MIMO Visible Light Communications Using a Wide Field-of-View Fluorescent Concentrator

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***Abstract*— This letter reports a demonstration of a 2×2 multiple-input multiple-output (MIMO) indoor visible-light communication (VLC) system using a novel fluorescent optical concentrator based receiver. This potentially allows a high degree of spatial multiplexing to be achieved using a simple receiver structure that can have a wide field-of-view (FOV). Details of a two-channel MIMO VLC system that operates at 32 Mbps with a receiver acceptance angle of ±22.5 degrees are given, and future directions discussed.**

***Index Terms*— FOV, MIMO, VLC, LED, Fluorescent Concentrator, Visible Light Communications**

I. Introduction

Visible Light Communication (VLC) is an emerging technology that combines efficient illumination with wireless communications. VLC enables access to hundreds of THz of unlicensed spectrum using low cost components [1], offering potential solution to the radio frequency (RF) spectrum crunch problem. However, the data rate performance of single channel VLC is limited [2].

In order to mitigate this problem, Multiple-input multiple-output (MIMO) techniques have been studied and implemented in VLC [2]–[7]. MIMO VLC is also attractive because in typical lighting applications a number of LEDs are used to achieve the required illumination level [8].

An ideal MIMO VLC receiver has a wide field-of-view (FOV) and a high optical gain. Non-imaging MIMO receivers can have wide FOV [9], but they have a relative small input apertures, which limits their optical gain. In contrast imaging MIMO receivers employ a lens which increases the optical gain of the receiver but limits its FOV [7].

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The FOV of an imaging MIMO VLC receiver can be increased using an architecture, such as the one shown in Fig. 1.a, which includes an array of photo-detectors (PDs). However, this array increases the system complexity and cost [4], [7]. These problems can be avoided by using a large PD in the receiver. However, larger PDs have smaller bandwidths, which is not desirable.

The Fluorescent Concentrator (FC) allows the normal étendue constraints of conventional concentrating optics to be broken and offers a combination of a wide FOV and a high gain [10]–[13]. This FC can be made from inexpensive fluorescent PMMA that is widely available. The combination of an imaging lens with a FC potentially enables a MIMO VLC receiver to combine the high optical gain advantage of imaging MIMO with the wide FOV advantage of non-imaging MIMO without using a large number of PDs in the receiver, as shown in Fig. 1.b.

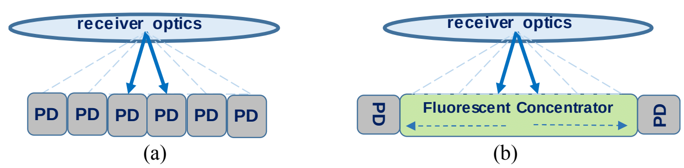

Fig. 1. 2-channel imaging MIMO receivers: (a) Conventional design using an array of PDs to increase FOV (b) Proposed FC-based design. Note that the figure shows a one dimensional design where beams arrive at different angles in one dimension only. For the two dimensional case a 2D detector array is used in (a) and multiple PDs are placed around the edge of a 2D concentrator in (b)

In this letter, the feasibility of a MIMO VLC system using a fluorescent concentrator (FC-MIMO) is investigated. Section II describes the working principles of the concentrator, together with the system model and parameters of the FC-MIMO. In section III, a proof-of-concept two channel FC-MIMO system, with a wide acceptance angle, is described and characterised. Lastly, section IV draws conclusions and details future work.

II. System Design

A. Fluorescent Concentrator (FC)

Fig. 2 shows a cross section of a FC. Light enters the FC and is absorbed by a fluorophore (a). This converts the incoming radiation to a longer wavelength emission. This light can either be re-absorbed (b), escape the FC (c), or retained by total internal reflection until it reaches the edge where a PD is located (d).

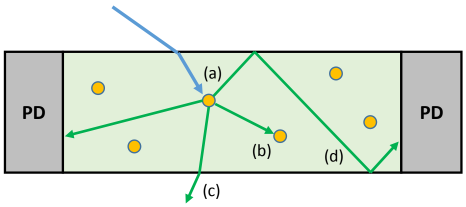

Fig. 2. A schematic of the physical processes in a fluorescent concentrator

A high concentration of fluorophore is desirable to absorb the incident light, but it can also lead to re-absorption (b), thus limiting the amount of emitted light that can reach the edge of the structure. However, a controlled level of re-absorption can be utilised to control the proportion of light reaching each edge of the FC. If the transmitters are imaged onto the FC the difference between signals received by the two PDs allows MIMO operation.

B. MIMO Fluorescent Concentrator demonstration

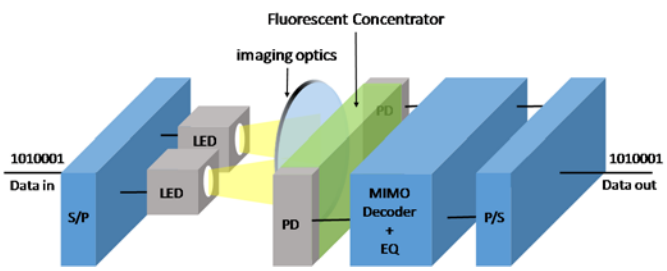

Fig. 3. Schematic of the FC-MIMO system

Fig. 3 shows a schematic diagram of a two channel MIMO system using the FC. Three modes of operation can be investigated.

i) A single input single output (SISO) mode, where each channel is individually operated.
ii) Ganging mode, where both LEDs transmit the same data, thus increasing transmitted power compared with a single device
iii) MIMO (or Spatial Multiplexing (SM) [7]) mode, where each LED transmits an independent data stream simultaneously.

The ganging mode offers higher transmit power compared to SISO and relatively low complexity in the receiver, but does not offer a linear increase in data rate with the number of transmitters. On the other hand, by transmitting independent and separately encoded data signals from each of the multiple LED sources the MIMO mode potentially offers a linear increment in data rate with the number of transmitters.

In a typical MIMO system, there are q receivers which receive different combinations of the signals from p transmitters. Mathematically, MIMO transmission can be modelled as

$$\boldsymbol{Y} = \boldsymbol{H}\boldsymbol{X} + \boldsymbol{N} \tag{1}$$

where $\boldsymbol{Y}$ is a q-by-1 received signal vector; $\boldsymbol{H}$ is the q-by-p channel matrix; $\boldsymbol{X}$ is a p-by-1 transmitted signal vector; and $\boldsymbol{N}$ is the q-by-1 noise vector.

The MIMO channel matrix $\boldsymbol{H}$ can be determined from the results obtained from transmitting MIMO training data and measuring the received signal y_{ij} from the i^{th} receiver and the j^{th} transmitter where $i \in \{1, \dots, p\}$ and $j \in \{1, \dots, q\}$. Each element h_{ij} of the channel matrix $\boldsymbol{H}$ is then obtained by

$$h_{ij} = \sqrt{y_{ij}^2 - \sigma_i^2} \tag{2}$$

where σ_i^2 is the noise variance corresponding to the i^{th} receiver , estimated from the received noise y_i when no signal is transmitted [4]. Using this measured channel information, the crosstalk penalty can also be calculated [14].

The estimated signal, $\bar{\boldsymbol{X}}$ can then be retrieved by multiplying the received signal vector with a pseudo-inverse channel matrix $\boldsymbol{G}$,

$$\bar{\boldsymbol{X}} = \boldsymbol{G}\boldsymbol{Y} \tag{3}$$

where $\boldsymbol{G}$ can be derived from the $\boldsymbol{H}$ matrix using zero-forcing (ZF) or Minimum Mean Square Error (MMSE) algorithms [14]. Once the estimates of the transmitted signal are obtained these are low pass filtered and equalized if appropriate. The received data streams are then compared with the transmitted data streams to calculate the Bit Error Rate (BER).

III. Experimental Proof-of-Concept

A. Characterisation of FC-MIMO system

The FC was fabricated using a 100 µm thin fluorescent layer made from Coumarin-6 (Cm6) dye embedded in UV curable epoxy NOA68 (n = 1.54). Cm6 is selected as the fluorophore dye because of its high quantum yield, absorption peaking in the blue region of the spectrum, and short fluorescence lifetime [11]. The Cm6 layer was sandwiched between two microscope slides (25 mm × 75 mm × 1 mm, n = 1.52).

The characterisation of the MIMO FC receiver is carried out by modulating each LED in the transmitter with a low frequency sinusoid and focusing the beams from the two LEDs into different spots on the FC. The resulting signals from the two PDs are amplified and the relative voltages recorded on an oscilloscope. This process is repeated for different illuminating spot diameters and different positions along the dotted line shown in Fig. 4 (a).

Fig 4 (b) shows the resulting voltages. Examining the blue line, it can be seen that there is an exponential decay in the receiver output voltage as the illuminating spot moves away from the corresponding detector as would be expected. The drop in voltage for spots close to the detector is due to the illumination missing the concentrator edge.

Using the data from Fig. 4.b, a 2-by-2 $\boldsymbol{H}$ matrix for a particular spot size and distance from the PD can be constructed. This allows the crosstalk penalty, which is the increase in SNR required by the MIMO to achieve the same target BER as perfectly separated channels, to be calculated [12].

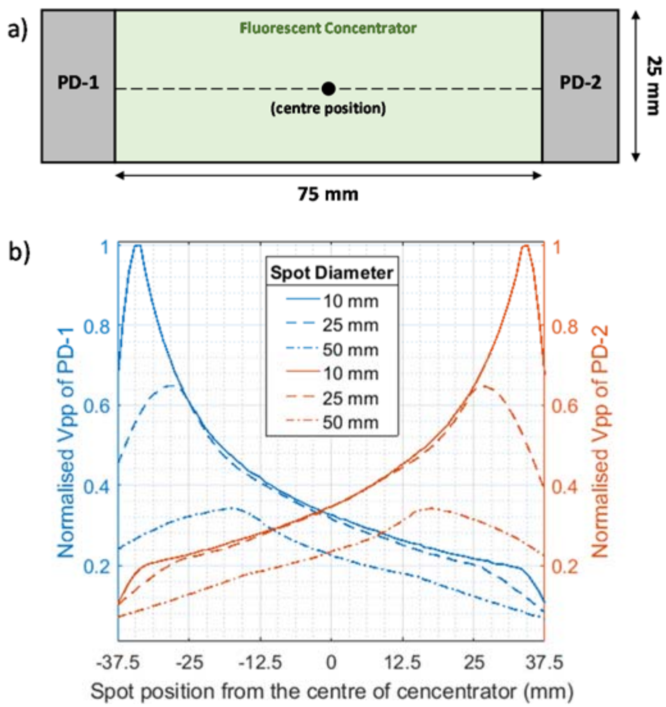

Fig. 4. FC-MIMO channel characterisation; a) incoming light is focused on the position along the black dashed line; b) recorded and normalised peak-to-peak voltage (Vpp) from the PDs to construct H matrix.

Typical cases of the FC-MIMO are considered in this experiment, where two spots of the same size, positioned symmetrically, either side of the centre position (marked in Fig 4.a) and lying along the dotted line. The contours of calculated crosstalk penalty for these cases with various spot separation and spot diameters are shown Fig. 5.

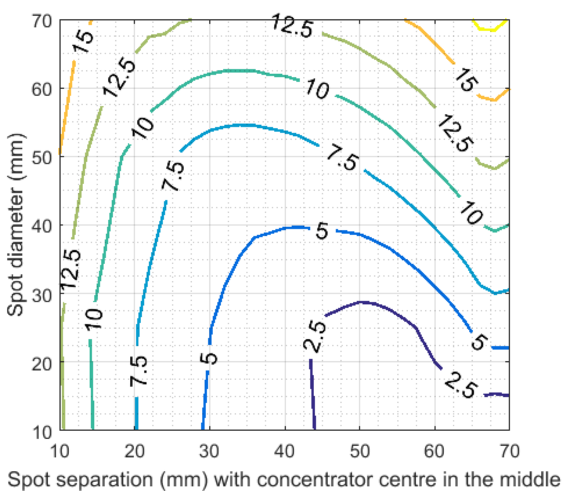

Fig. 5. Calculated crosstalk penalty (dB) from constructed H matrix

The re-absorption process limits the amount of emitted light that can reach the edge of the FC. Consequently, the crosstalk penalty decreases when spots of particular size are further apart. However, with further separation, the light from the spot can fall outside of the FC surface which in turn reduces the signal, thus increasing the penalty. Consequently, as shown in Fig. 5, for a particular spot size, there is an optimum separation distance between two spots which minimizes the crosstalk penalty.

B. Communications Experiment

The experimental setup for 2-channel communications experiments is shown in Fig. 6. Currently, the proposed configuration can only support two PDs at the receiver. At the transmitter two Lumileds LXHL-MW1B White LEDs with 2.5 MHz of bandwidth were used. Each of the two resulting channels was driven by a pseudo random binary sequence with luminous flux of 20 lm using a Keysight 81150A arbitrary waveform generator. The two LED transmitters are separated by 30 cm and the distance from the centre point between two LED transmitters to the receiver is also 30 cm, resulting in incident angles of approximately ±22.5 degrees.

At the receiver, a Comar Optics 61FQ63 Fresnel lens was used to focus the incoming light from each transmitter to separate spots on the FC which had a Hamamatsu S2551 Si Photodiode are coupled each to its left and right edges. The two spots are 20 mm in diameter and separated by 60 mm distance, which corresponds to crosstalk penalty of approximately 2.5 dB as shown in Fig. 5.

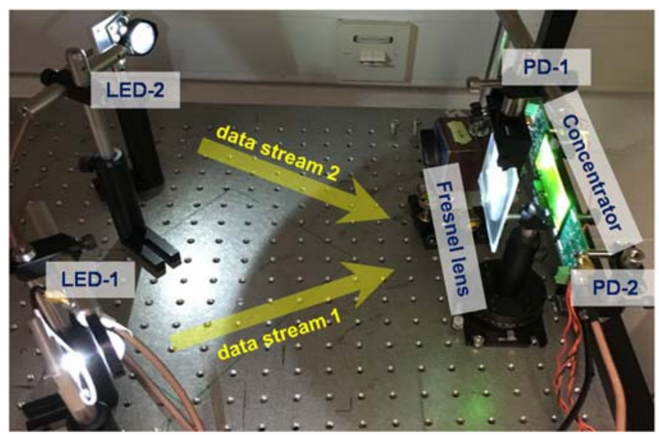

Fig. 6. Experimental setup of FC-MIMO

The received signals from both PDs were then captured simultaneously using a Keysight MSO6104A Oscilloscope, and further signal processing was performed offline. The received data sequences were then compared with the transmitted sequences to determine the bit error rate (BER).

The measured BERs of ganging and MIMO modes against data rate using on-off keying (OOK) modulation scheme are shown in Fig. 7. When the forward error correction (FEC) threshold bit error rate (BER) of 3.8×10^{-3} is considered [15], the ganging and MIMO modes achieve data rates of 26 Mbps and 32 Mbps, respectively. Configurations using the same individual channel power level with only 1 channel is active using either PD-1 or PD-2 (SISO mode) show almost identical data rates of 19 Mbps at the same reference BER. Summing the results of the two SISO mode channels suggest that the maximum data rate of the MIMO mode is 38 Mbps when no crosstalk is present. The ganging experiment uses the same data on both channels, showing that MIMO offers a significant increase in data rate for over a single channel data transmission operated at the same power levels. Although crosstalk between channels means that the gain in data rate of the MIMO mode is less than the factor of 2 that would be achieved in an ideal 2×2 MIMO system, these results show that MIMO mode still has significant benefits.

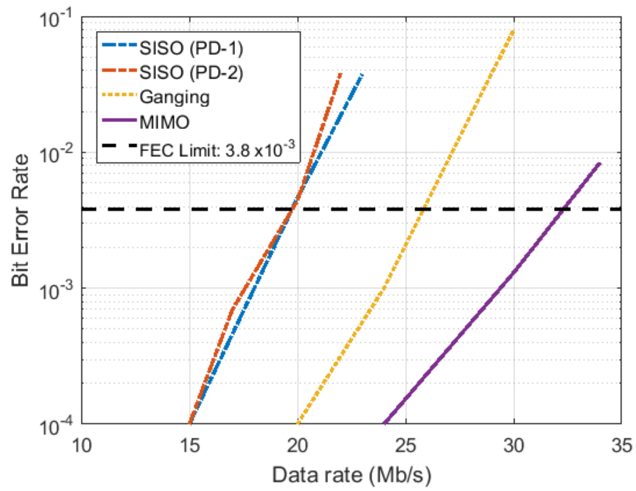

Fig. 7. Data rate against the BER for ganging and MIMO modes; the results with only 1 channel active (SISO) is shown for reference

IV. Conclusion and Future Work

A novel receiver design for MIMO VLC using an imaging lens and fluorescent concentrator (FC-MIMO) has been proposed. This receiver design allows a wide acceptance angle using substantially fewer photo-detectors than a conventional imaging MIMO VLC receiver. A proof of concept system with an acceptance angle of ±22.5 degrees was implemented using only two PDs at the receiver and an aggregate data rate of 32 Mbps was achieved.

The advantage of the FC-MIMO approach is that the number of detectors required at the receiver scales with the number of MIMO channels that are being transmitted, and that a wide FOV (which requires a physically large detector for practical cases) can be achieved. The alternative, using a detector array, offers potentially higher performance (as there is no crosstalk between each detector in the array). However, if two signals fall entirely on one detector it is not possible to distinguish between them in the MIMO decoding process. This, together with the requirement for small detectors (to enable high bandwidth) and wide FOV leads to arrays with large numbers of detectors, most of which are unused for any particular configuration. The trade-off is therefore between increased crosstalk for the FC-MIMO approach, but a much simpler scalable structure compared with the array approach. Understanding this trade-off is an area of future work.

Future work will focus on understanding this trade-off, material optimisation, and the implementation of receivers able to support greater numbers of spatial channels.

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