# Demonstration of Inter-cell Interference Mitigation in Multi-cell VLC Systems Using Optimized Angle Diversity Receiver

Chen Chen
School of Microelectronics and
Communication Engineering
Chongqing University
Chongqing 400044, China
e-mail: c.chen@cqu.edu.cn

Pengfei Du, Helin Yang, Wen-De Zhong
School of Electrical and Electronic
Engineering
Nanyang Technological University
50 Nanyang Avenue, Singapore 639798
e-mail: ewdzhong@ntu.edu.sg

Xiong Deng
Department of Electrical Engineering
Eindhoven University of Technology (TU/e)
5600MB Eindhoven, Netherlands
e-mail: X.Deng@tue.nl

Yanbing Yang
College of Computer Science
Sichuan University
Chengdu 610065, China
e-mail: yangyanbing@scu.edu.cn

*Abstract*—**In this paper, we numerically and experimentally demonstrate an inter-cell interference (ICI) mitigation scheme for multi-cell visible light communication (MC-VLC) systems using optimized angle diversity receivers (ADRs). An ADR usually consists of a non-tilted top detector and several tilted side detectors. We optimize the performance of the ADR by choosing an optimal tilting angle of each side detector. In comparison to the conventional frequency allocation-based ICI mitigation schemes, the optimized ADR-based ICI mitigation scheme enjoys three main advantages: 1) high cell capacity; 2) improved signal-to-interference-and-noise ratio (SINR); 3) reduced SINR fluctuation. The feasibility of using optimized ADRs for ICI mitigation in indoor MC-VLC systems is verified by both numerical analysis and experiments. Experimental results show that a two-cell VLC system using an optimized ADR can achieve an SINR improvement of 18.6 dB and a 1-dB SINR fluctuation, compared with the same VLC system using a single-element receiver without angle diversity.**

*Keywords-multi-cell visible light communication (MC-VLC); optimized angle diversity receiver; inter-cell interference*

## I. INTRODUCTION

Due to the fast development of solid-state lighting (SSL) technology, light-emitting diode (LED)-based visible light communications (VLC) has been envisioned as a promising complementary technique to traditional radio frequency (RF)-based techniques for indoor wireless data communications [1]. In comparison to wireless-fidelity (WiFi), VLC, which is also known as light-fidelity (LiFi), exhibits many advantages such as unregulated and license-free spectrum, inherent physical-layer security and no electromagnetic interference emission [2]. However, the achievable capacity of an indoor VLC system is relatively low due to the limited 3-dB bandwidth of commercial LEDs [3]. To increase the capacity of bandwidth-limited VLC systems, several approaches have already been reported in the literature, for example, frequency domain equalization [4], multiple-input multiple-output (MIMO)

transmission [5], orthogonal frequency division multiplexing (OFDM) modulation [6] and non-orthogonal multiple access [7], [8]. However, most of the existing work only considers the performance of VLC systems with a single cell. Practically, a typical indoor VLC system usually consists of many optical attocells so that full coverage can be achieved [9].

When the receivers are located within the overlapping zone of several neighbouring cells, their signal performance could be greatly deteriorated due to non-negligible inter-cell interference (ICI) in MC-VLC systems. To date, several schemes have been reported to mitigate ICI in indoor MC-VLC systems. In [10], a frequency allocation-based scheme was proposed where different cells are allocated with different RF subcarriers. Although ICI can be mitigated, cell capacity is inevitably reduced due to spectrum partitioning. A heuristic interference-constrained subcarrier reuse algorithm using discrete multi-tone was proposed in [11], which can improve the average bit rate on the condition of increased implementation complexity. In [12], a differential optical detection scheme was proposed. By using polarization division, the in-band interference can be efficiently reduced and thus spectrum partitioning is not required. However, to successfully implement such a scheme, the accurate control of polarization and careful cell planning must be ensured.

Lately, angle diversity receivers (ADRs) were proposed and applied in MIMO-VLC systems so as to improve system capacity by reducing channel correlation [13]. In [14], an ADR with multiple photodetectors (PDs) was designed to improve the signal-to-interference-and-noise ratio (SINR) in cellular VLC systems. Nevertheless, the performance of the ADR reported in [14] was not optimized. In [15], we have numerically studied an optimized ADR to substantially reduce SINR fluctuation in typical indoor MC-VLC systems. Nevertheless, no experimental verifications have ever been reported to show the practical feasibility of optimized ADR in MC-VLC systems. To address this issue, in this paper, we demonstrate an ICI mitigation technique using ADRs for
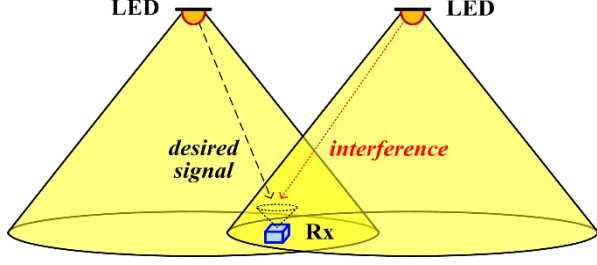
Figure 1. Illustration of inter-cell interference in an indoor MC-VLC system.

MC-VLC systems, whereby spectrum partitioning/cell planning is not needed. Two ADR schemes are proposed and further optimized. We verify the feasibility of ICI mitigation using ADRs in a two-cell VLC system via both numerical analysis and proof-of-concept experiments. Performance comparison between conventional single-element receiver (SER) and the proposed ADRs is also presented.

## II. MC-VLC USING ADR

We first describe the mathematical model of a typical indoor MC-VLC system and then introduce the principle of the proposed ADRs as follows.

### A. Channel Model

In indoor VLC systems, LED light is radiated into free space for simultaneous lighting and communication. The line-of-sight (LOS) irradiance of an LED generally follows a the Lambertian radiation pattern [3]. Let $N_t$ be the number of the LED transmitters and $N_r$ denote the number of the detectors in the optical receiver. The LOS optical channel DC gain between the $i$-th LED transmitter and the $j$-th detector, where $i = 1, 2, \cdots, N_t$ and $j = 1, 2, \cdots, N_r$, can be obtained by

$$h_{ij} = \frac{(m+1)A_d}{2\pi d_{ij}^2} \cos^m(\varphi_{ij}) \, T(\theta_{ij}) g(\theta_{ij}) \cos(\theta_{ij}), \qquad (1)$$

where the Lambertian emission order is $m = -\ln 2/\ln(\cos\Phi)$ and $\Phi$ denotes the semi-angle at half power of the LED transmitter, $A_d$ is the detector's active area, $d_{ij}$ is the transmission distance, $\varphi_{ij}$ is the emission angle, $\theta_{ij}$ is the incident angle, and $T(\theta_{ij})$ and $g(\theta_{ij})$ are the gains of the optical filter and lens, respectively.

### B. Inter-Cell Interference (ICI)

As shown in Fig. 1, when the receiver is located at the overlapping zone of a MC-VLC system, it will receive both the expected signal from its serving cell and the unexpected interference for the adjacent non-serving cells. Therefore, the performance of the received signal could be severely degraded due to ICI. Assuming the $i$-th LED serves the receiver, the SINR of the received signal by the $j$-th detector in the optical receiver is given by

$$SINR_{ij} = \frac{(R\xi h_{ij} P_0)^2}{\sum_{i'=1, i' \neq i}^{N_t} (R\xi h_{i'j} P_0)^2 + \sigma_{shot}^2 + \sigma_{thermal}^2}, \qquad (2)$$
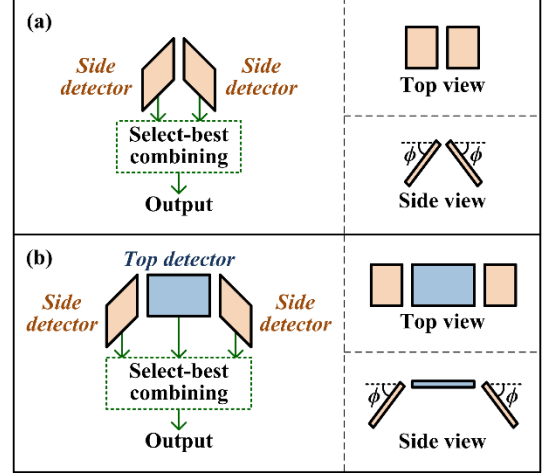


Figure 2. Structure of the proposed ADR with (a) $N_e = 2$ and (b) $N_e = 3$.

where $R$ denotes the detector's responsivity, $\xi$ represents the modulation index, $P_0$ expresses output optical power of the LED transmitter, $\sigma_{shot}^2$ and $\sigma_{thermal}^2$ are the powers of the shot noise and the thermal noise, respectively.

### C. Two Proposed Angle Diversity Receivers

Fig. 2 illustrates the structures of two proposed ADRs to mitigate ICI in indoor MC-VLC systems. The first ADR, as shown in Fig. 2(a), consists of $N_e = 2$ tilted detectors, where $N_e$ denotes the number of elements (detectors) in the ADR. Since these two detectors are tilted towards opposite directions on two sides, we call them side detectors. It can be observed from the top and side views that these two side detectors are tilted down from the horizontal plane with the same tilting angle $\phi$. As shown in Fig. 2(b), the second ADR consists of $N_e = 3$ detectors including one non-tilted detector in the middle and two side detectors. The non-tilted detector is named top detector and two side detectors have the same tilting angle $\phi$.

As we can see, multiple detectors are utilized in an ADR and hence multiple electrical signals can be obtained at the outputs of the detectors. The LOS optical channel DC gain of the top detector is calculated by (1). However, for each side detector, the angle of incidence $\theta$ is determined by: 1) the relative positions of the LED transmitter and the side detector and 2) the tilting angle and the azimuth angle of the side detector. The detailed calculation of the LOS optical channel DC gain of the side detector can be found in [15], which is omitted here for brevity. Since multiple signals are generated at the outputs of detectors in an ADR, diversity combining algorithms can be applied to generate a final output signal for demodulation. As a trade-off between SINR and complexity, select-best combining is used in the ADRs [14]. Moreover, the tilting angle $\phi$ of each side detector in the ADR is an adjustable parameter and an optimal value of $\phi$ can be selected to maximize the system performance, i.e., SINR.

## III. NUMERICAL AND EXPERIMENTAL RESULTS

In this section, we present the numerical analysis and the experimental results of a two-cell VLC system using ADRs.
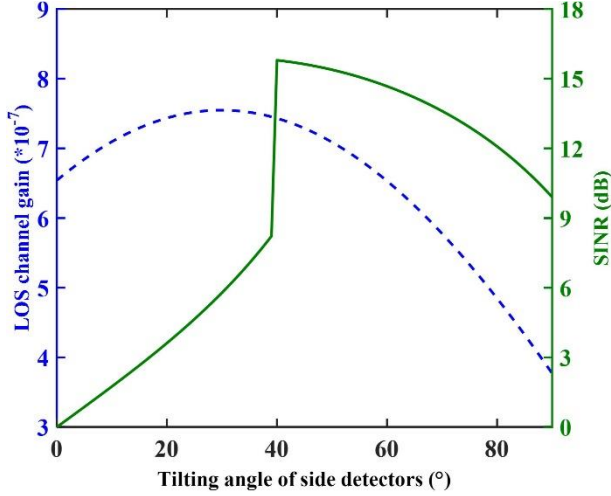
Figure 3.  LOS channel gain and SINR versus tilting angle of side detectors in the ADR with $N_e=3$.
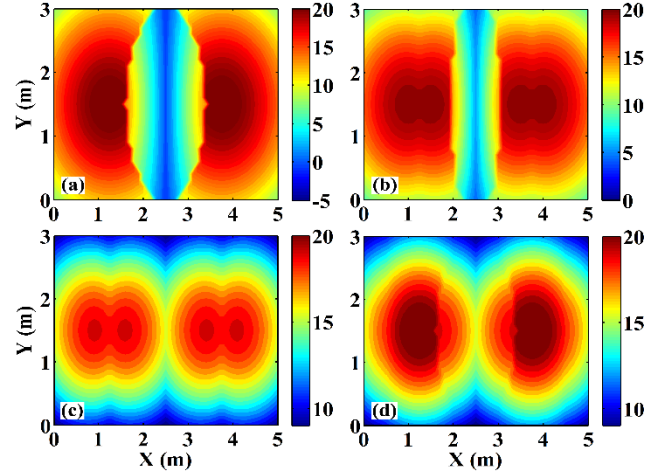


Figure 4.  SINR distribution in dB over the receiving plane employing (a) an SER, (b) an ADR with $N_e=2$ and $\phi=30°$, (c) an ADR with $N_e=2$ and $\phi=40°$, and (d) an ADR with $N_e=3$ and $\phi=40°$.

## A.  Numerical Analysis

A two-cell VLC system in a practical indoor room with a dimension of 5 m × 5 m × 3 m and a receiving plane height of 0.85 m is considered here. Two LEDs are located (1.25, 1.5, 3) and (3.75, 1.5, 3) in the ceiling, each with a semi-angle at half power of 45°. The LED's modulation index and output optical power are 0.3 and 5 W, respectively. The detector has a responsivity of 0.53 A/W and a half-angle FOV of 70°. The modulation bandwidth is set to10 MHz and the background noise is set to 5100 $\mu$A.

We firstly optimize the tilting angle $\phi$ of each side detector in the proposed ADRs. Since the severest ICI occurs at the central point of the receiving plane, the optimization is thus executed at the position (2.5, 1.5, 0.85). Fig. 3 shows the LOS channel gain and the SINR versus the tilting angle of each side detector in the ADR with $N_e=3$. As can be seen, the highest optical channel gain is achieved at $\phi=30°$, which is corresponding to an incident angle of 0°. However, the highest SINR is obtained at $\phi=40°$ although the signal power is maximal at $\phi=30°$. This is because that the ICI is un-negligible when $\phi=30°$ and thus the SINR performance is dominated by the ICI. When $\phi=40°$, ICI becomes negligible since the detector's half-angle FOV is 70°, although the signal power is slightly reduced. The SINR is gradually decreased as the tilting angle is further increased. Therefore, the optimal tilting angle of the ADRs is 40°. Next, we evaluate the SINR distribution of the two-cell VLC system over the receiving plane using different receivers. When an SER is used, as shown in Fig. 4(a), the system suffers from -0.1 dB. When an ADR with $N_e=2$ is utilized, as shown in Figs. 4(b) and (c), the SINR at the center is increased to 5.8 and 15.8 dB for $\phi=30°$ and 40°, respectively, resulting an SINR improvement of 10 dB. Furthermore, when an ADR with $N_e=3$ and $\phi=40°$ is employed, as shown in Fig. 4(d), the SINR at the overlapping area is the same as that using an ADR with $N_e=2$ and $\phi=40°$, but the SINR at the non-overlapping area is substantially improved. Therefore, an ADR with $N_e=3$ and $\phi=40°$ can

improve the SINR performance of the two-cell VLC system.

## B.  Experimental Demonstration

The experimental setup of a two-cell OFDM- VLC system is depicted in Fig. 5(a). Two LEDs (Luxeon SP-02) with a spacing of 35 cm are adopted and two lampshades each with a half-angle FOV of 26° are used to concentrate the light. The positions of $LED_1$ and $LED_2$ are set to –17.5 and 17.5 cm, respectively. Two independent OFDM signals are generated by MATLAB and then separately loaded to a multi-channel arbitrary waveform generator (AWG, Tabor WW2074) at 40 MSa/s. Each OFDM signal has a bandwidth of 10 MHz and uses 16QAM mapping. Therefore, the achievable cell capacity is 40 Mb/s. After amplification and DC bias addition, the resultant signals are utilized to drive the LEDs. The distance is 100 cm and the radiated light is captured by the receiver. The analog signal is sampled by a digital storage oscilloscope (DSO, Agilent infiniium 54832B) at 1 GSa/s. Subsequently, the output signal is demodulated offline by MATLAB. The SINR is estimated from error vector magnitude (EVM). In this experimental demonstration, two types of optical receivers are considered including an SER and the proposed ADRs. The SER is made up of a single non-tilted detector consisting of an optical lens, a blue filter (BF) and a photodiode (PD, Thorlabs PDA36A) with an active area of 13 mm². Meanwhile, the ADRs with $N_e=2$ and 3 are emulated by adjusting both the position and the tilting angle of the detector at different positions. The pitch length of the ADRs is set to 1 cm and the measured half-angle FOV of each detector is about 22°. The receiver position offset is assumed to be zero when the receiver is facing the central position of $LED_1$ and $LED_2$. Considering the geometric symmetry, the receiver position offset is set in the range of –17.5 to 17.5 cm.

We first find the optimal tilting angle of the ADRs by evaluating the SINR at the receiver position offset of 0 cm. Fig. 5(b) shows the measured SINR versus the tilting angle of the side detectors. Although the highest optical channel gain
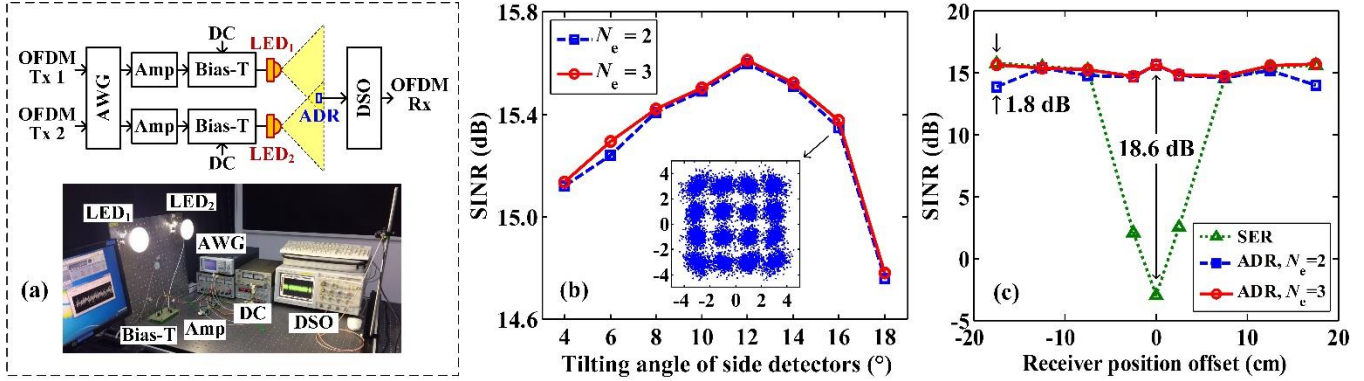
Figure 5. (a) Experimental setup, (b) measured SINR vs. tilting angle of side detectors in the ADR, and (c) measured SINR vs. receiver position offset.

is obtained with a tilting angle of $\arctan(17.5/100) \approx 10°$, the maximum SINR is achieved with a tilting angle of 12°, for both $N_e = 2$ and 3. This is because the detector's half-angle FOV is 22° and the ICI is un-negligible for a tilting angle of 10°. As the tilting angle is increased to 12°, the ICI becomes negligible and thus the highest SINR is achieved. Moreover, the SINRs for $N_e = 2$ and 3 are nearly the same. The inset in Fig. 5(b) shows the received 16QAM constellation.

We further evaluate the SINR performance of the two-cell OFDM-VLC system applying different optical receivers. Fig. 5(c) shows the measured SINR using an SER and two ADRs with an optimal tilting angle. It can be seen that the SINR at a receiver position offset of 0 cm is –3 dB when an SER is utilized. However, when the proposed ADRs are used, the SINR at the receiver position offset of 0 cm is increased to 15.6 dB, indicating an SINR improvement of 18.6 dB. Moreover, when the receiver position offsets are –17.5 and 17.5 cm, i.e., the receiver is directly facing the LEDs, the ADR with $N_e = 3$ outperforms that with $N_e = 2$ and a 1.8-dB SINR improvement is further achieved by adding one top detector in the ADR. When employing an SER, the SINR fluctuation is 18.7 dB. However, the SINR fluctuations are reduced to 1.8 and 1.0 dB when the ADR with $N_e = 2$ and 3 are employed, respectively. Therefore, the SINR distribution can be flattened within 1 dB by using an ADR with $N_e = 3$.

## IV. CONCLUSION

In this paper, we have for the first time numerically and experimentally demonstrated an optimized ADR-based ICI mitigation scheme for indoor MC-VLC systems. Considering that spectrum partitioning or cell planning is not needed, an indoor MC-VLC system using this technique achieves much improved cell capacity than that using frequency allocation-based schemes. The feasibility of the optimized ADR-based ICI mitigation technique has been verified by both numerical analysis and proof-of-concept experiments. The experimental results have shown that, by using an ADR with $N_e = 3$ and an optimal tilting angle, the SINR of a two-cell OFDM-VLC system is improved by up to 18.6 dB and the SINR fluctuation is reduced to as low as 1 dB, compared with the system using an SER. To our best knowledge, it is the first experimental

demonstration on ICI mitigation using optimized ADRs in indoor MC-VLC systems.

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