 16x4 MIMO system in Scenario−12 outperforms 4x4 MIMO system in Scenario−8 by 2 dB gain. Overall performance comparisons further demonstrate that the performance is more sensitive to transmitter alignment since the distances among the LEDs are larger than those among PDs.

In Fig. 7, we finally present the performance of 16x16 MIMO system in Scenario 13. Selected 4x4, 4x16, 16x4 MIMO systems as well as SISO systems are included as benchmarks. The 16x16 MIMO system provides both transmit and receive diversity and therefore achieves the best performance as expected among all given scenarios. It can be however that noted all MIMO systems saturate at the data rate of 1.14 Gbit/sec which is the same rate achieved by the SISO system. This is as a result of the fact that RC does not provide any multiplexing gain.

5. Conclusion

In this paper, we have proposed a rate adaptation algorithm for a MIMO OFDM VLC system with RC. The proposed algorithm was designed to maximize spectral efficiency while satisfying a given BER target. Our simulation results demonstrated data rates up to 1.14 Gbit/sec for RC based MIMO system. We further investigated the effects of different MIMO configurations, transmitter-receiver alignment and transmit/receive diversity on the system performance.

6. References

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