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Neural Network Based Joint Spatial and Temporal Equalization for MIMO-VLC System

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***Abstract*—The limited bandwidth of white light emitting diode (LED) limits the achievable data rate in a visible light communication (VLC) system. A number of techniques including multiple-input-multiple-output (MIMO) system are investigated to improvements the data rate. The high-speed optical MIMO system suffers from both spatial and temporal cross-talks. Spatial cross-talk is often compensated by MIMO decoding algorithm while temporal cross-talk is mitigated using an equalizer. However, the LEDs has a non-linear transfer function and the performance of linear equalizers are limited. In this paper, we propose a joint spatial and temporal equalization using an artificial neural network (ANN) for a MIMO-VLC system. We demonstrate using a practical imaging/non-imaging optical MIMO link that the ANN-based joint equalization outperforms the joint equalization using a traditional decision feedback as ANN is able to compensate the non-linear transfer function as well as cross-talk.**

***Index Terms*— Visible light communications, multiple input multiple output, joint equalization, artificial neural network, non-linear transfer function**

I. INTRODUCTION

The solid-state lighting (SSL) devices are not only energy efficient in comparison to traditional illumination devices, but also have potential to play an enormous role in overcoming bandwidth congestion in the future wireless communication system [1]. SSL devices can be modulated at a very high speed, enabling these devices for high-speed data communications. Besides dual functionality of illumination and data communication, the visible light communication (VLC) system using SSL devices has additional benefits including license-free operation, free from electromagnetic interference and inherent security.

A number of Gigabit/s VLC systems were demonstrated using commercial white light emitting diodes (LEDs) while multi-gigabit systems were demonstrated using multi-colored LEDs (see [1] and references therein for a detailed review of recent demonstrations of high-speed VLC systems). Recently, light bulbs have become available that comprise a large number of LEDs are packaged together in a single bulb using chips-on-board (COB) technology. These LEDs can be independently modulated, making high-density multiple-input-multiple-output (MIMO) system attractive for high-speed data communication. The spatial MIMO system has the potential to linearly increase the system capacity with the number of transmitter/receiver elements.

The performance of the high-speed MIMO-VLC systems suffers from spatial cross-talk and temporal cross-talk (intersymbol interference (ISI)). The bandwidth commercial white LEDs are limited to a few MHz to 10's of MHz due to slow yellow phosphor coating [1]. This leads to ISI when these LEDs are operated at a significantly higher data rate. Both the imaging and non-imaging optical MIMO system also have inter-channel interference. A commonly adopted approach in the MIMO-VLC system to overcome these shortcomings is to first compensate the spatial cross-talk by using a MIMO decoding algorithm, followed by ISI compensation, often by using decision feedback equalizer (DFE). The non-linear MIMO decoding algorithm like vertical Bell labs layered space-time (V-BLAST) offer improved performance in comparison to the zero-forcing (ZF) algorithm. V-BLAST can be considered as a matrix decision feedback equalizer (DFE) [2]. Hence, joint spatial and temporal equalization using a single DFE is feasible for a MIMO system [3].

The comparative studies of the transversal, Volterra and artificial neural network (ANN) based DFE to compensation ISI and non-linear effect for pulse amplitude modulation (PAM) demonstrates that ANN offers the optimum performance with less computational complexity then Volterra equalizer [4]. Though traditional DFE requires the least computational complexity, the performance is often unacceptable with a high bit error rate (BER) [4]. Furthermore, the theoretical and simulation studies in [5]–[7] indicates that PAM with DFE outperforms carrierless amplitude phase (CAP) modulation with DFE and discrete multitone (DMT)/optical orthogonal frequency division multiplexing (O-OFDM) with

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bit and power loading. Thus, in this study, we proposed an artificial neural network (ANN) for the joint temporal and spatial interference compensation for MIMO-VLC system with PAM scheme. Though the ANN is used for ISI compensation in MIMO system (for example, in [8] spatial cross-talk is first compensated using the ZF equalizer followed by ISI compensation using ANN);to the best of the authors' knowledge, this is the first study of joint spatial and temporal cross-talks compensation using ANN. In the joint equalization, a single set of training data can be used to estimate the channel H-matrix and the channel impulse response, thus reducing the overall all training time. Also, the interdependency of the spatial and temporal interferences are automatically compensated.

Furthermore, the LED's voltage-current response is non-linear for a large modulation signal [9]. In order to compensate the non-linear LED response, the pre-distortion and/or post-compensation can be used. For a bandlimited system, the pre-distortion can be problematic as this introduces further non-linearity to the system. The performance of the traditional DFE also suffers adversely in the presence of non-linearity as traditional equalizers like DFE have a linear decision boundary which is not optimal for systems with a non-linear response. The ANN with non-linear transfer functions can be used to create a non-linear decision boundary making it optimum for compensating both the non-linear response and ISI [4], [10]. Therefore, the function of the ANN based-equalizer in this study is three-fold: compensation of the non-linear transfer function of devices, spatial cross-talk compensation and ISI compensation. All these three compensations are performed by a single ANN, simplify the overall system architecture and training algorithm. Also, unlike many other LED non-linear response compensation technique, it is not necessary to know the impulse response of LED in advance as the ANN can estimate the response during the training.

Three types of MIMO receivers are studied here: a) ZF MIMO decoding followed by DFE, b) joint DFE and c) joint ANN equalizer. Through the comparative studies of these equalizers for imaging and non-imaging MIMO-VLC system, it is established that joint ANN decoding offers a significantly improved performance over the traditional joint DFE, especially for an ill-conditioned MIMO system.

Rest of the paper is organized as follows: Section II provides an overview of experimental MIMO-VLC system detailing the receiver structure. Section III summarizes the performance of different MIMO receiver structure. Finally, conclusions are drawn in Section IV.

II. System Descriptions

A schematic of MIMO-VLC system is given in Fig. 1. The system consists of spatially separated m LEDs, driven by independent data sources. The receiver consists of imaging/non-imaging optics, followed by a number of n photodiodes and corresponding amplifiers. The MIMO decoding algorithm is applied to the output of the amplifiers followed by temporal equalization to recover the data. For the MIMO system, the received signal can be represented as:

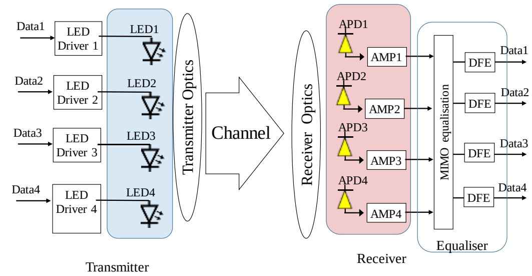


Fig. 1. Schematic of MIMO VLC system

$$\mathbf{Y} = \mathbf{H}\mathbf{X} + \mathbf{N} \quad \textbf{(1)}$$

where $\mathbf{H}$ is an $n \times m$ channel matrix; $\mathbf{X}$ is $m \times 1$ transmitted signal vector; $\mathbf{N}$ is the $n \times 1$ noise vector, $\mathbf{Y}$ is $n \times 1$ received signal vector and m and $n(\geq m)$ are the number of transmitter and receiver elements, respectively.

Traditionally, the channel $\mathbf{H}$-Matrix is estimated by transmitting a low-frequency signal from the individual transmitters and measuring the average channel gain for all the receivers as outlined in [11]. Then, the signal recovery, in the absence of ISI, can be carried out by multiplying the received signal with the inverse of channel $\mathbf{H}$-matrix (also known as ZF) as given by

$$\bar{\mathbf{X}} = \mathbf{H}^{-1}\mathbf{Y} \quad \textbf{(2)}$$

In the presence of both the spatial and temporal cross-talk, a common technique that had been adopted for the MIMO-VLC system is to use a spatial ZF algorithm to separate the spatial channel followed by temporal equalization [8], [11], [12].

In this paper, we propose a joint temporal and spatial equalization using the ANN for a MIMO-VLC system. A simplified block diagram of the proposed receiver structure is shown in Fig. 2 (a). The receiver structure is similar to a matrix DFE structure where the input and outputs are vectors. The received signal vector $\mathbf{Y}(n\times1)$ is fed to an ANN using an array of time domain feedforward tap delay line and the estimated signal vector $\bar{\boldsymbol{X}}$ $(m\times 1)$ is fed back to ANN using a feedback tap delay lines as in the DFE.

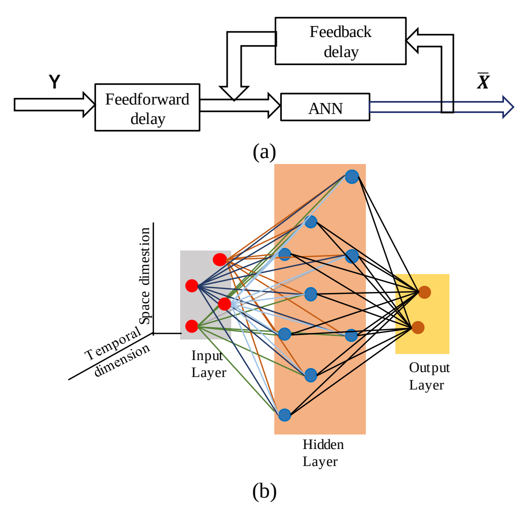


Fig. 2: a) A simplified block diagram of joint ANN-based decoding for MIMO-VLC system and b) architecture of ANN.

The detailed architecture of multilayer perceptron (MLP) ANN is shown in Fig. 2 (b). The MLP has an input layer, one hidden layer, and an output layer. The input layer is two-dimensional corresponding to the spatial dimension (i.e. the number of the receiver, n) and the temporal dimension (corresponding to the bandlimited channel/system impulse response). Since a fractionally-spaced equalization with an oversampling factor of 2 is adopted in this work with decision feedback structure, the number of input neurons is $(n \times FF \times 2 + m \times FB)$, where FF and FB are the number of feedforward and feedback tap delay lines and m is the number of output neurons (which is equal to MIMO order m). The ANN is trained using the feedforward backpropagation Levenberg Marquardt algorithm in a supervised manner. The details of the ANN structure and training algorithm can be found in [13].

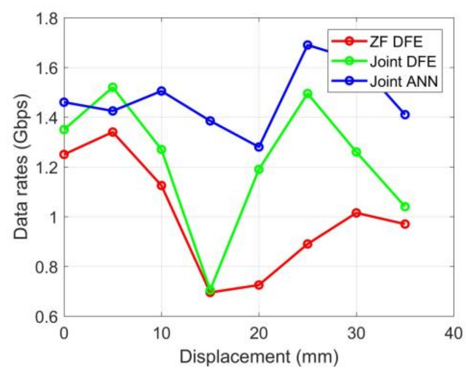
III. Experimental Set-up, Results and Discussion

The performance of the joint ANN and DFE equalizers is experimentally evaluated for imaging and non-imaging MIMO-VLC systems. Baseband PAM with multi-levels of 2 and 4 (i.e. 2-PAM and 4-PAM) is adopted. A pseudo-random binary sequence (PRBS) of $m \times 2^{14}$ length is generated using an arbitrary waveform generator (AWG, Agilent 81150A) and mapped to the required PAM level. The independent PAM symbol sequences are transmitted through independent LEDs. The receiver consists of an array of the photodiode and amplifier. Three decoding algorithms a) ZF followed by a DFE (ZF-DFE) b) joint temporal and spatial DFE (joint DFE) and c) joint temporal and spatial ANN based equalizer (joint ANN) were applied to the output of the amplifier. All the systems were trained using the same number of training bits.

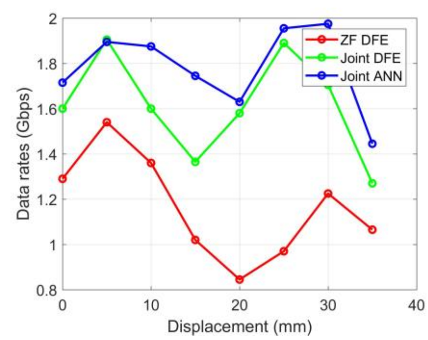
The performance of the joint ANN decoder is first tested in an imaging MIMO-VLC system. The transmitter consists of an array of four micro-LEDs (μLEDs), driven by the CMOS-based driver. The receiver consists of an array of nine avalanche photodiodes (APDs) with an associated transimpedance amplifier. Imaging MIMO optics designed using off-the-shelf lenses are used at the transmitter and receiver. The detailed specification of the system including transmitter and receiver circuit and optics system is given in [12], [14]. The system has an overall field of view (FOV) of 3.5 degrees and a link length of 1 m. In the experiment, the transmitter position was fixed, and the receiver was displaced horizontally perpendicular to the propagation of light to evaluate the link performance within the coverage area.

The achievable data rate at a BER of 3.8×10^{-3} versus displacement along the horizontal axis for a 1 m MIMO-VLC link is given in Fig. 3. The advantage of joint equalization is clearly demonstrated as a separate temporal and spatial equalizer (ZF-DFE) consistently performs inferior to the joint equalizer for both 2 and 4-PAM with significant performance difference. The joint ANN, on the other hand, offered the highest data rate. The highest and lowest data rate achieved using joint DFE is 1520 and 705 Mbps for 2-PAM whereas the joint ANN achieved 1690 and 1385 Mbps.

The performance penalty using ZF-DFE is higher for 4-PAM as the effect of non-linearity is more pronounced in higher level PAM. The highest and the lowest data rate for 4-PAM achieved using joint DFE and joint ANN are 1890 Mbps & 1365 Mbps and 1975 Mbps & 1745 Mbps, respectively. This is more than 25 % increase in the worst-case achievable data rate using ANN in comparison to joint DFE. It was also noticed that there is a relationship between the condition number of the **H-**matrix and the performance difference for the joint DFEs. The performance difference is higher when the **H**-matrix is ill-conditioned. For example, DFE and ANN show almost identical performance at the displacement of 20 mm and 25 mm (a difference of 50 Mbps and 65 Mbps in the data rate) where condition numbers are 1.99 and 1.79, respectively. On the other hand, data rate differences of 380 Mbps and 270 Mbps are observed at the displacement of 15 mm and 30 mm where condition numbers are 3.34 and 2.42, respectively. This indicates that joint decoding with ANN is very effective in compensating the adverse effect due to ill-condition **H**-matrix.



(a)



(b)

Fig. 3: Achievable date rate against the displacement for a number of decoding schemes for a) 2-PAM and b) 4-PAM.

In order to verify that joint-ANN decoding offers a better decoding gain than the traditional DFE for ill-conditioned channel matrices, we evaluate a 2×2 non-imaging MIMO system. The non-imaging MIMO system consists of two commercial LEDs with a bandwidth of 6 MHz and large area photodiodes with a dimension of 29 by 1.2 mm and bandwidth of 1.5 MHz. The goal of this experiment was not to maximize the data rate but to assess the performance of different equalizers when the channel is not well conditioned. The link was set-up in such a way that the cross-talk between channels was maximal. As described in [15], the non-imaging MIMO can have an ill-conditioned channel matrix and channel inversion using ZF may not always possible. The estimated channel condition number was 40 (significantly higher than for imaging system), indicating the channel H-matrix is ill-conditioned. As a result, the ZF-DFE completely failed, providing high (0.5) BER (not shown in Fig.). Fig. 4 shows the BER versus data rate of the 2×2 non-imaging MIMO-VLC system using joint DFE and ANN for the 2-PAM scheme. It can be observed that the joint DFE also completely fails to decode the MIMO channel and hence there is a high BER irrespective of data rates. The ANN, on the other hand, was capable of separating the channels and offered a data rate of ~27 Mbps per channel. This clearly demonstrates the advantage of joint ANN equalizer for MIMO-VLC system.

In this paper, we focused on proof-of-concept joint ANN equalizers for imaging and non-imaging MIMO-VLC systems. However, the proposed techniques can be equally applied to any other optical MIMO system. The ANN equalizer is expected to offer even better gain for higher level modulation schemes where the penalty due to non-linearity is severe. Further optimization and evaluation of the performance of the ANN for higher level PAM will be carried out in the future.

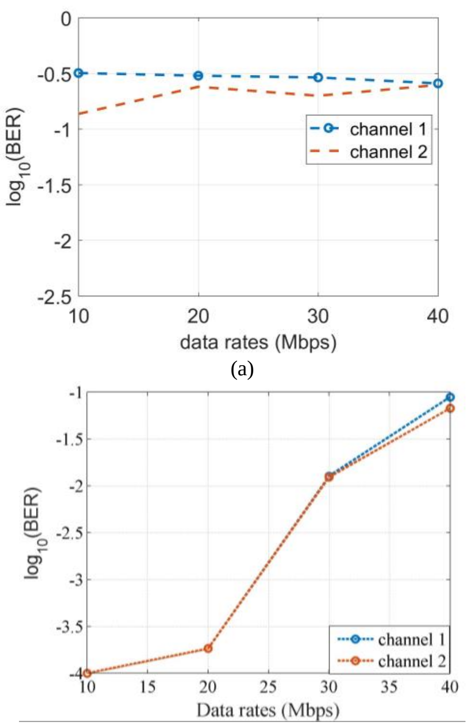


Fig. 4: BER vs data rate for a non-imaging MIMO-VLC system for 2-PAM with a) joint DFE and b) joint ANN equalizer.

IV. Conclusions

In this paper, we proposed a new joint temporal and spatial equalization using an ANN for MIMO-VLC system. We have experimentally studied three MIMO decoding techniques. The study showed that joint equalization outperforms separate compensation of temporal and spatial cross-talks. The ANN-based joint equalization offered the best performance in all cases for both 2-PAM and 4-PAM. The performance improvement of the ANN is higher when the channel is ill-conditioned demonstrating a clear advantage of the ANN.

The future work includes analyzing the performance of ANN-based equalizer for multi-level PAM systems where the power penalty due to LED non-linearity is severe.

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