Multiple-Input Multiple-Output Optical Communication with Arduino (MOCA)

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***Executive Summary*—This work details the design and development of Multiple-Input Multiple-Output Optical Communication with Arduino (MOCA), a proof-of-concept Multiple-Input Multiple-Output (MIMO) Visible Light Communication (VLC) link implemented using off-the-shelf LEDs and Arduino boards.**

Rapid urbanization around the world has brought new demands for faster and more reliable internet access and lighting. The current Wi-fi internet is becoming inadequate as more routers sharing the small ISM band will result in a slower, interference-prone network. On the other hand, VLC systems can provide more efficient internet access for the growing urban population since it has a larger bandwidth (hundreds of THz) and they are more secure as light does not travel through walls. Moreover, VLC systems provide LED lighting which is replacing incandescent and fluorescent light bulbs for their energy efficiency, low-cost, and longer lifetime. VLC systems are under serious consideration for implementation in most high-occupancy buildings including hospitals as they can be integrated into existing and emerging LED lighting systems to provide wireless communication. Implementing VLC systems will provide a more efficient, faster, and more versatile wireless communication and lighting infrastructure to the growing urban population. However, practical use and implementation of VLC systems has been limited. For this reason, MOCA aims to provide an inexpensive platform for developing MIMO VLC systems for both pedagogic and research purposes. MOCA is a step toward making VLC technology more accessible and affordable so that more efforts can be made to put the technology into practical use.

MOCA aims to lay the groundwork for low-power circuit design and MIMO signal processing as transistors and signal processing schemes must be able to operate at higher frequencies for VLC applications. This 2-by-2 MOCA achieves data throughput of 2 kbps over a link distance of 30 cm. The transceiver circuit has low power consumption and has a maximum switching frequency of 1 MHz. A 3-by-3 MOCA was built to show the system can be easily scaled up. Moreover, the 2-by-2 MOCA receiver built with an FPGA board in replacement of Arduino achieved a sampling rate of 1 Mbps. This shows that using more sophisticated microcontrollers can significantly improve the throughput.

Future works involve improving bit error rates at greater link distances and improving throughtput by implementing a more complex modulation scheme.

I. General Description and Introduction

The development of wireless communication technology has equipped urban areas of the world with high-speed and convenient internet access. At the same time, the internet is now challenged with demands for higher speed, data security, and efficiency as the urban population is projected to reach 5 billion by 2030 [1]. The traditional Wi-fi internet will become less effective in ever-growing urban areas as a high density of routers sharing the narrow ISM band will lead to slow data rates, interference, and bit errors.

Visible Light Communication (VLC) is an alternative technology under serious consideration to enhance and/or replace the RF wireless communication infrastructure. Visible Light Communication is an emerging technology that uses visible light in the range, 400 THz (780 nm) to 800 THz (400 nm) [2], as a carrier of information. VLC systems provide a viable networking solution to some of the problems associated with the existing RF communication systems, such as low energy efficiency and limited bandwidth. First, the use of LEDs in VLC systems serves the dual purpose of wireless communication and lighting, as shown in figure 1. LEDs are fast replacing incandescent and fluorescent light bulbs with the benefits of low-cost, high efficiency, and reliability. The wide availability of LEDs for general illumination in most buildings makes them an attractive choice for transmitters. Furthermore, VLC systems can be made energy efficient by implementing low-power LED drivers. In populous urban areas, LEDs are superior sources of light as they have better energy efficiency and life-time. Second, the lack of legal regulations for the visible light spectrum provides a cheaper and larger available bandwidth (hundreds of THz) than the existing RF systems can provide (hundreds of GHz). Third, VLC networks are inherently secure as light does not travel through walls. This allows for frequency re-use, and networks do not interfere between one room and the next. Lastly, the use of visible light as a carrier of data frees VLC systems from electromagnetic interference and associated health concerns. This allows for wireless communication in places where RF communication has been limited: hospitals, factories, under-water, labs, and airplanes.

The impact VLC will have on wireless communication and lighting is significant. Thus, we were inspired to develop a low-cost prototype MIMO VLC link that can be used for both pedagogic and research purposes. To put VLC systems into practical use, transistors are required to switch at higher frequencies, and more advanced signal processing schemes in the THz range are required. This work aims to lay the groundwork for high-speed circuit design and signal processing for VLC applications. We hope to make the VLC technology widely available to engineers and students so that the technology can be developed further to improve the current wireless communication and lighting technology, and the urban life which has become increasingly dependent on the aforementioned technology.

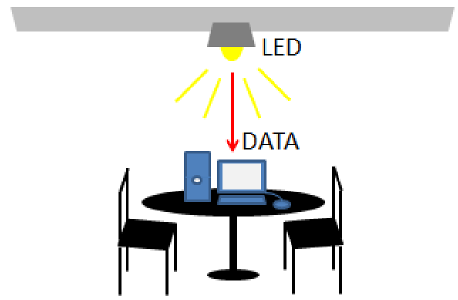


Fig. 1: VLC Merging Lighting and Communication

A. *Proposed Work*

The focus of this work is to develop the MOCA hardware to demonstrate the feasibility of MIMO visible light communication with inexpensive components such as Cree XM-L LEDs and Arduino boards. MOCA provides a low-cost prototyping platform that can easily be put together. The transceiver circuits have been designed for operation at frequencies up to 1MHz.

In figure 2, the high-level topology of the 2-by-2 MOCA is shown. The system consists of two Arduino boards acting as a signal generator and a processor. Two transmitters and two receivers are implemented to transmit and process two streams of data.

MIMO technology is commonly used in modern communication systems to achieve higher data throughput despite interference, signal fading, multipath, and system complexity [3]. Since there is little noise and multipath fading in a line-of-sight (LOS) channel, MIMO schemes can be implemented in VLC systems without extensive signal processing [4].

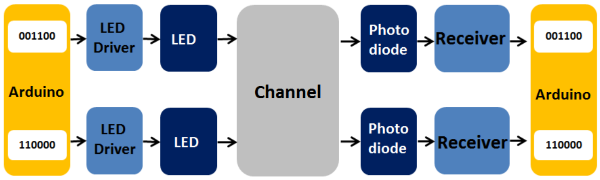
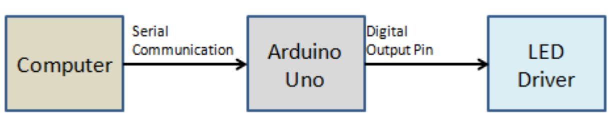


Fig. 2: High-level 2-by-2 MOCA Topology

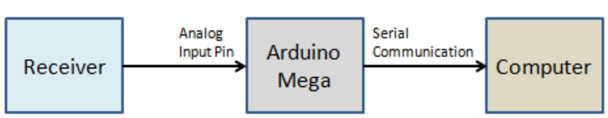
The use of multiple channels motivates power efficient designs since more power is consumed as the system scales up. In dynamic circuits, power consumption is proportional to frequency and inversely proportional to load capacitance, which makes data rates and power economy conflicting design goals. CMOS circuits and small component sizes are chosen to minimize power consumption. In the following sections, we discuss the design choices and resulting system performance.

II. Hardware Design

The block diagrams of the MOCA transmitter and receiver are shown in figure 3. In figure 3a, the computer transmits data to the Arduino Uno through serial communication. The Arduino Uno processes the data and outputs the resulting signal from its digital output pin to the LED driver. In figure 3b, the receiver outputs the received signals to the Arduino Mega through its analog input, and the Arduino Mega sends the recovered information to the computer through serial communication. The remainder of this section will discuss the LED driver and receiver in detail.



(a) Transmitter Block Diagram



(b) Receiver Block Diagram

Fig. 3: Block Diagram of MOCA Hardware

A. *Transmitter Design*

The transmitter hardware consists of an Arduino board and LED driver. The LED driver circuit conditions the signals generated by the Arduino Uno and sources switched-current to LEDs. It consists of a Schmitt trigger signal-conditioning circuit, an emitter follower, and a charge-pump. The crucial design considerations include minimizing power consumption, maximizing operating frequency, and minimizing component sizes.

1) Arduino Transceiver Interface: The transmitter side of MOCA uses an Arduino Uno, configured as a Software Defined Radio (SDR), to generate On-Off Keying (OOK) signals from DC to several MHz at a fraction of the cost of specialized SDRs such as the USRP2 [5]. The large number of Input/Output (I/O) pins available on Arduino makes it attractive for use in MIMO systems. The Arduino Uno has thirteen digital output pins; higher-end models provide more pins. Arduino provides a standard programming language complier written in Java, C, and C++, with full support for software packages such as MATLAB and Simulink.

The raw 5V OOK output signal, with a frequency in the MHz range, produced by Arduino is shown in figure 4.

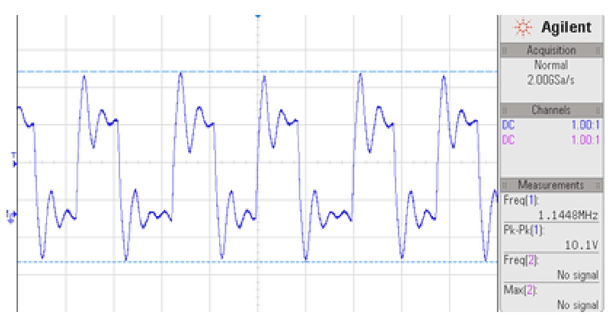


Fig. 4: 1MHz Arduino OOK Signal

B. *Schmitt Trigger*

To source stable currents up to 1.3 A to each LED, the output of Arduino must be filtered and amplified. A Schmitt trigger, used as a square wave generator (figure 5), is implemented in preference to an operational amplifier. The smaller circuit provides a larger bandwidth and faster switching, due to the reduced capacitance, while reducing the amplitude of the ripple, introduced by Arduino, as shown in figure 6.

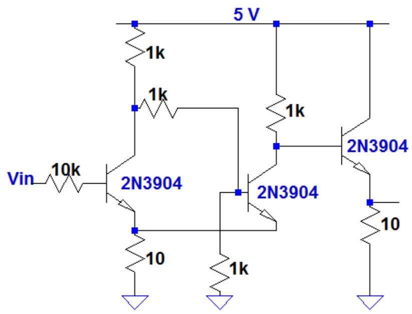


Fig. 5: Schmitt Trigger Followed by Emitter Follower

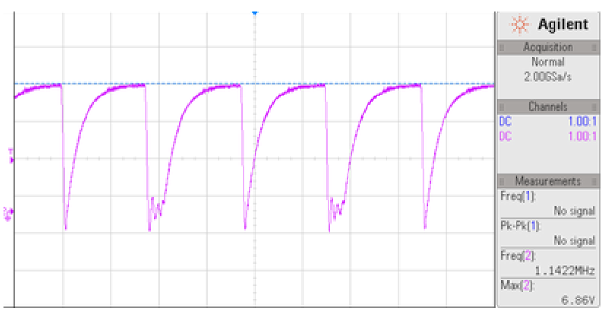


Fig. 6: 1MHz Arduino Signal After Signal Conditioning

An emitter follower current amplifier stage was added to source the requisite current to drive the capacitive load presented by the gates of the N-type MOSFETs shown in figure 7.

1) Charge-pump: Phosphor-based LEDs are the primary carriers of information in MOCA. A blue LED chip coated with yellow phosphor is the most common commercially available source of white light. This phosphor-based LED generates white light by phosphor conversion in which some of the blue light emitted from the InGaN-based LED chip excites yellow phosphors to emit yellow light while the remainder travels through the phosphor layer without alteration. Phosphor-based LEDs are more advantageous than trichromatic LEDs in that they are more easily modulated with less hardware and more stable in color [6]. They suffer from a small modulation bandwidth (2 MHz) due to the slow response of the yellow phosphor, but several techniques such as blue filtering and equalization can increase the bandwidth up to 45 MHz [7]. Cree XM-L LEDs are power LEDs that output 416 lumens with 1 A drive current [8]. A standard 60 W incandescent light bulb outputs 800 lumens, so 2 LEDs each driven with 1 A can replace one incandescent light bulb. Shown

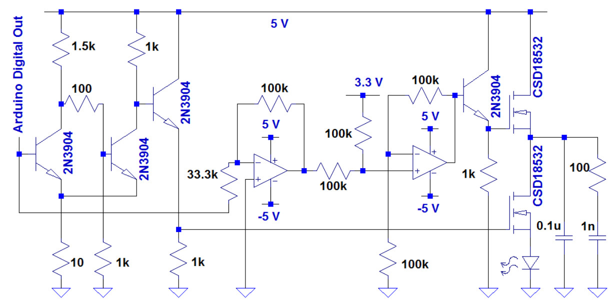


Fig. 7: LED Driver

in figure 7 is the LED driver circuit consisting of the Schmitt trigger and a charge pump. To source high currents efficiently, the charge-pump was connected to the output of the emitter follower. Power MOSFETs, CSD18532, are used to source large currents. The LED driver switches up to 1.3 A of current at 1 MHz and lower frequencies. Most importantly, it is a CMOS circuit and provides better energy efficiency than a linear regulator in which the power consumption is proportional to the square of the driving current.

The 2-by-2 MOCA has dynamic power consumption of 67 mW. The lowpass filter in parallel with the capacitor reduces high frequency noise.

2) Power Economy: The MOCA circuits have been carefully designed to maximize power economy. In the MOCA hardware, virtually all of the power is consumed in the transmitter circuit which sources about 1 A of current. Other parts of the circuit draw very little current. To minimize power consumption in the transmitter, the LED driver was designed as a CMOS circuit. Although two NMOS transistors are used instead of a NMOS-PMOS pair to achieve better symmetry, the circuit can still be modeled as a CMOS circuit since only one transistor is on at any given time. The power consumption of a CMOS circuit is determined by the static and dynamic power, a majority being the dynamic power consumed during high frequency switching. Dynamic power is consumed in charging and discharging the load capacitor, and is approximated by equation 1,

$$P_d = \alpha C_L V_{cc}^2 f \tag{1}$$

Where C_L is load capacitance, V_{cc} is supply voltage, and f is frequency. α, the activity factor, is the period of the change in output over the period of the clock. In the MOCA transmitter, this factor is 0.5 assuming the equal probability of 1's and 0's in binary-encoded data.

Additionally, the circuit consumes short-circuit power when both transistors are on simultaneously. This is due to the finite slew rate of the transistors. Short-circuit power is approximated by equation 2 [9],

$$P_{sc} = \frac{t_r + t_f}{2} V_{cc} I_{max} f \tag{2}$$

Where t_r and t_f are the rise time and fall time, respectively. The 2-by-2 MOCA transmits each bit at 1 kHz, and its total power consumption is 67 mW.

C. Receiver Design

The receiver circuit consists of a pair of inverting amplifiers to convert the received photocurrent to an output voltage in the range 0-2.5 V to interface with Arduino.

1) Receiver Circuit: The receiver circuit in figure 8 is designed with a pair of general-purpose op-amps, LF411.

The first stage converts photocurrent to voltage. The second stage inverts this signal to interface with the Arduino Mega. The output capacitor is used for noise reduction.

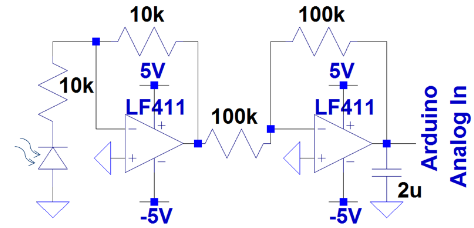


Fig. 8: Receiver Circuit

To receive higher frequency signals at 1MHz, the LF411 was replaced with the LT1222, a wide-band op-amp with the gain-bandwidth product of 500 MHz [10]. The input to the LED driver (top) and the received output (bottom) at 1 MHz are shown in figure 9. The delay in the received output is most likely due to the slow response of the yellow phosphor.

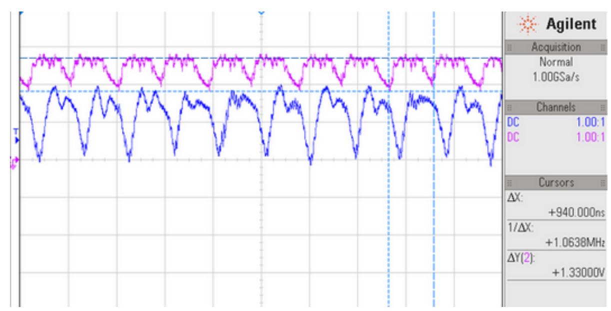


Fig. 9: Input Voltage (top) and Receiver Output (bottom) at 1MHz

The 2-by-2 MOCA hardware schematic is shown in figure 10, which consists of one computer, one Arduino Uno and two LED drivers in the transmitter side, and one computer, one Arduino Mega, and two receivers in the receiver side.

III. Signal Processing

In this work, we focus on demonstrating that real-time MIMO communication is feasible with Arduino. Two streams of text were encoded with On-Off Keying and were transmitted at a symbol rate of 135 Hz. Since there are two channels

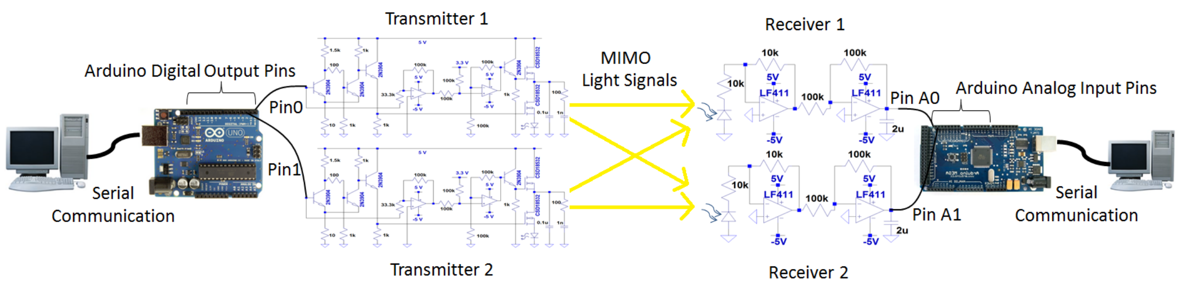


Fig. 10: 2-by-2 MOCA schematic

and eight bits in each ASCII character, the net throughput is about 2 kbps. 135 Hz was chosen to prevent the LEDs from flickering for human eyes ($\geq$ 60 Hz [11]) while staying well within the range of the Arduino's sampling rate.

A. *Transceiver Synchronization*

The MOCA receiver performs two tasks: sampling and decoding. Since Arduino runs on a single-core processor, multithreading must be achieved by an alternative means such as task scheduling or interrupts in which the processor switches from one task to another upon receiving a control signal. Since the limited memory space available on Arduino does not allow for oversampling or storing a large number of samples, the receiver and transmitter Arduino boards must be synchronized so that the receiver Arduino can efficiently switch between sampling and decoding.

The plots of the transmitter (top) and receiver (bottom) signals are shown in figure 11 to illustrate transceiver synchronization. The initial synchronization in the transceiver is achieved by having the transmitter output a long stream of 1's followed by a short trigger signal (0's) while the receiver continuously alternates between sampling and decoding. The transmitter sends 8 bits of an ASCII character shortly after transmitting the trigger signal. The time between the trigger signal and data is predetermined and is known to the receiver. The receiver is activated before the transmitter is activated, and it waits for the transmitter to start sending data. When the trigger signal, a short drop in the transmitter, is detected by the receiver, the receiver calculates the amount of delay needed to sample within the frame of the actual data. After the receiver samples the data, the transmitter sends a stream of 1's to allow the receiver to decode the data. Then, the same process is repeated for each ASCII character to re-synchronize since the execution time for each task varies slightly between iterations.

The communication overhead is about one-third of each symbol period as shown in figure 11. To reduce the overhead, re-synchronization can be performed less frequently. However, the focus of this work is demonstrating MIMO VLC with Arduino, so speed is sacrificed for better synchronization.

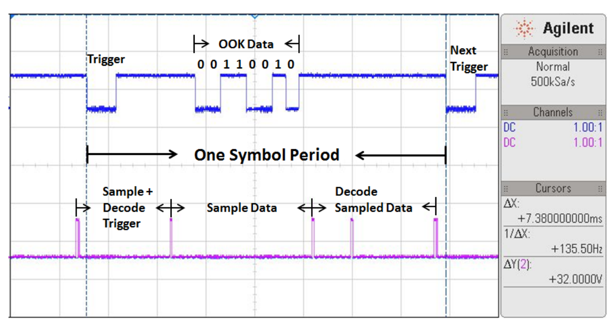


Fig. 11: Transmitter (top) and Receiver (bottom) Synchronization

B. *Decoding Algorithm*

Before a decoding algorithm is applied to the MIMO OOK signals, the received signals are truncated and filtered to mitigate the effect of desynchronization and to reduce noise. Each receiver collects 189 samples of each ASCII character. The sampling frame is set larger than the actual data frame to ensure the entirety of the data is sampled. Therefore, any excess samples must be discarded by truncation. After truncation, the resulting data contains 136 samples in which each of the 8 bits contains 17 samples. Then, the truncated data is downsampled to obtain its 8-bit representation. A moving average filter is applied in which 5 samples in the middle of every bit are averaged. The moving average filter is chosen for its simple implementation and effectiveness in reducing random noise in time-domain encoded signal [12]. After downsampling, the resulting data contains 8 samples which represent the 8-bit MIMO signal from each receiver.

After downsampling, the samples are scaled according to the ratio between the Arduino's Analog to Digital Conversion (ADC) readings and the actual output levels. Then, the samples are multiplied by the inverse channel matrix. The resulting products are still analog due to noise. To obtain binary representations, a threshold of 0.5 is imposed on each bit. The final step is taking the 8 bits and turning them into the corresponding ASCII character. More detailed explanation about the channel matrix is presented in section D.

C. Bit Error Rate

Bit error rates (BER) were obtained at varying distances from 12.5 cm to 30 cm. The link distance is limited by desynchronization between transmitters and receivers at longer distances and is due to the primitive synchronization technique. The trigger signal is received and decoded without any signal conditioning or pre-processing, making the synchronization process sensitive to noise and ambient light as the link distance increases. Shown in figure 12 is the plot of the bit error rate, where 100,000 bits of data were sampled for each link distance.

The BER can be improved in several ways. First, a better synchronization technique with more signal processing can be implemented. Second, more LEDs can be added to each transmitter to increase its luminous intensity so that the transmitted signals can be detected by the receivers at larger distances. Lastly, the BER can also be lowered by implementing forward error correction.

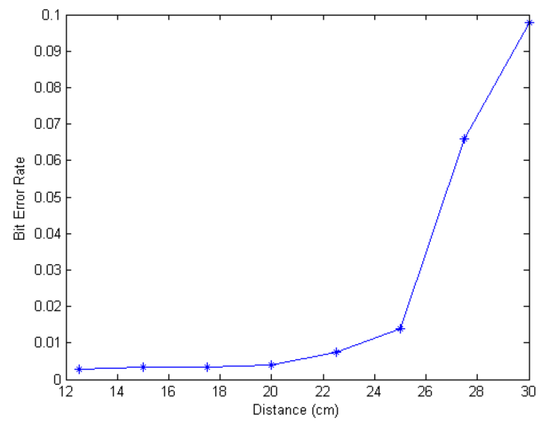


Fig. 12: BER as a Function of Link Distance

D. Channel Matrix

MOCA's decoding algorithm relies on intensity modulation and direct detection (IM/DD). IM/DD uses the relationship between the brightness of transmitter LEDs and the magnitude of the corresponding photocurrent. It estimates the amount of photocurrent as a function of transmitter intensity, distance, angle, and other geometrical properties [13].

The LOS channel can be modeled as a baseband channel in which the channel is lowpass due to the LED modulation bandwidth. Then, the received signal can be expressed as a convolution of the input signal and the channel impulse response, as shown in equation 3.

$$y(t) = x(t) \otimes h(t) + n(t) \tag{3}$$

where $n(t)$ is noise. Since the distance between a transmitter and a receiver is large compared to the detection area of a photodiode, it is assumed that the received signal intensity is uniform across the detector and that all signals arrive at the same time [14]. Then, the impulse response of the

LOS channel can be approximated as the time-independent function. Since h is independent of time, the convolution in equation 3 becomes a multiplication.

Each photodiode receives the superposition of each transmitted signal at different intensities. In a MIMO system, N independent streams of data can be decoded with N-by-M transceivers where $M \geq N$. The use of extra receivers (size denoted by M) reduces bit errors although it is more hardware intensive. The decoding algorithm for a 2-by-2 transceiver system is illustrated in figure 13.

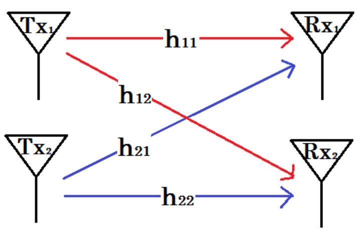


Fig. 13: Two Transmitter-Receiver Pairs

The channel transfer function matrix for the above system in figure 13 is given by equation 4.

$$H = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \tag{4}$$

Where h_{ij} is the impulse response of each channel. The received signals R_{x_1} and R_{x_2} can be written in terms of transmitted signals T_{x_1} and T_{x_2}, and the channel transfer function. With the knowledge of the channel, the individual transmitted signals can be recovered by inverting the channel transfer function, as shown in equation 5.

$$\begin{pmatrix} T_{x_1} \\ T_{x_2} \end{pmatrix} = H^{-1} \left(\begin{pmatrix} R_{x_1} \\ R_{x_2} \end{pmatrix} - n(t) \right) \tag{5}$$

IV. Conclusion

In this work, we demonstrated merging real-time MIMO wireless communication and LED lighting with inexpensive components including Arduino boards and off-the-shelf LEDs. The 2-by-2 MOCA has 2 kbps throughput over the maximum link distance of 30 cm and outputs 832 lumens while consuming 67 mW of power. A 3-by-3 MOCA was built by adding a third transceiver pair to show that the MIMO system can be scaled up. Moreover, the 2-by-2 MOCA receiver was built with an FPGA board (DE0-Nano Development and Education Board from Terasic) to demonstrate that throughput can be increased with more sophisticated microcontrollers capable of parallel processing. The FPGA-based 2-by-2 MOCA receiver currently achieves sampling rate of 1Mbps. This work provides an inexpensive platform for engineers and students to experiment with MIMO VLC systems and make appropriate modifications to meet their specific design goals. In this way, MOCA aims to make VLC technology more available and facilitate development and practical implementation of VLC systems. This can enhance the current wireless communication and lighting and further, improve quality of life in urban areas by implementing a newer, energy efficient, and faster technology.

Future works will involve improving the BER at greater link distances by implementing a better synchronization technique, adding multiple LEDs per transmitter, applying error coding and implementing an external ADC that has a higher bit resolution. Throughtput can be increased by using a different microcontroller with a higher clock speed and implementing a more complex modulation scheme such as Orthogonal Frequency Division Multiplexing (OFDM) [15].

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