Performance analysis of AGSM adaptive unipolar MIMO-OFDM for visible light communication

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Abstract. Visible light communication is a leading technology in wireless communication which provides free spectrum with high data rate. In this paper, improvement of the data rate is achieved in the adaptive transmission for U-OFDM system which works on switching of various MIMO modes. In VLC system different MIMO modes give different performance on the basis of their modulation size. The adaptive system switches between spatial modulation (SM), spatial multiplexing (SMUX), repetition code (RC) and adaptive generalized spatial modulation (AGSM) MIMO modes on the basis of received SNR and target Bit Error rate to attain high spectral efficiency ($\eta$). The performance of adaptive generalized spatial modulation mode is analysed and compared with the three modes (RC, SM, SMUX) over $2 \times 2$, $4 \times 4$, $8 \times 8$ MIMO systems in realistic channel models. The simulation results show that significant improvement in data rate and spectral efficiency is achieved using AGSM MIMO mode in comparison to SM, RC and SMUX MIMO modes.

1. Introduction
Visible light communication (VLC) corresponds to the usage of wavelength ranging from 380 to 780nm for the purpose of small range optical wireless communication. A different medium of wireless communication is needed because the radio spectrum is already crowded, due to the growing demand for rapid and more safe wireless communication. As a result of its energy efficient characteristic and the recent developments in Light Emitting Diode (LED) technology, VLC seems as a viable option for Radio Frequency (RF) communication. In VLC systems, photodetectors are used as receivers and LED's as transmitters, which means with the help of VLC data transfer and interior lightening of a room can be achieved simultaneously, leaving out any necessity of additional communication system. RF system can be replaced with VLC system to cater high capacity demands.

Previously VLC systems were focussed on elementary schemes like switching, to overcome the drawbacks of LED's, but due to frequency selective nature of VLC channels, there is substantial degradation in the performance of VLC systems due to the presence of inter-symbol-interference (ISI). Certain schemes depending on pulse modulation have been advanced to reduce the ISI associated with the VLC system. To mitigate the ISI OFDM has been considered. The approach of MIMO has been considered for attaining higher data rate for indoor environments. Adaptive transmission technique is used to improve the spectral efficiency using parameters like transmit power and modulation size,
dependent on channel quality. In [1] adaptive transmission dependent spatial modulation system (SM) has been proposed while in [2] adaptive transmission is adapted by the Spatial Multiplexing (SMUX) system. In [3] an adaptive transmission dependent energy efficient MIMO VLC system is presented. while in [4] Repetition Coding (RC) mode and SMUX mode both has been supported by the adaptive system for spectral efficiency betterment. A power efficiency enhancement over the conventional optical Generalized Spatial Modulation (GSM) is proposed in [5] where GSM-MIMO encoding has been considered based on collaborative constellation. A complete analysis on multiuser VLC system is provided in [6], discussing about the current advancement on multiuser precoding, allocation of resources, mobility management and multiple access. In [7] space time block coding has been performed using MIMO techniques in addition with pulse position modulation for data rate enhancement. Proposes an Adaptive Generalized Spatial Modulation (AGSM) mode where Huffman coding is used [8], in this paper performance enhancement over the conventional GSM mode is shown. In [9] depending on joint optimization an AGSM algorithm is proposed to improve the BER performance, and an optimisation algorithm is considered to reduce the complexity of the system. Higher power efficiency is achieved by the unipolar OFDM when comparing to the direct current biased OFDM (DCO-OFDM) at the cost of half the spectral efficiency, as there is no need of a DC bias same as DCO-OFDM, therefore. U-OFDM achieves lower BER as compared to DCO-OFDM. In this context, an adaptive transmission technique has been proposed in this paper to evaluate U-OFDM advantages for MIMOL VLC systems. The system which has been proposed in this paper is carried out to support four distinct MIMO modes which includes (SM, RC, AGSM and SMUX) enabling a group of distinct modulation sizes.

The adaptive system which has been proposed is made to switch between different MIMO modes and tune its modulation sizes depending on the BER targeted and the SNR received to achieve higher spectral efficiency [10].

2. System Model

Assume a MIMO system where j number of LEDs are used as transmitters and receiver nodes has k number of photodiodes as represented in figure 1. The system (MIMO) is aligned as such to cater four distinct MIMO modes (i.e. SMUX, SM, RC, and AGSM). The system model for RC,SM and SMUX is represented in figure 2. In SM [11], transmitter prefers erratically one LED from all the LEDs as active LED and carry the information through indexing. The RC mode is most effortless MIMO mode [12] where entire LEDs radiate the same signal for achieving diversity gain. In SMUX mode [13], all the LEDs are used for transmitting self-reliant information signal concurrently to attain multiplexing gain. Figure 3 represent the system model for AGSM mode, in which the detector detect’s both Quadrature Amplitude Modulation (QAM) constellation symbol and active antennas [14]. The SNR received determines the modulation sizes and select the MIMO modes and provide information through feedback link.

Figure 1. Block diagram of MIMO U-OFDM system with different MIMO modes.
3. Mathematical model

The light which is radiated from the LED transmitter is received by the receiver via the AWGN channel model. AWGN channel model is used for improved data rate, minimum bit error rate and less ISI. The signal is received from the LED at the transmitter.

\[ y_k(n) = \sqrt{E} \sum_j h_{k,j}(n)s_j(n) + w_k(n), \quad n = 1,2,\ldots,N, \quad (1) \]

\[ y_k(n) = \sqrt{\rho} h_{q,k} x + w, \quad (2) \]

The signal received is shown by \( y_k(n) \) pertaining to \( n \)-th subcarrier at the \( k \)-th photodiode, where overall subcarrier is represented by \( N \) in terms of FFT size.

Equation (1), is valid for RC, SM, SMUX modes, whereas \( s_j(n) \) depicts the transmitted signal coming out from \( j \)-th LED for the \( n \)-th subcarrier. The activated LEDs are represented by \( j = \{1,2,\ldots,J\} \) in SM mode. In SMUX and RC modes where \( s_1(n)=s_2(n)=s_j(n) \) for RC and \( s_1(n),s_2(n),\ldots,s_j(n) \) are symbols for SMUX and \( j = \{1,2,\ldots,J\} \) for both the modes. Here, \( h_{k,j}(n) \) represents the VLC channel gain for \( n \)-th subcarrier between the \( k \)-th photodiode and the \( j \)-th LED. \( w_k(n) \sim N(0,N_o) \) is the AWGN term at the \( k \)-th photodiode with zero mean and variance=\( N_o \) [where \( N_o \) symbolize the noise power spectral density]. In equation (1), \( J_a \) is the triggered LEDs, where in case of the RC and SMUX modes \( J_a = J \), whereas for SM mode \( J_a = 1 \).

Equation (2), is valid for AGSM mode [15], the received signal at a specified transmission instance is given as \( \rho \) is the average SNR at each receive antenna. \( x \) is the modulated signal transmitted by
wireless MIMO channel. \( w \) is AWGN with \( \frac{N_0}{2} \) variance and zero mean. Here \( h_{q'} = \sum_{k=1}^{N_a} h_{qk}' \), where \( h_{qk}' \) is channel vector from active transmit antenna \( q_n \) to all receive antenna. \( h_q' \) is summation of active antennas channel vector.

\[
\gamma_n = \frac{E}{JN_0} \sum_{k=1}^{N_a} \left| \sum_{j=1}^{J} h_{k,j} \right|^2
\]

\[
\gamma_n = -\frac{2}{3} \ln(5 P_{bo}) \left( 2^{\frac{n-1}{3}} \right)
\]

Here \( \gamma_n \) is received SNR. Where, eq.(3) is valid for \{RC,SM,SMUX\} MIMO modes, based on \( H \) and eq.(4) is SNR for modulation mode \( n = \{0,1,2,3,\ldots,N\} \) at a target BER of \( P_{bo} \).

\[
\eta_{RC} = \frac{1}{2} \left( \frac{N/2 - 1}{N + N_{CP}} \right) \log_2(M_{RC}^{(\text{max})})
\]

\[
\eta_{SM} = \frac{1}{2} \left( \frac{N/2 - 1}{N + N_{CP}} \right) \log_2(N_t M_{sm}^{(\text{max})})
\]

\[
\eta_{SMUX} = \frac{N_t}{2} \left( \frac{N/2 - 1}{N + N_{CP}} \right) \log_2(M_{SMUX}^{(\text{max})})
\]

\[
\eta_{(av\_g)\_AGSM} = \log_2 m_n + \log_2 \left[ \log_2 \left( \frac{N_t}{N_a} \right) \right]
\]

\( \eta_{RC}, \eta_{SM}, \eta_{SMUX} \) are the spectral efficiencies for RC, SM and SMUX mode respectively. \( M_{RC}^{(\text{max})}, M_{sm}^{(\text{max})}, M_{SMUX}^{(\text{max})} \) are the maximum constellation sizes for RC, SM and SMUX mode respectively. \( N_r, N_t \) is no of receiving and transmitting antenna. \( \eta_{(av\_g)\_AGSM} = \eta_{AM} + \eta_C \), is spectral efficiency for AGSM where \( \eta_{AM} \) is signal dimension and \( \eta_C \) is spatial dimension. \( S_0 m_n = 2^n \). And \( N_t \) and \( N_a \) is transmitted and active antennas, respectively.

4. Algorithm (pseudo – code for adaptive transmission technique)

1. Given \( P_{th}, E \) and \( H, P_{bo} \).
2. Determine \( \gamma \) from (3) and (4).
3. For \( \Xi \epsilon \{ \text{RC,SM,SMUX,AGSM} \} \), do
4. Calculate \( M_{\Xi}^{(\text{max})} \) which BER \( (M_{\Xi}^{(\text{max})}) \leq P_{th} \).
5. Calculate \( \eta_{\Xi} (M_{\Xi}^{(\text{max})}) \) using (5) – (8).
6. End
7. Find \( \Xi^{(\text{max})} \) resembling to maximum \( \eta_{\Xi} (M_{\Xi}^{(\text{max})}) , \forall \ \Xi \).
8. Operating mode switch to $\Xi^{(\text{max})}$.

**Table 1.** SIMULATION PARAMETER FOR ADAPTIVE TRANSMISSION IN VLC

| Parameters                     | Symbol | Value                  |
|--------------------------------|--------|------------------------|
| System Bandwidth              | $B$    | 20MHz [4]              |
| Noise power spectral density  | $N_0$  | $8.1 \times 10^{-19}$ W/Hz |
| Target BER                    | $P_{th}, P_{bo}$ | $10^{-6}, 10^{-3}$ |
| FFT size                      | $N$    | 1024 [4]              |
| Modulation sizes available    | $M$    | 4 - 4096               |
| MIMO setup                    | $N_r \times N_t, N_a \times N_t$ | $2 \times 2, 4 \times 4 \text{ and } 8 \times 8$ |
| Cyclic prefix size            | $N_{CP}$ | 4                      |

The simulation parameters with symbol and detailed values are represented in Table 1.

5. Indoor MIMO VLC channel

The $8 \times 8, 4 \times 4$ and $2 \times 2$ MIMO channels are respectively given by:

$$H = 10^{-6} \times \begin{pmatrix} 0.377 & 0.4830 & 0.4460 & 0.5230 & 0.4000 & 0.4660 & 0.2730 & 0.4300 \\ 0.455 & 0.4070 & 0.3950 & 0.4270 & 0.3840 & 0.3620 & 0.3040 & 0.1410 \\ 0.236 & 0.2430 & 0.3000 & 0.1360 & 0.3560 & 0.3840 & 0.3880 & 0.3820 \\ 0.316 & 0.2020 & 0.3000 & 0.1190 & 0.3530 & 0.1640 & 0.3490 & 0.4780 \\ 0.211 & 0.2060 & 0.2700 & 0.2660 & 0.3270 & 0.3620 & 0.4280 & 0.4260 \\ 0.240 & 0.2240 & 0.2850 & 0.3430 & 0.3040 & 0.3880 & 0.4260 & 0.4200 \\ 0.391 & 0.5010 & 0.3880 & 0.4130 & 0.3450 & 0.3440 & 0.3120 & 0.1220 \\ 0.490 & 0.3970 & 0.4010 & 0.3890 & 0.3500 & 0.3380 & 0.3150 & 0.1530 \end{pmatrix} \tag{9}$$

$$H = 10^{-6} \times \begin{pmatrix} 0.5356 & 0.6831 & 0.3838 & 0.5762 \\ 0.3354 & 0.3440 & 0.5461 & 0.5121 \\ 0.3414 & 0.3161 & 0.5987 & 0.6031 \\ 0.6958 & 0.5614 & 0.4428 & 0.2052 \end{pmatrix} \tag{10}$$

$$H = 10^{-6} \times \begin{pmatrix} 0.6958 & 0.7644 \\ 0.7182 & 0.6447 \end{pmatrix} \tag{11}$$

This indoor VLC model is developed in [1] and is used for our simulation. The normalised channel matrices for $j = (1, 2, 3 \ldots J)$ for $8 \times 8, 4 \times 4, 2 \times 2$ MIMO setups.

6. Results and discussions

The data rate and the spectral efficiency are evaluated in this section for different MIMO modes based on formula depicted in section 5.
Figure 4. BER vs. SNR of 8×8 MIMO for RC mode.

Figure 5. BER vs. SNR of 8×8 MIMO for SM mode.

Figure 6. BER vs SNR of 8×8 MIMO for SMUX mode.

Figure 7. BER vs SNR of 8×8 MIMO for AGSM mode.
Figure 4 – 7 represent the BER performance of $8 \times 8$ MIMO for all the four modes [RC, SM, SMUX and AGSM], with different M-array quadrature amplitude modulation where $M = [4, 8, \ldots, 4096]$. Here maximum spectral efficiency is fulfilled by switching between SM, SMUX, RC and AGSM MIMO modes by assuring the BER targeted based on the SNR received. The BER increases with increasing SNR in all four modes to attain target BER of $10^{-6}$. It has been found that the modes are more efficient in the graphs having the lowest BER values. The average BER reaches the minimum value of $10^{-5}$ in RC, SM and AGSM mode and for SMUX mode the minimum value of BER achieved is $10^{-4.7}$.

In Figure 8 the $8 \times 8$ MIMO VLC system has been considered and the depiction of the spectral efficiency and the corresponding data rate of the proposed adaptive transmission system has been performed. It is observed from the figure 8 that SM, SMUX and AGSM mode are being outperformed by RC in the low SNR region, due to diversity gains. As a result, RC mode is selected by the adaptive system when $\gamma < 65$ dB. The SM mode is selected by the adaptive system for the range of 65 dB to 100 dB. After 100dB, the AGSM mode clearly outperforms all the other modes, therefore, it is selected by the adaptive system as soon as SNR crosses 100 dB. The highest spectral efficiency obtained by the RC, SM and SMUX modes are respectively 2.982, 3.782 and 23.86 b/s/Hz, and the corresponding data rate are 59.64 Mb/s, 74.56 Mb/s and 477 Mb/s, while AGSM achieve the highest spectral efficiency of 27 b/s/Hz corresponding to data rate of 470 Mb/s.

In figure 9 the $4 \times 4$ MIMO VLC system has been considered, the data rate and the corresponding spectral efficiency has been depicted. It has been observed from figure 9 that the RC mode is selected by the adaptive system for $\gamma < 55$ dB. The SMUX mode is selected by the adaptive system for the range of 55 dB to 86 dB. Beyond 86 dB, the AGSM mode is selected by the adaptive system, as it outperforms every other mode. The data rate corresponding to the highest achievable spectral efficiency almost drop to half when compared to the $8 \times 8$ MIMO system.
In figure 10 the $2 \times 2$ MIMO VLC system has been considered, the data rate and the corresponding spectral efficiency has been depicted. In figure 10 the RC mode is chosen by the adaptive system for $\gamma < 54$ dB. The SMUX mode is selected by the adaptive system for the range of 54 dB to 68 dB. For $\gamma > 63$ dB the AGSM mode is selected over any other mode. It can be observed from the graph, that in $2 \times 2$ MIMO modes, the highest spectral efficiency achieved, reduce from 27 b/s/Hz to 10.85 b/s/Hz and data rate reduces from 470 Mb/s to 218 Mb/s when compared to $8 \times 8$ MIMO system. Better spectral efficiency is exhibited by the proposed adaptive MIMO U-OFDM VLC System over the standalone modes, due to the benefits attained by the switching between RC, SM, SMUX and AGSM modes relying on received SNR.

### Table 2. COMPARISON BETWEEN EXISTING MODEL AND PROPOSED MODEL

| Parameter and MIMO modes | Existing Model | | Proposed Model |
|--------------------------|----------------|---|----------------|
|                          | $2 \times 2$   | $4 \times 4$ | $8 \times 8$ |
| Spectral efficiency ($\eta$), b/s/Hz, | $\eta = 2.9$ | $\eta = 3.01$ | $\eta = 2.982$ |
| Data rate ($d$), Mb/s, | $d = 50$ | $d = 60$ | $d = 59.64$ |
| for RC mode | Mb/s | Mb/s | Mb/s |
| Spectral efficiency ($\eta$), b/s/Hz, | $\eta = 3.2$ | $\eta = 3.8$ | $\eta = 3.782$ |
| Data rate ($d$), Mb/s, | $d = 70$ | $d = 70$ | $d = 74.56$ |
| for SM mode | Mb/s | Mb/s | Mb/s |
| Spectral efficiency ($\eta$), b/s/Hz, | $\eta = 6$ | $\eta = 12$ | $\eta = 23.86$ |
| Data rate ($d$), Mb/s, | $d = 120$ | $d = 240$ | $d = 477.2$ |
| for SMUX mode | Mb/s | Mb/s | Mb/s |
| Spectral efficiency ($\eta$), b/s/Hz, | $\eta = 10.85$ | $\eta = 14$ | $\eta = 27$ |
| Data rate ($d$), Mb/s, | $d = 218$ | $d = 279$ | $d = 470$ |
| for AGSM mode | Mb/s | Mb/s | Mb/s |
The Table 2 shows the comparison between the existing MIMO model and the proposed model. Here the comparison is done on the basis of spectral efficiency and data rate which gives us the full information about the trend of changes between $2 \times 2$, $4 \times 4$ and $8 \times 8$ existing and proposed MIMO modes.

7. Conclusion
This paper has been proposed to maximize the data rate of different channel model and compare the performance of AGSM mode with respect of the other three modes (RC, SM, and SMUX). The proposed adaptive system helps us to increase high data rate through switching between four modes. Our simulation results shows that AGSM mode outperforms all the other three modes and helps to achieve high data rate of $218 \text{Mb/s}$ in $2 \times 2$ MIMO setup, $279 \text{Mb/s}$ in $4 \times 4$ MIMO setup and $470 \text{Mb/s}$ in $8 \times 8$ MIMO setup, and spectral efficiency increases up to $10.85 \text{b/s/Hz}$, $14 \text{b/s/Hz}$ and $27 \text{b/s/Hz}$ respectively in $2 \times 2$, $4 \times 4$ and $8 \times 8$ MIMO modes.

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