Increasing Throughput of Dense-Transmitter VLC Networks Through Adaptive Distributed MISO

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Abstract—LED luminaries are densely deployed indoors to provide uniform illumination for better user comfort. To achieve energy efficient uniform illumination, the ‘cells’ of neighboring LED luminaries are *strongly overlapping* to increase the cell edge light intensity. Visible Light Communication (VLC) can also benefit from this dense LED infrastructure by exploiting Distributed Multiple-Input-Single-Output (D-MISO). However, overlapping LED cells cause strong interference when multiple transmitters are active. Therefore, in this work, we propose an *Adaptive and Distributed MISO (AD-MISO)* method to improve the system throughput of a dense-LED-transmitter VLC network that communicates with multiple users. We formulate an optimization problem for deriving the D-MISO transmission strategy adapting the inter-cell interference dynamically, with the goal to increase the system throughput of multiple users. Given the measured link qualities between the distributed transmitters and users, AD-MISO exploits both spatial and time-division multiplexing by dynamically allocating the transmitters to multiple users such that the system throughput is maximized. We also design a heuristic algorithm to reduce the complexity of AD-MISO, and propose a technique to support heterogeneous service requirements. We evaluate the performance of AD-MISO through simulations under various scenarios. Our results demonstrate that AD-MISO outperforms the pure time-division based D-MISO greatly by increasing the average system throughput up to 35.6%, and our heuristic can achieve similar gains while reducing the complexity by 94%.

Index Terms—Visible light communication, Dense LED deployments, Distributed MISO, Heuristic, Multi-service, Evaluation

I. INTRODUCTION

In 2016, global mobile data traffic increased by 63% and analysts foresee a sevenfold increase between 2016 and 2021 [1]. This will lead to a lack of available Radio Frequency (RF) spectrum to meet the next-generation traffic demands. Visible Light Communication (VLC) is a promising candidate to alleviate the pressure on the RF spectrum by complementing traditional RF networks. In VLC systems, Intensity Modulation of LEDs with Direct Detection using a photodiode (IM/DD) is employed for data communication, resulting in an interference free channel with respect to the RF spectrum.

LEDs are densely deployed in both industrial and domestic settings to improve user comfort. Moreover, this dense deployment also benefits communication, since LEDs’ spatial diversity facilitates the Distributed Multiple-Input-Multiple-Output (D-MISO) [2], [3] technique. However, this dense usage *causes users to receive light signals from more than one transmitter, resulting in undesired inter-user interference.*

In literature, multiple access techniques have been assessed to improve system performance with multiple users and dense LED layout. In [4], a Time-Division-Multiple-Access (TDMA) scheme is employed to assign users with different time slots to avoid all inter-user interference. However, TDMA *does not fully* exploit the system resources, e.g. under scenarios where inter-user interference is negligible due to large distances among users. Frequency-Division-Multiple-Access (FDMA) is employed to create a cellular network and joint transmission scheme in [5], but decreasing the available bandwidth in each cell. To better exploit the system resources and improve the spectral efficiency, multi-user precoding techniques are investigated for VLC [6], [7]. These techniques rely on a well-conditioned channel matrix that could degrade the system performance when users are closely spaced. Besides, the adoption of direct current (DC) bias to ensure non-negative signals reduces the system power efficiency. To overcome these limitations, transmitter selection algorithms are proposed in [8], [9]. They assume average metrics over all users in their optimizations, instead of considering multi-service requirements of individual users. In [10], an interference-free LED allocation scheme is presented for fisheye based photodetector. Compared to [10], in this work, we will exploit both the inter-cell interference and the interference-free to increase the system throughput.

In this paper, we propose an Adaptive Distributed Multiple-Input-Single-Output (AD-MISO) technique for the multi-user multi-service scenarios. Based on measured link qualities between the transmitters and the users, AD-MISO exploits both the *spatial multiplexing* (with interference) and the *time-division multiplexing* (interference-free) to dynamically allocate the transmitters to multiple users such that the system throughput is maximized. We summarize our contributions as follows:

- **Method:** we propose AD-MISO to increase the system throughput in multi-user scenarios. By collecting measured channel qualities between transmitters and users, our technique adapts the D-MISO channels by tuning the inter-cell interference dynamically, to maximize the sum throughput of all users in the system.
- **Heuristic:** to further reduce the computation complexity of AD-MISO, we design a lightweight heuristic algorithm based on the insights we draw from the optimal solutions.

- *Evaluation:* we evaluate the performance of the proposed AD-MISO and the heuristic algorithm under different scenarios. Our results demonstrate that AD-MISO outperforms the TDMA based D-MISO greatly by increasing the average system throughput up to 35.6%. Our heuristic algorithm can achieve the similar gains while reducing the computation complexity by an average of 94%.

The rest of this paper is organized as follows. The system model is described in Sec. II, followed by the proposed AD-MISO, insights into the optimal solutions, and the heuristic algorithm in Sec. III. We present the simulation setup and results in Sec. IV, and finally conclude the paper in Sec. V.

II. SYSTEM MODEL

We consider an area with N LED transmitters (TXs) densely deployed in a grid on the ceiling, as shown in Fig. 1. The set of TXs is denoted as $\mathcal{N} = \{1, 2, \dots, N\}$. *Without loss of generality, we assume all the LEDs are identical.* To provide uniform illumination, the cell coverage of neighboring LEDs *overlaps 'strongly'*. Beyond illumination, each LED can also acts as a TX to communicate with mobile users. Therefore, each LED has two modes, *illumination mode* and *communication+illumination mode*. We assume all TXs are synchronized through a central *controller*. Thus, neighboring TXs can enable Distributed MISO (D-MISO) to communicate with users, i.e., sending synchronized communication signals to users. The controller orchestrates the D-MISO communication by implementing the decision logic, the MAC protocol and the synchronization signal. TXs integrate simple additional electronics to seamlessly switch between being for illumination and communication+illumination, and support the synchronization signal from the controller.

We consider K mobile users in the system, with the set of users denoted as $\mathcal{K} = \{1, 2, \dots, K\}$. Each user is equipped with a photodiode (PD) to receive light signals from the TXs through VLC. We only consider line-of-sight signals since they dominate the received signal at the photodiode [11]. *We assume all users have an identical PD.* Each user can measure the channel qualities between itself and surrounding TXs, and report this feedback to the controller via Wi-Fi¹.

Uniform illumination model: Based on the desired average illuminance E_{avg} over the area-of-interest, the minimal optical LED power can be derived. The desired uniformity $\bar{U}$, together with the semi-angle of the LEDs, determines the minimal LED spacing (the deployment of LED luminaries). The uniformity $\bar{U}$ over the area-of-interest is calculated as $\bar{U} = E_{\text{min}}/E_{\text{avg}}$, where E_{min} is the minimum illuminance and E_{avg} is the average illuminance.

Channel propagation: the light intensity from an LED TX is described by the Lambertian propagation model. Denoting P_n^t as the optical power of the TX n , $n \in \mathcal{N}$. Let $P_{n,k}^r$ be the

Fig. 1: System architecture for the AD-MISO technique. The *downlink* is performed with VLC and *uplink* with Wi-Fi.

received optical power at the user k from TX n , where $k \in \mathcal{K}$. Then $P_{n,k}^r$ is given as follows:

$$P_{n,k}^r = H_{n,k} \cdot P_n^t, \quad (1)$$

where $H_{n,k}$ is the line-of-sight path loss between the n th TX and the k th user, and is given by:

$$H_{n,k} = \begin{cases} \frac{(m+1)A_{pd}}{2\pi d_{n,k}^2} \cos^m(\phi_{n,k}) \cos(\psi_{n,k}), & 0 \leq \psi_{n,k} \leq \Psi_c \\ 0, & \text{otherwise} \end{cases} \quad (2)$$

where $m = \frac{-\ln(2)}{\ln(\cos \phi_{1/2})}$ is the Lambertian order of the LED in which $\phi_{1/2}$ denotes the half power semi-angle, A_{pd} the sensing area of the PD, $d_{n,k}$ the distance between the n th TX and the k th user, $\phi_{n,k}$ and $\psi_{n,k}$ the irradiation angle and incidence angle, respectively, and Ψ_c the field-of-view of PD².

D-MISO adaptation policy: In each decision-making period, the controller decides how to form the D-MISO channels to serve the users. This decision takes into account the current channel qualities between the TXs and the users, including the inter-cell interference. The adaptation policy of the D-MISO channels is defined through an $N \times K$ matrix σ as follows:

$$\sigma = \begin{bmatrix} \sigma_{1,1} & \cdots & \sigma_{1,K} \\ \cdots & \sigma_{n,k} & \cdots \\ \sigma_{N,1} & \cdots & \sigma_{N,K} \end{bmatrix}, \quad (3)$$

where $\sigma_{n,k}$ is a binary indicator and $\sigma_{n,k} = 1$ means to assign the n th TX to the k th user. The set of all the possible adaptation policies is defined as

$$\mathcal{C} \equiv \left\{ \sigma : \left(\sum_{k \in \mathcal{K}} \sigma_{n,k} \right) \in \{0, 1\}, \quad \forall n \in \mathcal{N} \right\}. \quad (4)$$

Objective: the performance metric used in this paper is the system throughput, i.e. the sum throughput of all the users. Our objective is to find the optimal policy σ^* that maximizes the system throughput:

$$\sigma^* = \arg \max_{\sigma \in \mathcal{C}} \sum_{k \in \mathcal{K}} S_k(\sigma), \quad (5)$$

where $S_k(\sigma)$ denotes the throughput achieved at user k when the adaptation policy $\sigma \in \mathcal{C}$ is used.

¹In VLC systems, it is very common to use RF techniques, such as Wi-Fi, for the uplink transmission.

²No concentrator nor filter gain of the photodiode is used in this work.

III. PROPOSED ADAPTIVE AND DISTRIBUTED MISO

In this section, we derive the details of our objective function and introduce the insights drawn from its optimal solution. Based on these insights, we will present our heuristic algorithm to reduce the complexity of the optimization.

A. Formulation of the optimization problem

Although interference is commonly considered to be Gaussian distributed, this is not valid for VLC due to the directionality of light, i.e. the central limit theorem cannot be applied. In [12], an interference model for VLC is proposed, taking into account only the most dominant interferer. In our system, we assume all the TXs are synchronized. Therefore, we can extend the above interference model for all the interferers. The Interference-to-Noise-Ratio (INR) [12] in our system at user k is defined as:

$$\text{INR}_k(\sigma) = \frac{(\rho \sum_{n=1, k \neq k'}^N \sigma_{n,k'} P_n^t)^2}{N_0 R}, \quad (6)$$

with ρ the responsivity of the PD, N_0 the noise spectral density and R the raw bit rate. Moreover, the Signal-to-Noise-Ratio (SNR) at user k is given by:

$$\text{SNR}_k(\sigma) = \frac{(\rho \sum_{n=1}^N \sigma_{n,k} P_n^t)^2}{N_0 R}. \quad (7)$$

In our system, we use the common On-Off Keying (OOK) modulation. This leads to the following expression for the BER at user k :

$$\text{BER}_k(\sigma) = \frac{1}{2} Q\left(\sqrt{\text{SNR}_k(\sigma)} + \sqrt{\text{INR}_k(\sigma)}\right) + \frac{1}{2} Q\left(\sqrt{\text{SNR}_k(\sigma)} - \sqrt{\text{INR}_k(\sigma)}\right), \quad (8)$$

with $Q(x) = \frac{1}{2} \text{erfc}\left(\frac{x}{\sqrt{2}}\right)$. Assuming a frame size of l bits, then the throughput $S_k(\sigma)$ can be written as

$$S_k(\sigma) = (1 - \text{BER}_k(\sigma))^l \cdot R. \quad (9)$$

Now we derive the details of our objective in Eq. (5) as below:

$$\max_{\sigma \in \mathcal{C}} \sum_{k \in \mathcal{K}} S_k(\sigma) = \max_{\sigma \in \mathcal{C}} \sum_{k \in \mathcal{K}} (1 - \text{BER}_k(\sigma))^l \cdot R. \quad (10)$$

To maximize the system throughput by solving Eq. (10), exhaustive search (brute-force) over all the possible adaptation policies $\mathcal{C}$ can be performed. Since each TX has $K+1$ options, the complexity of solving the optimization through brute-force is $\mathcal{O}((K+1)^N)$.

B. Insights from the optimal policies

As presented in the previous subsection, the complexity of brute-force search grows exponentially with the number of TX as well as the number of users. However, it is not always required to search over all the possible policies. To illustrate this, we present two different setups in Fig. 2 and Fig. 3, of which the details can be found in Sec. IV-A. In the former, the distance between the users is small, resulting in small channel differences among the users. In the latter, the distance

Fig. 2: Illustration of channel quality differences for a distance of 0.4 m between the users.

Fig. 3: Illustration of channel quality differences for a distance of 3.3 m between the users.

Fig. 4: Illustration of different operation regions. U1 is fixed at the position (1.3, 1.3, 0.8) m.

is larger, and channel differences are more pronounced. Fig. 4 presents the optimal allocation region of TX5 to user 2 (U2), obtained via brute-force search. Next to it, also the region where time-division multiplexing is preferred is shown. This optimal solution leads to the following two insights:

Insight 1: for small distances between users, the channel difference among the users is limited, as illustrated in Fig. 2. In this case, it is straightforward to choose time-division multiplexing (interference-free) due to large inter-user interference.

Insight 2: for larger distances between users and a pronounced channel quality between a certain TX and a user, the TX can be directly assigned to the user and should not be taken into account anymore for the exhaustive search. For example, in the setup of Fig. 3, TX5 is assigned to U2.

C. Heuristic algorithm

Based on the two insights presented in Sec. III-B, we design a lightweight two-step heuristic algorithm, as described in Algorithm 1. In the first step, the algorithm determines

Algorithm 1: Heuristic algorithm for AD-MISO

Input : $\Delta H_n, \forall n \in \mathcal{N}; \alpha; \beta$

Output: Optimal policy σ^*

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1  $\mathcal{N}_{free} \leftarrow \mathcal{N}$ 
2 if  $\max_{n \in \mathcal{N}}(\Delta H_n) \leq \alpha$  then
3   form all TXs into a D-MISO channel to serve
   users through time-division multiplexing
   (interference-free)
4 else
5   for  $n \in \mathcal{N}$  do
6     if  $\Delta H_n > \beta$  then
7        $\sigma_{n,k'}^* = 1$  with  $k' = \arg \max_{k \in \mathcal{K}}(H_{n,k})$ 
8        $\mathcal{N}_{free} \leftarrow \mathcal{N}_{free} \setminus n$ 
9    $\mathcal{C}_{free} \leftarrow$  set of channel adaptation policies with the
   new set  $\mathcal{N}_{free}$  of TXs, refer to Eqs. (3) and (4)
10  use brute-force on  $\mathcal{C}_{free}$  to find  $\sigma^*$ , refer to Eq. (10)

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whether to use time-division multiplexing based on the channel similarity among the users. The difference in channel quality from TX n to the users is calculated by:

$$\Delta H_n = \frac{\max_{k \in \mathcal{K}} H_{n,k} - \min_{k \in \mathcal{K}} H_{n,k}}{\min_{k \in \mathcal{K}} H_{n,k}}, \quad \forall n \in \mathcal{N} \quad (11)$$

If the maximum difference $\max_{n \in \mathcal{N}}(\Delta H_n)$ is smaller than or equal to a predefined parameter α , time-division multiplexing is selected and no exhaustive search is required. However, if $\max_{n \in \mathcal{N}}(\Delta H_n)$ is larger than α , the algorithm proceeds to the second step. In this step, TXs with a channel difference ΔH_n larger than a predefined parameter β are first assigned to the user with the best channel. Afterwards, exhaustive search is performed over the remaining set of configurations to find the optimal set. Since the exhaustive search set depends on the user positions, it is not straightforward to provide a complexity formula for the heuristic.

D. Multi-service support

In above subsections, we have presented how to derive the channel adaptation policy to maximize the system throughput. In practical systems, multi-service is required by users where a minimal throughput for certain users is demanded. In this paper, we design a *sub-optimal* method based on pure time-division multiplexing to provide multi-service support.

Without loss of generality, we consider two mobile users in the system, U1 and U2, to illustrate our method. Under pure time-division multiplexing, the TXs are multiplexed in time domain (all TXs serve U1 or all TXs serve U2 at a time), to support users with heterogeneous service requirements. We extend this idea to scheduling in time between the optimal point for one user, and the optimal sum rate point for both users, as illustrated in Fig. 5. This is a sub-optimal way to approximate the rate region by first searching the best channel adaptation policy (using the heuristic presented in Sec. III-C), and then further approximating the rate region using two linear functions.

Fig. 5: Throughput allocation among two users with multi-service support. U2 is located at a horizontal distance of 2.4 m to U1.

Let $S^* = \{S_1^*, S_2^*\}$ be the normalized throughput for both users achieving the maximum system throughput. If $S_1 < S_1^*$, the two left points $(0, 1)$ and (S_1^*, S_2^*) are multiplexed in time and the achievable throughput for U2 is given by:

$$S_2 = (S_{2,\max} - S_2^*) \left(1 - \frac{S_1}{S_1^*}\right) + S_2^*, \quad (12)$$

with $S_{2,\max}$ the maximum S_2 . If $S_1 > S_1^*$, the two right points $(1, 0)$ and (S_1^*, S_2^*) are multiplexed in time and the achievable throughput for U2 is given by:

$$S_2 = \frac{S_2^*}{S_1^* - S_{1,\max}} (S_1 - S_{1,\max}), \quad (13)$$

with $S_{1,\max}$ the maximum S_1 .

IV. PERFORMANCE EVALUATION

In this section we present evaluation results of the proposed AD-MISO technique and the heuristic algorithm.

A. Simulation setup

We consider an indoor area with $N = 6$ equidistant TXs aligned in a 2×3 array, as illustrated in Fig. 2. The distance between the TXs is determined such that the uniformity requirement of $\bar{U} \geq 0.7$ is achieved. The luminous flux of the LEDs is chosen to fulfill the recommended illumination level of 400 lux in office scenarios [13]. They are attached at a height of 2.8 m from the ground, facing downwards. Further, $K = 2$ users are considered, both placed at a height of 0.8 m

TABLE I: System parameters for simulations

Parameter	Notation	Value
Noise spectral power density	N_0	$2.3 \times 10^{-22} \text{ A}^2/\text{Hz}$
Bit rate	R	10 Mbps
Coding/decoding frame size	l	128 bits
Half power semi-angle of TX	$\phi_{1/2}$	30°
Luminous efficacy of TX	η	170 lm/W
Field of view of PD	Ψ_c	90°
Collection area of PD	A_{pd}	1 mm^2
Responsibility of PD	ρ	0.45 A/W

Fig. 6: Gain of AD-MISO over TDMA when $\bar{U} = 0.73$. Each block represents U2's position; U1 is fixed at (1.3, 1.3, 0.8) m. Note that the inter-TX distance depends on the value of $\bar{U}$.

Fig. 7: Gain of AD-MISO over TDMA when $\bar{U} = 0.82$. Each block represents U2's position; U1 is fixed at (1.3, 1.3, 0.8) m. Note that the inter-TX distance depends on the value of $\bar{U}$.

Fig. 8: Illustration of time multiplexing region and the $\max_{n \in \mathcal{N}}(\Delta H_n)$ isolines, facilitating the choice for parameter α .

Fig. 9: Illustration of allocation region of TX1 to U2 and ΔH_n isolines, facilitating the choice for parameter β .

Fig. 10: Illustration of allocation region of TX5 to U2 and ΔH_n isolines, facilitating the choice for parameter β .

and facing upwards to the ceiling. Without loss of generality, user 1 (U1) is located in the center of the left part of the grid, as shown in Fig. 2 and Fig. 3. In case all transmitters are assigned to U1, BER_1 equals 1.73×10^{-6} . User 2 (U2) can move freely within the whole area. Table I lists other system parameters used in the simulation.

We compare the performance of AD-MISO with pure Time-Division Multiplexing Access (TDMA). In TDMA, all TXs are assigned to a certain user at a given time instant. Therefore, it is interference-free. To compare the performance between brute-force AD-MISO and TDMA, the average system throughput over the envelope of the rate region is considered. The envelope of pure TDMA consists of a line between the optimal points for a single user, as shown in red in Fig. 5. AD-MISO can achieve a rate region larger than pure TDMA, depending on the location of the users.

B. Evaluation results

Next we present the results under different methods.

1) *Brute-force search*: The gain of AD-MISO over TDMA is presented in Fig. 6 and Fig. 7, where the desired uniformities $\bar{U}$ (refer to Sec. II) are set to $\bar{U} = 0.73$ and $\bar{U} = 0.82$, respectively. First, we can clearly observe a region where time-division multiplexing (interference-free) is preferred in AD-MISO (the region in dark-blue color where the gain over

TABLE II: Comparison between AD-MISO and TDMA

Setup	AD-MISO [Mbps]	TDMA [Mbps]	Gain [%]
$\bar{U} = 0.73$	12.4763	9.9988	24.8
$\bar{U} = 0.82$	13.5649	10.0000	35.6

TDMA is 0). Next, from Fig. 6 we can see that when U2 is within the left region where U1 is located, AD-MISO is still able to achieve a gain within the range of 20% to 30% when the users are not close to each other. The gain increases to a range of 30% to 45% when $\bar{U}$ is higher, as shown in Fig. 7 (b). The average system throughputs of AD-MISO and TDMA in the two settings are given in Table II. We can see that the former achieves an average gain of 24.8%, while the latter achieves a gain of 35.6%. The reason behind this is that the inter-TX distance decreases when $\bar{U}$ increases, resulting in a higher increase in SNR compared to INR, and thus a higher throughput gain.

2) *Heuristic algorithm*: As can easily be observed from Algorithm 1 presented in Sec. III-C, the two parameters α and β are important for the performance of the heuristic. To get good performance, suitable values of α and β must be determined first. To get more insight in α , Fig. 8 presents the time-division multiplexing (interference-free) region for the setup used in Fig. 6 as well as isolines for the maximum channel difference among the transmitters. We conclude that

Fig. 11: Comparison of the relative error ϵ (a) and search space (b) between the heuristic and brute-force algorithm with $\alpha = 2$.

$\alpha > 5$ leads to a significant error because in that case, time multiplexing will be selected for locations that could achieve a higher system throughput than time multiplexing. Instead, $\alpha = 2$ is a better choice, showing a good match with the time multiplexing region. A similar analysis is conducted for parameter β . As an example, the allocation region of TX1 and TX5 to U2 is depicted in Fig. 9 and Fig. 10, respectively. From these figures, it is observed that for $\beta < 3$, the isolines are not inside the allocated region, resulting in a possible mistake. Furthermore, the smallest acceptable β can differ for different TXs and hence multiple values of β are used in our simulation.

The empirical Cumulative Distribution Function (CDF) of the relative error between the heuristic and the brute-force is shown in Fig. 11(a). It can be observed that by selecting $\beta \geq 1$, a maximum error of 4.7% is introduced for 90% of the positions of U2. Fig. 11(b) presents the CDF of the search space, i.e. the number of tested policies to find the maximum system throughput. For $\beta = 2$, only a search space of 81 has to be evaluated in 90% of the positions of U2. On average, a search space of 40.6 must be performed, which is an improvement of 94% compared to brute-force search, as shown in Fig. 12. The accuracy drops on average by 0.88% and maximally by 7.32% compared to brute-force search.

3) *Multi-service support*: Evaluations of the multi-service support is straightforward based on the results we present in Sec. IV-B1 and Sec. IV-B2. Due to the space limitation, these evaluation results for multi-service support are omitted.

V. CONCLUSION

Motivated by the dense deployment of LEDs where cells are heavily overlapping to achieve uniform illumination, we proposed a novel scheme AD-MISO to improve the system throughput of VLC networks with multiple mobile users. AD-MISO adapts the transmitter strategy according to the channel dynamics resulting from users' movement. We formulated the adaptation policy as an optimization problem and proposed a heuristic algorithm to reduce the computational complexity. We evaluated AD-MISO through extensive simulations. Our evaluation results demonstrated that AD-MISO improved the system throughput up to 35.6%, and our heuristic achieved similar results while reducing the search space by 94%.

Fig. 12: Average search space vs. β ($\alpha = 2$). The first bar is the brute-force (BF) search.

In the future, we will study the scalability of AD-MISO with more transmitters and users in various LED arrangements, and exploit other metrics, such as fairness, spectral efficiency and energy efficiency, to evaluate the system performance. We believe that dense deployment of LED luminaries will create great benefit for providing uniform illumination, and also can benefit the communications with VLC. As such, improving the performance of such a dense LED architecture, as done in this work, will intrigue more research on the topic.

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