DOI: https://doi.org/10.1109/tvt.2024.3438793

Colored Reconfigurable Photodetectors for Aligning the Light in Vehicular VLC

Máximo Morales-Céspedes, *Member, IEEE,* Borja Genovés Guzmán, *Member, IEEE,* Alejandro López Barrios, *Student Member, IEEE,* Víctor P. Gil Jiménez, *Senior Member, IEEE,*

***Abstract*—Vehicular visible light communications have been proposed in the framework of 6G communications to potentially achieve high data rates and extremely low-latency simultaneously. Although multiple-input multiple-output schemes may achieve high data rates they are subject to closed-loop transmission in order to achieve multiplexing gain, also known as degrees of freedom (DoF). In this work, we propose the concept of colored reconfigurable photodetector that generates tuples of colors each providing channel responses linearly independent among them in order to derive a novel transmission scheme referred to as colored blind interference alignment (cBIA). It gets rid of the closed-loop transmission while achieving multiplexing gain, i.e., cBIA achieves both low-latency, depending on the data packet size, and high data rates. The proposed cBIA achieves three times the DoF obtained by traditional non-colored blind interference alignment (BIA). Simulations results show that the achievable rate of cBIA outperforms closed and open loop baseline schemes. Besides, cBIA satisfies the latency requirements of 6G communications.**

***Index Terms*—Vehicular visible light communications, low-latency, blind interference alignment, multi-color LED.**

I. Introduction

The vehicular ecosystem has recently proposed the vehicle-to-vehicle (V2V) communications for increasing the reliability and robustness in vehicular traffic [1]. Achieving high data rates subject to low-latency is required in vehicular environments, which leads to bandwidth-demanding communications. Although radio-frequency (RF) is the most mature technology for V2V communications, the overcrowded and limited RF spectrum, the data traffic congestion in a medium or large user density scenarios, as well as the risk of security attacks, are pushing back the RF-based V2V conceptual design.

Visible light communications (VLC) are proposed as a means of exploiting the wide and unregulated optical domain. The light emitting diodes (LEDs) already employed in vehicles for illumination and the possibility of deploying multiple photodiodes around the vehicle structure offer a unique opportunity to convert VLC into an enabling technology for vehicular communications [2]. Besides, the short-range and line-of-sight (LoS) links that characterize the V2V scenarios are favourable for vehicular VLC (V-VLC). The fact that two or more optical transmitters, e.g., the two front or brake lights, are typically installed in vehicles, enables the implementation of multiple-input multiple-output (MIMO) techniques.

Obtaining high data rates by increasing the multiplexing gain in MIMO systems, also known as degrees of freedom (DoF), typically requires closed-loop transmission to obtain channel state information at the transmitters (CSIT), and then invoking precoding techniques such as zero forcing (ZF) [3]. It is worth noticing that the feedback step in closed-loop transmission has a direct impact on the transmission period of data, hampering the achievability of low-latency. Focusing on open-loop schemes, blind interference alignment (BIA) based on the concept of reconfigurable photodetector for VLC is proposed in [4] to achieve multiplexing gain without CSIT. Fundamentally, a reconfigurable photodetector provides a set of linearly independent channel responses selecting one of them through a selector connected to a single signal processing chain. In [5], it is shown that this concept can be implemented in vehicles exploiting the angular and lens diversity that their structure inherently provides. Although BIA applied to V-VLC based on phosphor coated LEDs obtains satisfactory data rates and allows us to manage the transmission frame in open-loop fashion, it is subject to a transmission pattern that may hamper to achieve extremely low-latency.

In contrast to phosphor coated LEDs, multi-colored LEDs provide additional DoF to transmit multiple data streams simultaneously based on wavelength division multiplexing [6]. Then, multiple data streams assigned to each color can be transmitted simultaneously during a single time slot, which motivate their use for reducing the latency. However, the extension of BIA to multi-colored LEDs is not straightforward since photodetectors just equipped with color filters does not provide linearly independent channels, which are required for implementing BIA schemes. In this paper, we propose a new approach based on exploiting multi-color LEDs referred to as colored BIA (cBIA) for V-VLC. The target latency of 0.1 ms proposed for 6G extremely low-latency services is assumed. The contributions of this paper can be summarized as follows,

1) The concept of colored reconfigurable photodetector is firstly proposed. It is based on creating tuples composed of a set of colors, e.g., red, green and blue, following an angular diversity arrangement. This photodetector architecture provides linearly dependent channel responses among the colors of each tuple while the channel re-

M. Morales, A. López and V. P. Gil are with the Department of Signal Theory and Communications, Universidad Carlos III de Madrid, Leganés, Spain (maximo@tsc.uc3m.es, albarrios@tsc.uc3m.es, vgil@ing.uc3m.es).

B. Genovés is with the Electrical and Computer Engineering Department, University of Virginia, Charlottesville, USA (bgenoves@virginia.edu).

This work is supported by the following research projects funded by MICIU/AEI/10.13039/501100011033; IRENE (PID2020-115323RB-C33), ViDiT (TED2021-129869B-I00), also funded by NextGenerationEU/PRTR and, for the work of M. Morales, Ramón y Cajal RYC2022-036053-I, also funded by FSE+. The work of B. Genovés is supported by the Marie Sklodowska-Curie grant No. 101061853.

sponses from different tuples are linearly independent.

2) The transmission pattern and received signal combination for subtracting the interference that define cBIA are derived for a V2V scenario. The same DoF as for non-colored BIA can be achieved while reducing the latency by exploiting both the angular and color diversity of the colored reconfigurable photodetector.
3) The general vehicle-to-multiple vehicles cBIA is derived. The closed-form expressions of the latency, DoF and achievable rate are determined. The impact of interfering vehicles on the achievable rate is also analyzed.

The performance of cBIA is analyzed considering the low-beam and high-beam lights models [7]. Simulation results show that cBIA outperforms the achievable rate of non-colored BIA and closed-loop schemes such as ZF while ensuring extremely low-latency in line with the 6G requirements.

II. System model

We consider a V-VLC system in which the $L = 2$, $l = \{1, 2\}$, headlights of a vehicle provide illumination and transmit data to K, $k = \{1, \dots, K\}$, receivers as it is shown in Fig. 1. Each front light corresponds to a multi-color (red (R), green (G), blue (B)) optical transmitter and the vehicles are equipped with colored reconfigurable photodetectors as receivers, which are composed of multiple RGB tuples following an angular diversity arrangement each referred to as a *mode*. At the receiver, the signal associated to color $c = \{R, G, B\}$ is filtered at color c' with an efficiency $\gamma_{c,c'}$, where $\gamma_{c,c} = 1$. The concept of colored reconfigurable photodetector is detailed below. The transmitted signal is denoted by $\mathbf{x} = \left[\mathbf{x}_R, \mathbf{x}_G, \mathbf{x}_B\right]^T \in \mathbb{R}^{3 \cdot L \times 1}$, where $\mathbf{x}_c = \begin{bmatrix} x_{c,1} & \dots & x_{c,L} \end{bmatrix}$ is the signal associated to the L optical transmitters at color c and $x_{c,l}$ is the signal of transmitter l at color c. Thus, the RGB signal of receiver k for mode m at time t can be written as

$$\mathbf{y}^{[k]}[t] = \delta \Gamma \mathbf{H}^{[k]}\left(m[t]\right)\mathbf{x}[t] + \mathbf{z}^{[k]}[t], \tag{1}$$

where δ is the responsivity of the photodiode and Γ is the color filtering matrix given by

$$\Gamma = \begin{bmatrix} \gamma_{R,R} & \gamma_{R,G} & \gamma_{R,B} \\ \gamma_{G,R} & \gamma_{G,G} & \gamma_{G,B} \\ \gamma_{B,R} & \gamma_{B,G} & \gamma_{B,B} \end{bmatrix}, \tag{2}$$

and $\mathbf{H}^{[k]}\left(m[t]\right) \in \mathbb{R}_{+}^{3 \times 3L}$ is the channel matrix of user k given by the mode selected at time t,

$$\mathbf{H}^{[k]}\left(m[t]\right) = \mathbf{I}_3 \otimes \mathbf{h}^{[k]}\left(m[t]\right), \tag{3}$$

where $\mathbf{h}^{[k]}\left(m[t]\right) \in \mathbb{R}^{1 \times L}$ contains the channel responses between the L transmitters and user k for mode m and $\otimes$ denotes the Kronecker product. After color filtering, $\mathbf{h}^{[k]}\left(m[t]\right)$ generates three colored channel responses $\mathbf{h}_c^{[k]}\left(m[t]\right)$, $c = \{R, G, B\}$, while color leakage is given by $\gamma_{c,c'} \cdot \mathbf{h}_c^{[k]}\left(m[t]\right)$, $c \neq c'$. Note that color leakage is generated by the simultaneous transmission of multiple data streams associated to each color, which are demultiplexed at the receiver by filtering them. The impact of color leakage directly depends of the quality of the optical filters [8]. Moreover, in (1), $\mathbf{z}^{[k]}$ is real additive white Gaussian noise with variance σ_z^2.

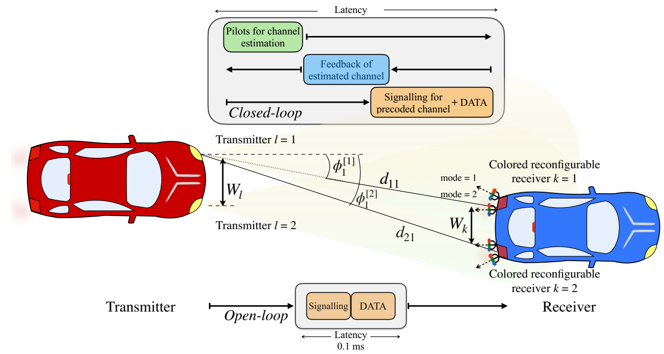

Fig. 1. Geometry of the scenario for V2V communications. Closed-loop and open-loop transmission approaches are described.

A. Optical channel

The geometrical scenario for V2V communications is depicted in Fig. 1. The distance between transmitter l and receiver k is denoted as d_{kl} and the irradiance and incidence angles are denoted as $\phi_l^{[k]}$ and $\varphi_l^{[k]}$, respectively. The distance between the two headlights and the two photodetectors is denoted by W_l and W_k, respectively. At this point, the signal propagation in vehicular scenarios can be classified into low-beam and high-beam models [7].

For the low-beam lights, the signal propagation can be modeled following the Lambertian model. Thus, omitting the color index for the sake of simplicity, the channel $h_l^{[k]}$ is

$$h_l^{[k]} = \begin{cases} \frac{A}{d_{kl}^2} R(\phi_l^{[k]}) T\left(\varphi_l^{[k]}\right) \cos\left(\varphi_l^{[k]}\right) & \varphi_l^{[k]} \leq \Psi_c \\ 0 & \varphi_l^{[k]} > \Psi_c \end{cases} \tag{4}$$

where A is the area of detection of the photodiode, Ψ_c denotes the field of view (FoV), $T\left(\varphi_l^{[k]}\right)$ is the gain of the optical concentrator and $R\left(\phi_l^{[k]}\right) = \frac{\nu+1}{2\pi}\cos^{\nu}\left(\phi_l^{[k]}\right)$ is the Lambertian beam distribution, where ν is the radiation index for the radiation semi-angle $\phi_{1/2}$ given by $\frac{-\log(2)}{\log\left(\cos\left(\phi_{1/2}\right)\right)}$.

The path loss for high beam headlights based on ray tracing is derived in [9] considering the impact of weather effects. In this case, the resulting channel can be written as

$$h_l^{[k]} = D^2 \cos\left(\phi_l^{[k]}\right)^{\frac{1}{\epsilon}} \cos\left(\varphi_l^{[k]}\right)^{\frac{1}{\epsilon}} \exp\left(\mu d_{kl}\left(D\right)^{\frac{\epsilon}{2}}\right), \tag{5}$$

where $D = \frac{D_R}{\zeta d_{kl}}$, D_R is the diameter of the receiver lens, μ is related with the extinction coefficient and, ϵ and ζ are the correction coefficients for different weather conditions [9].

B. Colored reconfigurable photodetector

The concept of reconfigurable photodetector is based on deploying multiple photodiodes in angle and lens diversity connected to a single signal processing chain through a selector. For the sake of simplicity, only angular diversity is considered in this work. For the colored application, the photodiodes of each RGB tuple follow the same pointing angle as described in Fig. 2. Each tuple is referred to as a *mode* of the colored reconfigurable photodetector. Since the channel

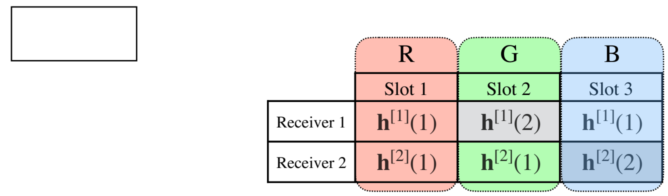

Fig. 2. Architecture of the colored reconfigurable photodetector. Signal processing for BIA and cBIA schemes assuming a 2 transmitters and 2 receivers. It comprises 3 symbol extensions (time slots) for BIA. The same structure can be applied to cBIA assuming that each symbol extension corresponds to a color.

variations in each tuple are exclusively given by the filtering efficiency, the channel responses belonging to the same mode are linearly dependent. On the other hand, the RGB tuples of different modes are characterized by distinct angles of incidence. Since the optical channel depends on the cosine of the incidence angle, i.e., a non-linear function, the channels between distinct RGB tuples are linearly independent [4]. Therefore, the proposed colored reconfigurable photodetector satisfies $h_{l,c}^{[k]}(m) \neq \alpha h_{l,c}^{[k]}(m') + \beta$, $\forall \alpha, \beta \in \mathbb{R}$, $m \neq m'$, where $h_{l,c}^{[k]}(m)$ is the channel response from transmitter l to receiver k at color c of mode m.

III. Colored BIA for V2V communications

Achieving multiplexing gain based on precoding schemes requires to implement a closed loop for pilot transmission, channel estimation and transmission of the precoded data that may lead to a large latency, hampering their implementation in V-VLC. On the other hand, BIA schemes get rid of the closed-loop transmission so that both signalling to determine CSI at the receiver and data are transmitted in the same frame (open-loop) as described in Fig. 1. Therefore, the latency mainly depends on the length of this frame, which can repeat or expand the BIA pattern subject to the latency requirements. It is worth remarking that the key idea is based on varying the channel response artificially by selecting modes that provide linearly independent channel responses, while the physical channel remains constant. Applied to 6G vehicular environments, the target latency of 0.1 ms involves a distance variation of only 3.33 mm for vehicles moving at $120\ \frac{\text{km}}{\text{h}}$. As a consequence, it can be assumed that the optical channel remains constant subject to the considered target latency.

A. Classical non-colored BIA

Let us consider a V2V system in which the two headlights of a vehicle transmit a data stream each to a vehicle equipped with two conventional reconfigurable photodetectors as described in [5]. Non-colored BIA generates a signal processing pattern comprising 3 time slots as described in Fig. 2, during which the signal at transmitter l is given by

$$\begin{aligned} x_l[1] &= u_l^{[1]} + u_l^{[2]}, \\ x_l[2] &= u_l^{[1]}, \\ x_l[3] &= u_l^{[2]}, \end{aligned} \tag{6}$$

where the color index has been omitted and $u_l^{[k]}$ is the symbol transmitted by the headlights $l = \{1, 2\}$ intended to reconfigurable photodetector k. That is, during the first slot each transmitter l sends the sum of the symbols intended to both users, i.e., two independent symbols per transmitter, generating interference at the receivers. During the second and third time slots the transmitters consider a specific user transmitting exclusively the symbols intended to that user from the symbols considered in the first slot, i.e., free of interference because of transmission to the other user.

For the considered example, non-colored BIA transmits 4 symbols comprising 3 time slots, i.e., $\frac{4}{3}$ DoF are achievable. For a vehicular implementation, the BIA pattern can be expended or repeated to meet the latency requirements subject to this DoF performance as described in [5]. In the following, an alternative colored BIA is proposed for exploiting the use of RGB transmitters with the aim of reducing the latency.

B. BIA based on colored reconfigurable photodetector

For the proposed cBIA scheme the headlights of a vehicle correspond to two RGB optical transmitters. Each color can be managed as an orthogonal transmission resource. Thus, each time slot can be assigned to an independent color as depicted in Fig. 2. Therefore, the switching pattern occurs in a single time slot instead of wasting three of them. For the considered cBIA scheme, the transmitted signal is

$$\mathbf{x} = \begin{bmatrix} \mathbf{x}_R \\ \mathbf{x}_G \\ \mathbf{x}_B \end{bmatrix} = \begin{bmatrix} \mathbf{I}_2 \\ \mathbf{I}_2 \\ \mathbf{0}_2 \end{bmatrix} \underbrace{\begin{bmatrix} u_1^{[1]} \\ u_2^{[1]} \end{bmatrix}}_{\mathbf{u}^{[1]}} + \begin{bmatrix} \mathbf{I}_2 \\ \mathbf{0}_2 \\ \mathbf{I}_2 \end{bmatrix} \underbrace{\begin{bmatrix} u_1^{[2]} \\ u_2^{[2]} \end{bmatrix}}_{\mathbf{u}^{[2]}}, \tag{7}$$

where $u_l^{[k]}$ is the symbol of transmitter l intended to receiver k. Notice that cooperation among transmitters is not required, i.e., they do not know the symbols sent by other transmitters.

The colored reconfigurable photodetector obtains 6 received signals in two RGB tuples. However, it is necessary to manage the linear/non-linear channel responses to satisfy the alignment criterion; the photodetector k must receive the intended symbol in linearly independent channel responses, while transmission of the interfering symbols occurs in linearly dependent channel responses. Let us focus on decoding the symbol $\mathbf{u}^{[1]}$ without loss of generality. Specifically, the red and blue signals are selected from mode 1 while the green signal is selecte mode 2. Then, the received signal can be written as

$$\begin{bmatrix} y_R^{[1]}(1) \\ y_G^{[1]}(2) \\ y_B^{[1]}(1) \end{bmatrix} = \begin{bmatrix} \mathbf{h}_R^{[1]}(1)\left(\mathbf{u}^{[1]}+\mathbf{u}^{[2]}\right) \\ \mathbf{h}_G^{[1]}(2)\mathbf{u}^{[1]} \\ \mathbf{h}_B^{[1]}(1)\mathbf{u}^{[2]} \end{bmatrix} + \begin{bmatrix} \gamma_{R,G}\mathbf{h}_R^{[1]}(1)\mathbf{u}^{[1]} + \gamma_{R,B}\mathbf{h}_R^{[1]}(1)\mathbf{u}^{[2]} \\ \gamma_{G,R}\mathbf{h}_G^{[1]}(2)\left(\mathbf{u}^{[1]}+\mathbf{u}^{[2]}\right) + \gamma_{G,B}\mathbf{h}_G^{[1]}(1)\mathbf{u}^{[2]} \\ \gamma_{B,R}\mathbf{h}_B^{[1]}(1)\left(\mathbf{u}^{[1]}+\mathbf{u}^{[2]}\right) + \gamma_{B,G}\mathbf{h}_B^{[1]}(1)\mathbf{u}^{[1]} \end{bmatrix} +$$

where $y_c^{[k]}(m)$ is the signal received at color c for m of the proposed colored reconfigurable photodetector. Ig the noise for the sake of simplicity, the signal received during the selected modes and colors for decoding $\mathbf{u}^{[1]}$ is given by

$$\mathbf{y}^{[1]} = \underbrace{\begin{bmatrix} \mathbf{h}_R^{[1]}(1) \\ \mathbf{h}_G^{[1]}(2) \\ \mathbf{0} \end{bmatrix}}_{\text{rank=2}} \begin{bmatrix} u_1^{[1]} \\ u_2^{[1]} \end{bmatrix} + \underbrace{\begin{bmatrix} \mathbf{h}_R^{[1]}(1) \\ \mathbf{0} \\ \mathbf{h}_B^{[1]}(1) \end{bmatrix}}_{\text{rank=1}} \begin{bmatrix} u_1^{[2]} \\ u_2^{[2]} \end{bmatrix} + \underbrace{\left(\mathbf{I}_3 - \Gamma\right)\mathbf{H}^{[1]}\mathbf{x}}_{\text{Inter-color interference}}. \quad (9)$$

Notice that cBIA requires to manage both color and angular diversity of the colored reconfigurable photodetector to align the interference. Thus, the symbol $\mathbf{u}^{[1]}$ must be contained in a 2-rank matrix, while the interference due to $\mathbf{u}^{[2]}$ is aligned in a 1-rank matrix. Both conditions, which are referred to as BIA criterion, are satisfied exploiting the architecture of the colored reconfigurable photodetector so that the red and green components are linearly independent, i.e., $\mathbf{h}_R^{[1]}(1) \neq \alpha\mathbf{h}_G^{[1]}(2) + \beta$, $\forall\alpha, \beta \in \mathbb{R}$, while the red and blue components are linearly dependent, i.e., $\mathbf{h}_B^{[1]}(1) = \kappa\mathbf{h}_R^{[1]}(1)$, where κ is the constant channel difference between both colors of the same mode. Notice that a term corresponding to the inter-color interference depending on the efficiency of the color filtering appears in (9).

Thus, it is possible to align the interference without the need for three time slots as occurs in non-colored BIA. Notice that the signal received in the blue component corresponds to the interference in the red component because of transmission to user 2. Applying the unitary post-coding matrix $\mathbf{U}^{[1]} = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 0 & -1 \\ 0 & 1 & 0 \end{bmatrix}$, the received signal is

$$\mathbf{U}^{[1]}\mathbf{y}^{[1]} = \tilde{\mathbf{H}}_1\mathbf{u}^{[1]} + \mathbf{\Upsilon}_I + \tilde{\mathbf{z}}^{[1]}, \quad (10)$$

where $\tilde{\mathbf{H}}_1 = \left[\mathbf{h}_R^{[1]}(1)^T, \mathbf{h}_G^{[1]}(2)^T\right]^T$ is the resulting 2-rank channel matrix, $\mathbf{\Upsilon}_I = \mathbf{U}^{[1]}\left(\mathbf{I}_3 - \Gamma\right)\mathbf{H}^{[1]}\mathbf{x}$ corresponds to the inter-color interference and $\tilde{\mathbf{z}}^{[1]}$ is the noise after post-coding. Then, the 2 DoF in $\mathbf{u}^{[1]}$ can be decoded in a single time slot.

Similarly, the 2 DoF in $\mathbf{u}^{[2]}$ can be decoded by selecting the red and blue signals, and the green signal from the modes 2 and 1, respectively. Therefore, the 4 DoF in (7) are achievable in a single time slot without the need for CSIT, i.e., following an open-loop transmission scheme. Therefore, the latency is reduced three times in comparison with non-colored BIA.

IV. Colored BIA. General Case

For the general case, a vehicle transmits information to V, $v = \{1, \ldots, V\}$ vehicles equipped with two colored reconfigurable photodetectors each. In contrast to the single vehicle-to-vehicle case, multiple time slots must be considered if transmission to two or more vehicles is assumed.

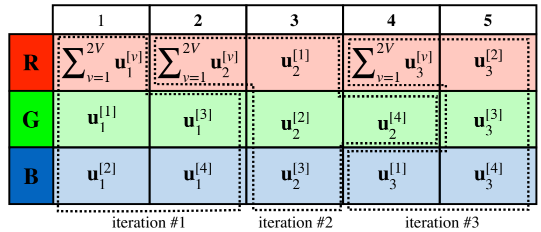

Fig. 3. Signal transmission for cBIA considering $V = 2$ vehicles.

Let us first focus on the case in which a vehicle transmits data to $V = 2$ vehicles. The transmitted signal is described in Fig. 3. First, in a dedicated color, e.g., the red color for the proposed example, $2V$ symbols comprising 2 DoF each are transmitted simultaneously. After that, each symbol is transmitted in orthogonal fashion during the green and blue colors of the first and second time slots. Notice that two time slots are required to allocate the resulting transmission pattern. However, the red color in time slot 2 still remains idle, so that a new iteration of the proposed scheme can be considered. Let us define $\mathbf{u}_t^{[k]} = \left[u_{t,1}^{[k]} \quad u_{t,2}^{[k]}\right]$ as the symbol comprising 2 DoF intended to reconfigurable receivers k at iteration t, where $k = \{1, 2\}$ and $k = \{3, 4\}$ corresponds to vehicles $v = 1$ and $v = 2$, respectively, and $u_{t,l}^{[k]}$ is the symbol from transmitter l. The 4 new symbols for iteration $t = 2$ are transmitted simultaneously in this idle slot. Afterwards, they are transmitted in orthogonal fashion during the following time slots. This procedure is extended until considering 5 time slots, from which the same structure as described above can be repeated. For the considered example, 4 symbols comprising 2 DoF each are transmitted 3 times during 5 time slots. Therefore, $\frac{2\times4\times3}{5} = \frac{24}{5}$ DoF per time slot can be achieved.

A. Latency, Degrees of Freedom and Achievable Rate

The methodology described above can be applied straightforwardly for V vehicles equipped with two reconfigurable photodetectors each. Then, transmitting $2V$ symbols simultaneously and in orthogonal fashion while satisfying the BIA criterion given by the colored reconfigurable photodetector. For the general case, the cBIA pattern comprises

$$L_{\text{cBIA}} = \begin{cases} \frac{2V+1}{3} & \text{if } \operatorname{mod}(2V+1, 3) = 0 \\ 3\left\lfloor\frac{2V+1}{3}\right\rfloor + 1 & \text{if } \operatorname{mod}(2V+1, 3) = 1 \\ 3\left\lceil\frac{2V+1}{3}\right\rceil - 1 & \text{if } \operatorname{mod}(2V+1, 3) = 2 \end{cases} \quad (11)$$

time slots, which determine the length of the transmitted frame, and therefore, the latency. Besides, the achievable DoF per time slot are

$$\text{DoF}_{\text{cBIA}} = 3 \times \frac{4V}{2V+1} = 3 \times \text{DoF}_{\text{BIA}}, \quad (12)$$

where DoF_{BIA} is the DoF achieved by non-colored BIA.

The power allocated to each data stream is denoted by P_{str}. Constant power allocation during the BIA pattern is assumed, i.e., the optical power is uniformly distributed among the colors and time slots. After subtracting the interference, the received signal follows the same structure as in (10). Thus, the achievable rate, as lower bound of the capacity [10], of cBIA for vehicle v is given by the rate obtained by its two reconfigurable photodetectors

$$R_{\text{cBIA}} = \frac{1}{2}\sum_{k=2v-1}^{2v} \eta \log_2\left(\det\left(\mathbf{I}_2 + \frac{e\delta}{2\pi}P_{\text{str}}\tilde{\mathbf{H}}_k\tilde{\mathbf{H}}_k^H\mathbf{R}_{z_I}^{-1}\right)\right) \tag{13}$$

where η is the ratio of DoF per time slot assigned to each receiver, $\tilde{\mathbf{H}}_k$ is the channel matrix of receiver k as in (10) so that $\tilde{\mathbf{H}}_k = \begin{bmatrix}\mathbf{h}_c^{[k]} & \mathbf{h}_{c'}^{[k]}\end{bmatrix}^T$ and $\tilde{\mathbf{H}}_{k+1} = \begin{bmatrix}\mathbf{h}_c^{[k+1]} & \mathbf{h}_{\hat{c}}^{[k+1]}\end{bmatrix}^T$, $c' \neq \hat{c}$, and $\mathbf{R}_{z_I}$ is the noise plus interference covariance matrix,

$$\mathbf{R}_{z_I} = \mathbf{R}_z + P_{\text{str}}\boldsymbol{\Upsilon}_I\boldsymbol{\Upsilon}_I^H, \tag{14}$$

where $\mathbf{R}_z = \begin{bmatrix}2V & 0\\ 0 & 1\end{bmatrix}$ is the noise covariance matrix after interference subtraction as derived in [11].

Assuming synchronization and joint transmission with additional vehicles, the cBIA pattern can be straightforwardly expanded to consider more than two optical transmitters as proposed in [5]. In this case, the achievable rate is given by (13) simply considering the proper size of the resulting channel and noise plus interference covariance matrices.

However, this approach may result too complex to implement in vehicular environments. Assuming that the BIA patterns of the vehicles are synchronized, note that the measurement of interference in linearly dependent channel responses also includes the co-channel interference, which is subtracted from the slots originally polluted by interference. However, this interference still remains in the color/time slots employed for measuring interference. This issue is widely analyzed in [11]. Subject to synchronization among external interfering vehicles, the achievable rate is given by (13) in which the noise plus interference covariance matrix is given by

$$\mathbf{R}_{z_I} = \mathbf{R}_z + P_{\text{str}}\boldsymbol{\Upsilon}_I\boldsymbol{\Upsilon}_I^H + \underbrace{\sum\nolimits_{v_I=1}^{V_I} P_{v_I}\beta_{v_I}\mathbf{I}}_{\mathbf{I}_v}, \tag{15}$$

where $v_I, v_I = \{1,\dots,V_I\}$, refers to the interfering vehicle, P_{v_I} is the optical power transmitted by the interfering vehicle and β_{v_I} is the signal-to-interference ratio regarding the interfering vehicle. On the other hand, interference may appear in all the color/time slots if external interfering vehicles are not synchronized in time. In this case, the term $\mathbf{I}_v$ in the resulting noise plus interference covariance matrix is given by $\sum_{v_I=1}^{V_I}\beta_{v_I}P_{v_I}\mathbf{H}_{v_I}\mathbf{H}_{v_I}^H$, where $\mathbf{H}_{v_I}$ corresponds to the channel matrix associated to the interfering vehicle v_I.

V. Simulation results

We consider a V2V communication in which the two headlights of a vehicle transmits to another vehicle in the same lane equipped with 2 reconfigurable photodetectors. The total optical power of each front light is $P_{\text{opt}} = 28$ W distributed uniformly among the data streams. The distance between headlights/photodetectors is $W_l = W_k = 1.5$ m, the radiation semi-angle for the low-beam is $\phi_{1/2}$=10° and the lens diameter is equal to D_R = 5 cm for high-beam model [5], [7]. The reconfigurable photodetectors are located at the car rear and follow an angle diversity arrangement in which each tuple is oriented $\pm 10°$ parallel to the road and composed of photodiodes with an area of detection equal to $A = 1$ cm^2, a responsivity equal to $\delta = 0.53$ A/W and a FoV equal to $40°$. The concentrator gain is set to $T = 1$. The noise variance as in [12] and clear weather [9] are assumed. The following baseline transmission schemes are considered; ZF precoding with the aim of comparing with a closed-loop scheme and non-colored BIA to determine the impact of implementing a colored VLC system. Besides, orthogonal transmission of each symbol is also considered as the simplest open-loop scheme.

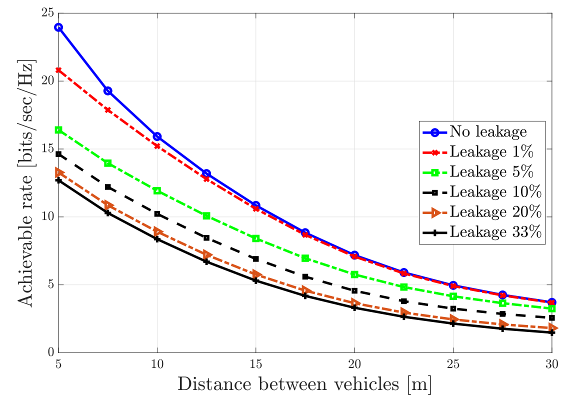

Fig. 4. Achievable rate of cBIA for different levels of color leakage. Low-beam model.

The impact of color leakage on the achievable rate of cBIA is analyzed in Fig. 4. As commented before, the color leakage depends very much on the LEDs and optical filters used. Designers must make sensible design-related decisions, such as the quality of the optical filters and multi-color LEDs. For this reason, we model the inter-color interference with different percentages. It can be seen that a rate above 7 bits/sec/Hz is achievable for distances up to 20 meters between vehicles. For a 1% color leakage the performance of cBIA is barely affected. However, the achievable rate is reduced about 15% and 25% for a leakage of 5% and 10%, respectively.

The achievable rates of cBIA are shown in Fig. 5 and Fig. 6 for low and high beam models, respectively, compared to the baseline schemes. It can be seen that cBIA outperforms all the considered schemes even assuming a color leakage of 10%. Interestingly, the rate of ZF suffers an abrupt degradation since it depends directly on the correlation among channel responses, which increases as the distance between vehicles becomes greater. The achievable rate for the low-beam model decreases abruptly for distances beyond 30 m while the high-beam lights are more suitable for large distances. However, the channel responses of the photodetector becomes more correlated since the high-beam model concentrates the light into a more narrow beam. As a consequence, orthogonal transmission outperforms ZF, non-colored and cBIA at some distance, which is equal to 40 m, 57 m and 80 m, respectively, for the considered simulation.

The latency of cBIA and other open-loop schemes is depicted in Fig. 7 as a function of the packet size. The modulation bandwidth is 10 MHz and a 2 bits per symbol modulation, e.g., a 4 pulse amplitude modulation, for each data

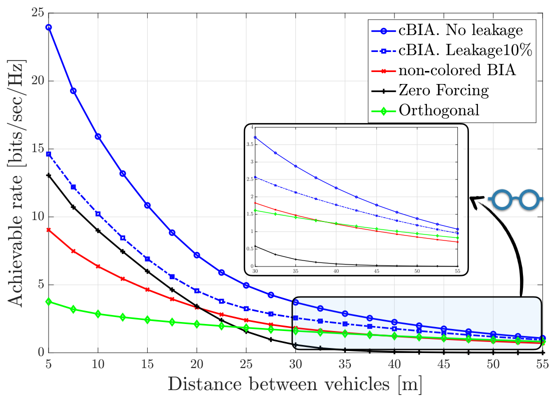

Fig. 5. Achievable rate of cBIA in comparison with non-colored BIA, ZF and orthogonal resource allocation. Low-beam model.

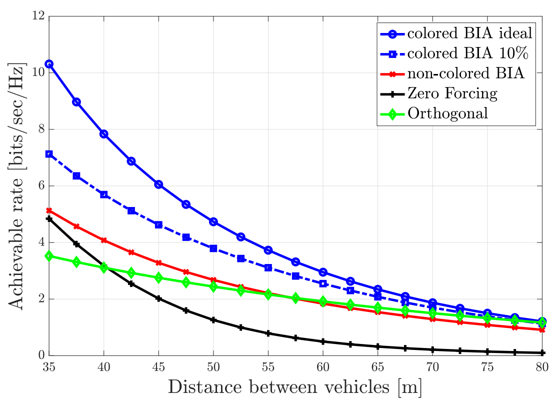

Fig. 6. Achievable rate of cBIA in comparison with non-colored BIA, ZF and orthogonal resource allocation. High-beam model.

stream is assumed. In other words, the data rate is exclusively given by the multiplexing gain. Note that the latency of ZF is not depicted since it corresponds to a closed-loop transmission scheme, and therefore, the latency is much greater than open-loop schemes due to the feedback stage. It can be seen that cBIA ensures a latency below 0.1 ms for data packets with a size lower than 8 Kbits, while non-colored BIA and orthogonal resource allocation are subject to a latency greater than 0.3 ms and 0.4 ms, respectively, for this packet size.

VI. Conclusions and future directions

In this work, the architecture of a colored reconfigurable photodetector is proposed to obtain linearly independent channel responses among multiple colored tuples. Based on this concept, an open-loop transmission scheme referred to as cBIA is derived, which exploits the colored transmission to achieve a multiplexing gain three times greater than non-colored BIA and reduces the length of the transmission pattern considerably. Simulation results show that the proposed cBIA allows us to satisfy the requirements of 6G vehicular communications such as high data rates or a extremely low-latency. As future directions, experimental work must be done to implement and verify the good performance of this proposal in comparison to the state of the art. Besides, multiple LED color combinations can be considered, while providing the white color imposed by road safety regulations. White target color

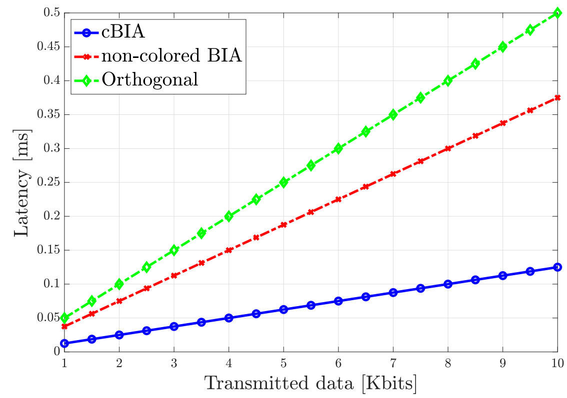

Fig. 7. Latency vs. packet size.

can be obtained by combining multiple color LEDs, and each LED has its own electrical and optical characteristics that may lead to different results in terms of power and communication efficiency. Finally, this work must be extended to scenarios where each vehicle may have more than two transmitters and two receivers as well as considering the communication links between vehicles and unmanned aerial vehicles.

References

[1] X. Cheng, C. Chen, W. Zhang, and Y. Yang, "5G-enabled cooperative intelligent vehicular (5GenCIV) framework: When Benz meets Marconi," *IEEE Intelligent Systems*, vol. 32, no. 3, pp. 53–59, 2017.

[2] A. Memedi and F. Dressler, "Vehicular visible light communications: A survey," *IEEE Communications Surveys & Tutorials*, vol. 23, no. 1, pp. 161–181, 2021.

[3] T. V. Pham and A. T. Pham, "Coordination/cooperation strategies and optimal zero-forcing precoding design for multi-user multi-cell VLC networks," *IEEE Transactions on Communications*, vol. 67, no. 6, pp. 4240–4251, 2019.

[4] M. Morales-Céspedes, M. C. Paredes-Paredes, A. Garcia Armada, and L. Vandendorpe, "Aligning the light without channel state information for visible light communications," *IEEE Journal on Selected Areas in Communications*, vol. 36, no. 1, pp. 91–105, 2018.

[5] M. M. Céspedes, B. G. Guzmán, V. P. Gil Jiménez, and A. G. Armada, "Aligning the light for vehicular visible light communications: High data rate and low-latency vehicular visible light communications implementing blind interference alignment," *IEEE Vehicular Technology Magazine*, vol. 18, no. 1, pp. 59–69, 2023.

[6] T. Z. Gutema, H. Haas, and W. O. Popoola, "WDM based 10.8 Gbps visible light communication with probabilistic shaping," *Journal of Lightwave Technology*, vol. 40, no. 15, pp. 5062–5069, 2022.

[7] B. Aly, M. Elamassie, and M. Uysal, "Vehicular visible light communication with low beam transmitters in the presence of vertical oscillation," *IEEE Transactions on Vehicular Technology*, vol. 72, no. 8, pp. 9692–9703, 2023.

[8] A. A. Dowhuszko and B. G. Guzmán, "Closed form approximation of the actual spectral power emission of commercial color LEDs for VLC," *Journal of Lightwave Technology*, vol. 40, no. 13, pp. 4311–4320, 2022.

[9] M. Karbalayghareh, F. Miramirkhani, H. B. Eldeeb, R. C. Kizilirmak, S. M. Sait, and M. Uysal, "Channel modelling and performance limits of vehicular visible light communication systems," *IEEE Transactions on Vehicular Technology*, vol. 69, no. 7, pp. 6891–6901, 2020.

[10] J.-B. Wang, Q.-S. Hu, J. Wang, M. Chen, and J.-Y. Wang, "Tight bounds on channel capacity for dimmable visible light communications," *Journal of Lightwave Technology*, vol. 31, no. 23, pp. 3771–3779, 2013.

[11] C. Wang, H. C. Papadopoulos, S. A. Ramprashad, and G. Caire, "Design and operation of blind interference alignment in cellular and cluster-based systems," in *2011 Information Theory and Applications Workshop*, 2011, pp. 1–10.

[12] P. Sharda, G. S. Reddy, M. R. Bhatnagar, and Z. Ghassemlooy, "A comprehensive modeling of vehicle-to-vehicle based VLC system under practical considerations, an investigation of performance, and diversity property," *IEEE Transactions on Communications*, vol. 70, no. 5, pp. 3320–3332, 2022.