Aligning the Light for Vehicular Visible Light Communications

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***Abstract*—Vehicle-to-vehicle (V2V) communications are one of the most promising 6G scenarios. However, it demands high data-rates and extremely low-latency requirements that are difficult to satisfy nowadays. Recently, vehicular visible light communications (V-VLC) have been proposed as a promising technology to guarantee such requirements. Multiple-input multiple-output (MIMO) techniques can potentially achieve high data-rates. However, applied to V-VLC, they confront challenges such as the latency because of the need for closed-loop transmission or the correlation among optical channel responses. This article explains the use of blind interference alignment (BIA) for V-VLC based on the concept of a reconfigurable photodetector to provide linearly independent channel responses. It is shown that BIA solves the issues of MIMO techniques and may comply with the 6G V-VLC requirements. Besides, the vehicles are a convenient platform for implementing a reconfigurable photodetector. Finally, the open issues for the BIA implementation in V-VLC are discussed to inspire future research.**

I. Introduction

Intelligent devices, autonomous cars or smart unmanned aerial vehicles (UAVs) are some of the active elements in the future vehicular communications, commonly known as Internet of vehicles (IoV). They demand ubiquitous mobile, ultra-high speed, and low-latency services, which are also considered critical challenges for future 6G wireless systems [1]. In this context, more efforts must be invested to lead a complete paradigm shift in the future vehicular communications [2].

The performance requirements of vehicular networks cannot be met by 5G long-range communication technologies. In this context, dedicated short-range communications (DSRC) and visible light communications (VLC) have been considered as proper technologies for enabling future vehicular communications. Besides, in intelligent transport systems (ITS), platooning applications with autonomous vehicles are expected to be a key 6G use case, where communication links are performed with vehicles located in the front and rear parts. In this way, line of sight (LoS) between transmitter and receiver is highly probable, and DSRC and VLC perform well.

Since light-emitting diodes (LEDs) have been commonly adopted in vehicular systems, they can be used for converting them into a cost-effective technology to implement vehicular VLC (V-VLC). Wide and unlicensed bandwidths, controllable emission patterns and affordable components are some of the advantages that make VLC a suitable technology for vehicular communications. For indoor applications, the coherence time of VLC is one order of magnitude larger than that for radiofrequency (RF) systems [3], which reduces the overhead processing when updating the channel state information (CSI). However, the optical channel for vehicular communications is subject not only to transmitters and receiver's movement but also to other parameters such as atmospheric turbulence and weather conditions, which hamper the use of a channel estimation within a large time period [4].

The biggest challenges for V-VLC are the interference management and the achievement of extreme low-latency (below 0.1 ms for 6G systems). Thus, achieving high-capacity and reliable long-range communication links may be hampered by these unresolved issues. To solve the first one, multiple-input multiple-output (MIMO) VLC is proposed so that multiple optical sources are treated as different transmitters generating multiple parallel data streams and maintaining the same total power budget [5]. The second issue may be solved by novel cooperative schemes requiring more simple decoding techniques. Although MIMO techniques have been developed for RF communications during the last decade for achieving both spatial diversity and multiplexing gain, their application to V-VLC is not straightforward and several issues must be faced as described below.

A. Issues for the use of MIMO techniques in V-VLC

1) MIMO precoding techniques typically require accurate CSI at the transmitters (CSIT). This requires to feed the estimated channel back to the transmitters, which generates a feedback delay as it is shown in Fig. 1(a). For VLC, the feedback channel is typically carried out through RF or infrared links, which increases the complexity and cost of the devices. Moreover, the mobility between vehicles, i.e., the longitudinal and lateral shift, generates channel variations more frequently than in indoor scenarios [6]. Therefore, the feedback delay in closed-loop transmission may lead to outdated or stale CSI, which causes a poor performance of MIMO precoding techniques. Open-loop transmission and short block-length theory have been proposed for achieving low-latency in vehicular RF systems in [7] and [8], respectively. To the best of our knowledge, these approaches have not been considered for V-VLC yet. In this sense, a latency of around 1 ms is shown to be

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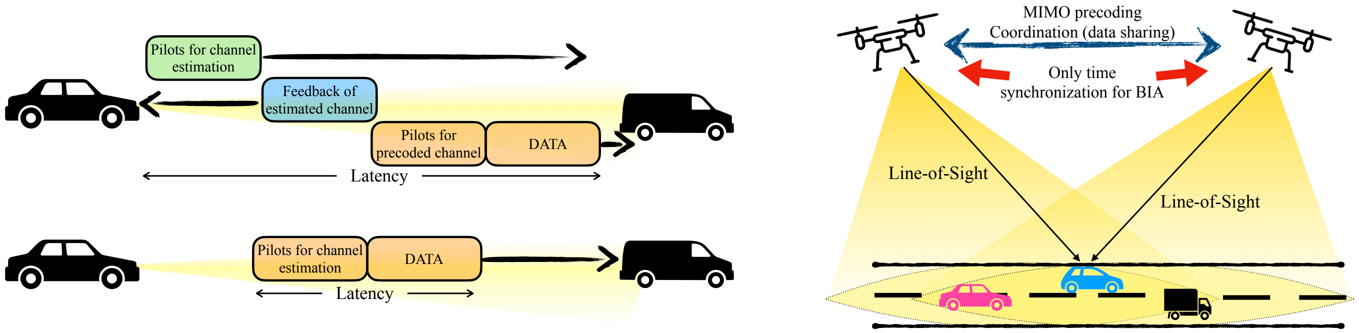

(a) Closed-loop for obtaining CSIT in MIMO precoding techniques (top) vs. open-loop transmission for BIA (bottom).

(b) Need for coordination among transmitters, e.g., UAVs providing connectivity to vehicles.

Fig. 1. Issues for implementing transmit precoding schemes that can be potentially solved by BIA in vehicular environments.

achieved for V-VLC in [9], which is above the 0.1 ms proposed for 6G.

2) The number of uncorrelated paths in VLC is not as high as in RF because of its real nature and the lack of small scale effects (the photodiode size is much larger than the optical wavelength). As a consequence, MIMO techniques are penalized because of the high correlation among channel responses. This issue is even more challenging in vehicle-to-vehicle (V2V) communications based on VLC. Considering the front lights of a vehicle, the optical channel is more correlated as the distance between vehicles increases, i.e., both lights can be considered to come from the same transmitter.
3) Differently from RF, VLC depends on the availability of a LoS link as light does not go through opaque objects. However, V-VLC scenarios have moving elements, they include narrow and directional light beams and the field-of-view of the PDs is commonly narrow to minimize interference. These V-VLC features may jeopardize the LoS transmitter-receiver link, and V-VLC designs must consider these issues to make the communication reliable.

B. Blind Interference Alignment for 6G V-VLC

In this article, the use of blind interference alignment (BIA) techniques for enabling 6G V-VLC is proposed based on the concept of a reconfigurable photodetector, which is discussed below. BIA techniques do not require CSI knowledge at the transmitter side for achieving multiplexing gain while using a very simple decoding technique. Then, they fulfill the requirements of road safety applications, demanding low-latency and reliable communication links. At the same time, BIA exploits the use of multiple transmitters and receivers, which is in accordance with the ISO 26262 'Road vehicles - Functional safety' standard establishing that every vehicle safety system cannot rely only on a single sensor.

C. V-VLC standardization efforts

V-VLC have always been considered as a fundamental use case in multiple VLC-related standards; IEEE 802.15.7, IEEE 802.15.13 and IEEE 802.11bb. However, most of the current standardization efforts have been focused on the exploitation of well-known RF chipsets to be adapted to Light-Fidelity (LiFi) systems. Besides, a LiFi ecosystem called Light Communication Alliance has been recently created involving agents in the full chain to guarantee a widespread deployment of LiFi solutions. However, a dedicated study of V-VLC to address the issue of that particular scenario is required, and it would fill the gap between academic research and industry. The light communication IEEE 802.11bb standard is expected to be concluded in 2022. Considering that a new mobile communication standard is conceived every decade, we foresee that the first group activities on 6G standardization will start in around 2026. By that time, deployments and use cases based on the IEEE 802.11bb standard will have matured and a new light communication group can harmonize new LiFi-based 6G scenarios such as V-VLC.

II. Blind Interference Alignment: An overview.

BIA was initially proposed as a signal processing technique for achieving a growth in degrees of freedom (DoF), which can be interpreted as the multiplexing gain or simply the number of parallel channels transmitted free of interference, as the number of users increases without the need for CSIT [10]. The implementation of BIA requires receivers able to switch among a set of linearly independent channel responses, denoted by preset modes. Then, a data frame following a specific switching pattern is generated to allow the interference subtraction as shown in Fig. 2.

A. Two transmitters - two receivers example

For illustrative purposes, let us consider a scenario comprising two transmitters, e.g., the two front lights of a vehicle that send a data stream each to another vehicle equipped with two reconfigurable receivers, i.e., a reconfigurable photodetector for VLC. The period for data transmission comprises three symbol extensions, which correspond to three time slots in the time domain. Thus, the reconfigurable receiver of each user follows a pattern as shown in Fig. 2.

Focusing on reconfigurable photodetector #1 in Fig. 2, to which the symbols $u_1^{[1]}$ and $u_2^{[1]}$ are addressed, the interference

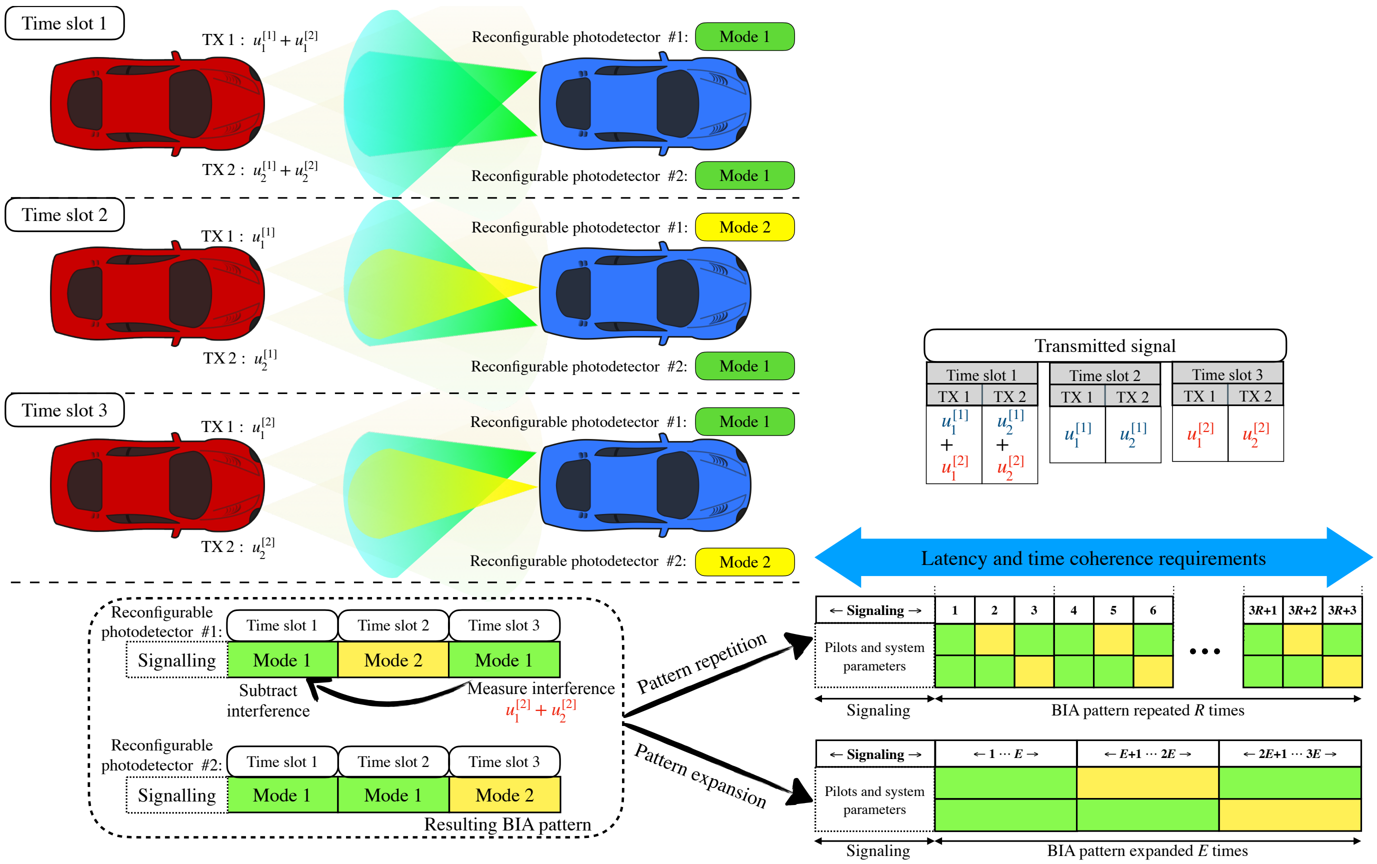

Fig. 2. BIA example. The two front lights transmit data to a vehicle equipped with two reconfigurable photodetectors. The symbol transmitted by LED m to user k is denoted by $u_m^{[k]}$. Symbols $u_1^{[1]}$, $u_2^{[1]}$ and $u_1^{[2]}$, $u_2^{[2]}$ are intended to reconfigurable photodetectors #1 and #2, respectively, which are allocated in the same car. The mode selected by each reconfigurable photodetector corresponds to a color, either green or yellow. Mode switching during 3 time slots generates the resulting BIA pattern. This pattern can be repeated or expanded to adapt the frame transmission to the latency or coherence time requirements.

because of transmission to reconfigurable photodetector #2, i.e., $u_1^{[2]} + u_2^{[2]}$, can be measured in time slot 3. Since this interference is received by reconfigurable photodetector #1 in the same mode as in time slot 1 (mode 1, associated to green color in Fig. 2), in which simultaneous transmission occurs, the interference can be subtracted from the signal received in time slot 1. Thus, transmission of $u_1^{[1]} + u_2^{[1]}$ is contained in two modes of reconfigurable photodetector #1, which correspond to linearly independent responses. Therefore, the two symbols, $u_1^{[1]}$ and $u_2^{[1]}$ are decodable by solving the corresponding equation system. Similarly, the symbols $u_1^{[2]}$ and $u_2^{[2]}$ can be decoded by reconfigurable photodetector #2 following the same procedure. Therefore, 4 symbols are decodable during 3 time slots, i.e., $\frac{4}{3}$ DoF are achievable using BIA for the considered scenario. At this point, notice that other transmission schemes without CSIT, e.g., orthogonal resource allocation, are constrained to achieve 1 DoF.

B. General case: M transmitters - K receivers

For a broadcast channel (BC) composed of M transmitters and K users, BIA achieves $\frac{MK}{M+K-1}$ DoF comprising a specific switching pattern of preset modes, i.e., time slots in the time domain [10]. Note that achieving this performance requires a reconfigurable receiver providing at least M linearly independent channel responses. It is demonstrated that BIA obtains the maximum achievable DoF without CSIT. Furthermore, other alternative BIA schemes are also optimal for partially connected or cognitive networks.

C. Benefits of BIA for vehicular communications

1) Channel state information at the transmitter: Since VLC are inherently frequency division duplex (FDD) with uplink and downlink operating at different wavelengths, obtaining CSIT requires a closed-loop procedure as described in Fig. 1(a), which penalizes the latency of the system because of feedback delay. Moreover, the lack of quality in the obtained CSI may lead to a poor performance of the MIMO precoding techniques. BIA allows us to get rid of this closed-loop.

2) Managing the latency and coherence time requirements: Getting rid of the closed-loop allows us to transmit the signaling and data within the same frame as is shown in Fig. 2. That is, the intended data in each frame can be decoded without the need for previous or following frames, avoiding the feedback delay. Therefore, coherence time and latency requirements mainly depend on the frame length. In this sense, the resulting BIA pattern can be repeated or expanded in order to adapt the frame to these requirements. For instance, assuming a sampling rate equal to 10 Msamples/sec and 8

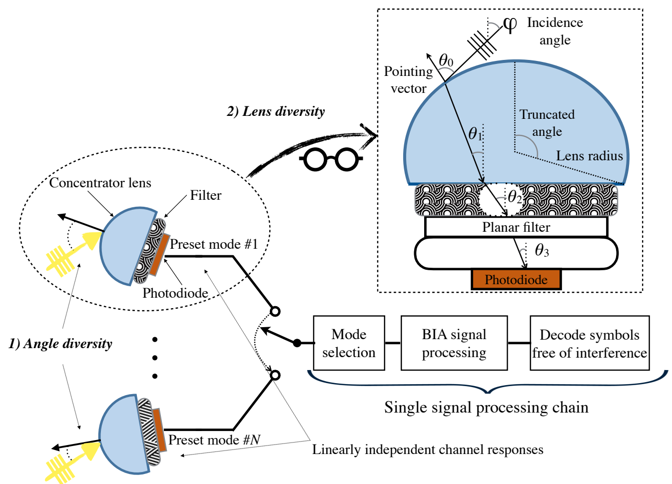

Fig. 3. Architecture of the reconfigurable photodetector. It is composed of multiple photodiodes oriented in such a way that guarantees distinct incidence angle for each photodiode, connected to a single signal processing chain through a selector. Each photodiode can be also equipped with a filter plus a concentrator lens.

samples per symbol, the BIA pattern described in Fig. 2, which comprises 2 symbols for estimating the CSI at the receiver (recall that it is not fed back) and 3 for data, is transmitted in 4 μs. Moving to a more realistic application, expanding or repeating the pattern 30 times (see Fig. 2) and considering that 10% of the frame is assigned to signaling, i.e., 9 time slots for signaling and 90 for data, transmission of the frame comprises 79.2 μs. On the other hand, latency for closed-loop schemes also depends on the feedback delay, which hampers to achieve low-latency below 0.1 msec.

3) Coordination among transmitters: Achieving high data rates requires not only to exploit the benefits of MIMO assuming a single access point made of multiple transmitters, but also spatial MIMO based on coordination among transmitters as shown in Fig. 1(b). BIA does not require data sharing among transmitters and the cooperation is limited to synchronizing the vehicles in time, i.e., pairing two or more vehicles in order to create a bigger access point covering a wider area of the road.

4) Correlation among channel responses: Vehicular communications are typically LoS. As a consequence, the channel response corresponds to a frequency-flat fading channel. However, the rate achieved by MIMO precoding techniques is very sensitive to correlated channel responses and then, the predominant LoS channel may handicap the implementation of precoding techniques in vehicular communications. On the other hand, the performance of BIA does not depend on the correlation among the channel responses of the users but on the correlation among the preset modes of the reconfigurable receiver of each user, which is in fact a design parameter that can be easily handled.

III. Blind Interference Alignment for V-VLC

A. Channel models for V-VLC

Motivated by the benefits of BIA, its implementation for VLC is firstly proposed in [11]. Interestingly, it is shown that BIA inherently satisfies the transmitted signal constraints for VLC and, in contrast to closed-loop precoding schemes, a DC bias depending on the transmitted signal is not required. Thus, the entire optical power range of the emitters can be exploited while maintaining their initial illumination function. Furthermore, it is demonstrated that by deploying photodiodes in angle and lens diversity, connected to a single signal processing chain through a selector, the receiver can modify the optical channel among a set of linearly independent responses. This receiver structure, referred to as reconfigurable photodetector from now on, is described in Fig. 3. Notice that, the orientation angle has a direct impact on the incidence angle of each photodiode, which contributes non-linearly to the resulting channel as a cosine function. The lens diversity also generates non-linear responses as distinct geometries, e.g., hemispherical, coated or truncated at different angles, are considered.

However, the Lambertian channel model for indoor scenarios is not valid for dynamic outdoor V-VLC, since it does not consider crucial effects such as the weather conditions, reflections on the road or the lateral shift between vehicles. In [12], a channel model for V-VLC is provided combining the attenuation and geometrical losses, which result from the scattering/absorption and the transmitter beam spread, respectively. The different weather conditions, such as clear weather, rain or fog, are modeled by applying correlation factors in the closed-form expression of the resulting path loss. Based on this model, a more practical channel is derived in [6] considering specific parameters of vehicular scenarios such as the width of the road and each lane, the probability of blocking or the random lateral shift between vehicles.

B. Reconfigurable photodetectors in vehicles

It is worth noticing that those models for V-VLC still depend non-linearly on the incidence angle and the lens response. Therefore, the reconfigurable photodetector based on angle and lens diversity can be applied to V-VLC. Furthermore, beyond the need for reconfigurable photodetector for implementing BIA, they are also useful to uncorrelate the channel responses among users for precoding techniques as proposed in [13].

1) Lens diversity: Deploying multiple photodiodes pointing to distinct orientations in an angle diversity arrangement generates different incidence angles, which contributes to the optical channel in a non-linear manner. In contrast to the angle diversity receiver (ADR) concept proposed in [14], the reconfigurable photodetector exploits the angle diversity of multiple photodiodes deployed around the vehicle structure without the need for deploying them adjacent to each other. Moreover, the use of a selector to switch among the photodiodes instead of considering a signal processing chain per photodiode leads to reducing the receiver complexity.

2) Filter and concentrators diversity: Another way of obtaining linearly independent channel responses is exploiting the diversity between filters and concentrators, whose gain depends on the incidence angle in a non-linear manner. For

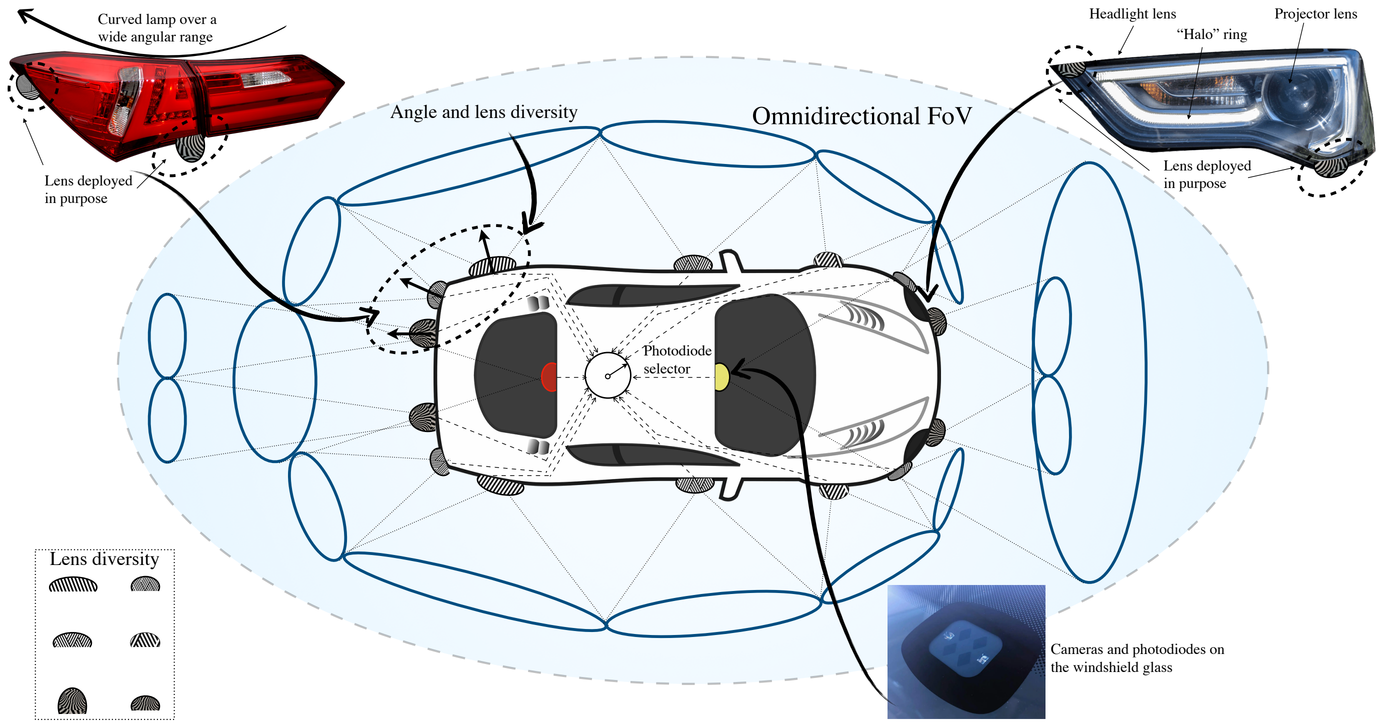

Fig. 4. Arrangement of photodiodes in angle and lens diversity exploiting the vehicles structure.

instance, using coated and spherical lenses as shown in Fig. 3. In this sense, the gain of the optical filter plus concentrator is

$$g(\varphi) = \frac{\int_{S_0} T(\theta_0)T(\theta_1)T(\theta_2)T(\theta_3)dS}{\int_{S_0} \cos(\theta_0)dS}, \tag{1}$$

where S_0 is the integration area over the surface for which light passing through eventually hits the photodiode and $T(\theta)$ is the gain function of each step inside the lens described in Fig. 3. It can be seen that lens design provides multiple possibilities for obtaining linearly independent channel responses.

C. Exploiting the vehicles structure

Nowadays vehicles contain LED lamps and photodiodes that can be used for communications too. We do not need to redesign our cars, motorbikes, trunks or any other vehicle. The structure of the lamps in vehicles typically covers a wide angular range, e.g., headlamps usually cover not only front but they are curved to the lateral sides, and inherently provide a set of filters and lens as is shown in Fig. 4. Enough angle and lens diversity can be achieved exploiting this structure, guaranteeing linearly independent channel responses. It is worth noticing that the integration of photodiodes close to the lights must include a barrier structure to avoid the self-interference. Besides, additional photodiodes can be deployed with a minimum impact on the electrical, electronic, aerodynamic and aesthetic aspects.

Vehicles front

When a communication link is established with the front part of the vehicle, linearly independent channel responses can be guaranteed taking into account the different elements. Allocating multiple photodiodes inside the headlamps can be distributed within a wide range of angles in both horizontal and vertical planes, which likely guarantees the linear independence among the channel responses [15]. Moreover, there are two blocks of lamps separated more than 1 m, which add more diversity to the communication channel. We also have the possibility of exploiting other structures such as the fog lamps, the side mirror structures or the car brand symbol for allocating additional photodiodes. On top of that, most of the medium-high range vehicles allocate photodiodes and cameras on the surface of the windshield glass for security reasons. Although these photodiodes typically provide a low bandwidth, specific photodiodes for VLC can be integrated in this structure.

Vehicles rear

There is also enough diversity in the rear part of the vehicle thanks to its architecture and number of elements. There are tail lamps that, as in the case of headlamps, are curved and cover both sides of the vehicle partially. We also find the back license structures, a separate brake lamp on top of the back window and turn signals.

Trucks, motorbikes and other vehicles

Everything mentioned above is even more valid for the case of trucks, because the number of lamps, i.e., the structures in

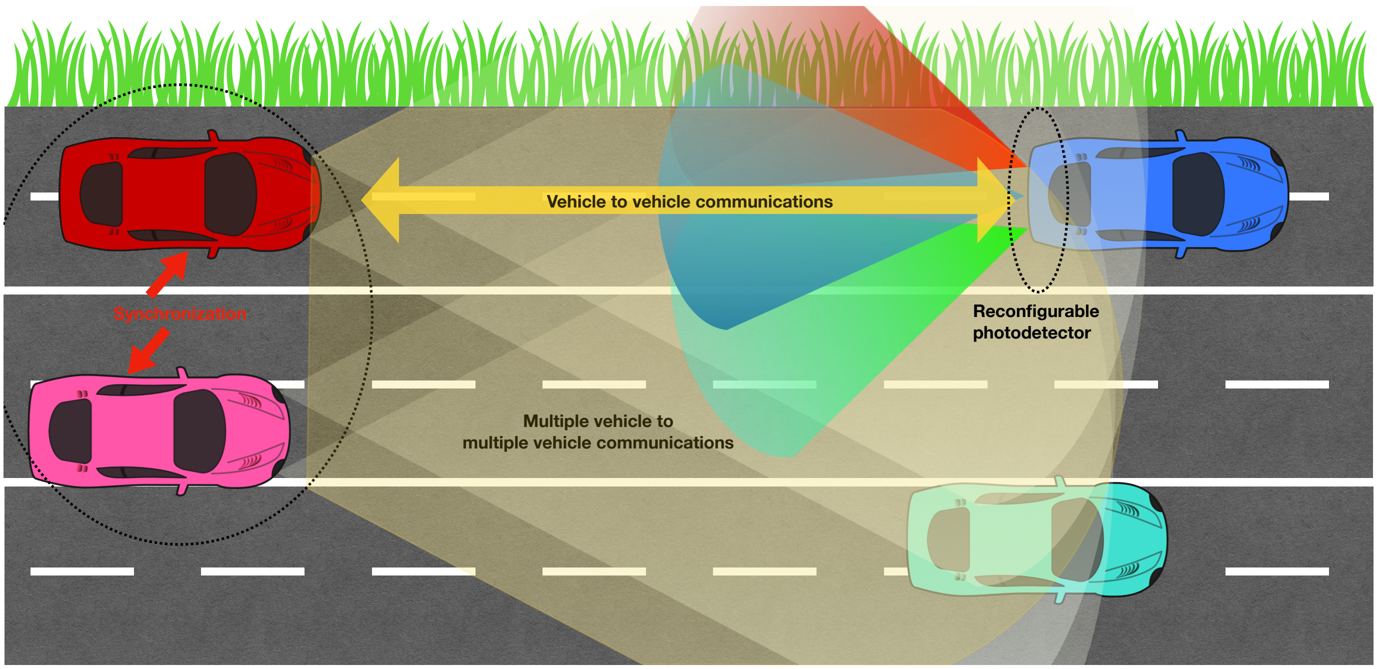

Fig. 5. V2V communications scenario. BIA allows the transmission of multiple streams to the same vehicle or multiple vehicles. Moreover, assuming that cooperation is limited to time synchronization, i.e., no data sharing, BIA can be exploited to generate a multiple V2V system.

which to deploy photodiodes in angle and lens diversity, the size and the positions are wider than in usual cars. In the case of motorbikes, the location is a bit more complex due to size constraints. They could be replaced by a set of photodiodes placed on the helmet in order to exploit angle diversity. Notice that current helmets get communication systems for comfort such as music or hands-free. However we foresee that, in the near future, novel augmented reality such as virtual reality (VR) scout or driver-assistance systems will be incorporated for safety reasons, which may require V-VLC.

UAVs

Once the angle diversity has been shown valid in the communication between vehicles, we can also think on communications between vehicles and UAVs. This scenario is specially useful in cities and large roads. As it can be seen in Figures 1(b) and 4, the link between the UAVs and the vehicles with diversity angle receivers can be easily established using the extra brake lights, the place of the front camera, the upper part of headlamps and tail lights. On the UAV side, the normal structure of UAVs (plane-shape or spider-shape) offers a perfect location for allocating photodiodes with enough angle and lens diversity to implement the concept of reconfigurable photodetector.

IV. Performance of BIA in V-VLC

The proposed vehicular scenario is depicted in Fig. 5. We consider V2V communications so that the two front LED lights of the vehicle transmit two data streams to a vehicle equipped with reconfigurable photodetectors similarly as it is described in Fig. 2. A simple photodetector configuration is considered in which 9 photodiodes following a geometrical arrangement, comprising an azimuthal angle equal to $[\pm 40, \pm 30, \pm 20, \pm 10, 0]$ degrees pointing parallel to the road, are deployed around the car. For the sake of simplicity, the use of lenses is not considered.

The considered vehicle LEDs satisfy the regulation No. 48 of the Economic Commission for Europe of the United Nations and the United States National Highway Traffic Safety Administration with a luminous flux equal to 6000 lm, which corresponds to an optical power about 24 W assuming a typical luminous efficiency of radiation. All other parameters used for our simulations are:

- Beam width: 20 degrees.
- Receiver aperture diameter: 5 cm.
- Width of single lane: 3.6 m.
- Width of vehicle 1.8 m.
- Channel parameters: clear weather [12].

Note that clear weather is considered for the sake of simplicity. Adverse weather effects such as rain or fog would penalize the sum-rate of all the transmission schemes similarly.

Achievable sum-rate

The achievable sum-rate obtained by BIA, ZF, maximum ratio combining (MRC) and orthogonal resource allocation in a V2V communication is evaluated in Fig. 6 as a function of the distance between vehicles. First, assuming perfect CSI at the transmitter and that both vehicles are in the same lane, it is worth noticing that the performance of ZF decreases abruptly as the vehicle moves away. This effect is given by the high correlation between the channel response of the photodiodes located in the receiving vehicle. Indeed, this correlation is more noticeable with the distance between vehicles, since the

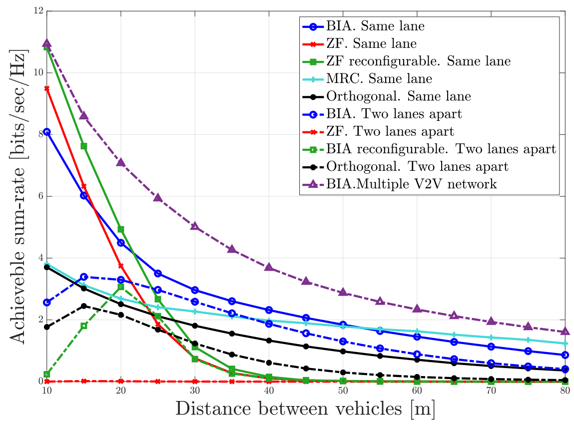

Fig. 6. Achievable sum-rate for ZF precoding, BIA and orthogonal resource allocation as a function of the distance between vehicles.

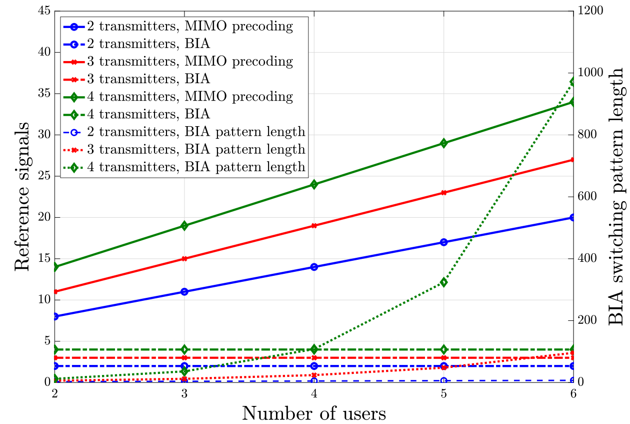

Fig. 7. Number of reference signals for MIMO precoding and BIA and length of the BIA switching pattern as a function of the number of users.

two front LED lights of the vehicle can be considered as a single optical channel when the distance increases. On the other hand, the implementation of a reconfigurable photodetector in vehicles allows us to improve the achievable rate of ZF by selecting the photodiode that maximizes the performance of ZF (ZF reconfigurable) as proposed in [13]. Moreover, orthogonal resource allocation achieves lower sum-rate in the whole distance range. MRC only outperforms BIA for long distances, i.e., at low sum-rate values since it exploits the channel diversity provided by the reconfigurable photodetector for maximizing the signal-to-interference-plus-noise ratio of the link instead of achieving multiplexing gain.

DoF vs. sum-rate

Maximizing the DoF requires closed-loop transmission, e.g., in this case ZF precoding achieves $\min(M, K) = 2$ DoF. On the other hand, BIA achieves the optimal DoF without CSIT, $\frac{MK}{M+K-1} = \frac{4}{3}$, although still below the DoF achievable by closed-loop schemes. Since the DoF metric is primarily concerned with the limit when the total transmission power goes to infinity, i.e., as the distance between vehicles becomes shorter, it can be seen that ZF outperforms BIA at very short distances with greater sum-rate slope, which is given by the influence of the DoF. However, the optical channel is more correlated as the distance between vehicles becomes larger. This correlation makes sum-rate decrease abruptly for ZF. On the other hand, since BIA does not depend on the correlation among the channel responses of the users, it obtains greater sum-rate in a wide range beyond short distances between vehicles.

Different lanes

If the V2V communication occurs between vehicles that are located in different lanes, it can be seen that ZF is considerably penalized, and indeed, the use of photodiode selection [13] is mandatory to achieve useful sum-rates. On the other hand, BIA achieves an acceptable sum-rate in a wide range of distances between vehicles. It is worth noticing that the performance of both ZF and BIA can be potentially improved considering more preset modes to the reconfigurable photodetector of the vehicles, i.e., adding more photodiodes pointing to other directions or using lens diversity. Furthermore, assuming synchronization based on pairing two vehicles, the performance of the multiple V2V system outperforms the sum-rate achieved by V2V BIA transmission.

Latency. Closed-loop vs. open-loop

The latency depends directly on; 1) the reference signals required for achieving CSI at both transmitter and receiver sides (i.e., the larger the number of reference signals, the larger the frame and, as a consequence, the latency increases), and 2) the size of the data packet. As represented in Fig. 7, the number of reference signals in MIMO precoding increases with the number of users since each user must feed the estimated channel back to the transmitter and, afterwards, the specific precoded pilots are transmitted for each data stream. On the other hand, open-loop transmission based on BIA requires only a single reference signal per transmitter for achieving CSI at the receivers. However, as represented in the right-hand y-axis of Fig. 7, the length of the switching pattern grows exponentially with the number of users and transmitters. As a consequence, current BIA schemes achieve extremely low latency for configurations with a reduced number of transmitters and receivers, which might satisfy the challenge pointed out for 6G wireless systems.

V. Open Research Challenges

A. Wavelength BIA (WBIA)

As introduced in Section II, BIA does not require CSIT at the expense of using more time slots to cancel the interference. The number of time slots needed depends on the number of different transmitters. Besides, these slots must be within the coherence time to guarantee that the interference is aligned and can be cancelled. In scenarios where there is a high mobility, i.e., the coherence time is short, BIA schemes cannot be that promising because the channel changes too fast so that the light cannot be aligned on time. In these scenarios, it would be interesting to explore what we call here wavelength BIA. By using the same example of Section II with two users and two transmitters, in which three time slots are required, we can substitute the three slots by three different colors in red-green-blue (RGB) LEDs so that transmission is sent at the three different wavelengths. In this way, only one time slot is needed. In this sense, alternative reconfigurable photodetector architectures considering color filtering must be designed.

For a more complicated scenario with more users and/or transmitters, a combination between time slots and colors may be needed, but there will still be a reduction on the coherence time constrains. We could leverage commercial tri-color (RGB) or quadri-color (red-green-blue-yellow (RGBY)) LEDs and the target colour can be obtained by the corresponding weighted combination of those colours.

B. *Reconfigurable photodetector for vehicles*

The fundamentals of BIA are based on a reconfigurable photodetector that can align the interference without the need of CSI knowledge. Photo-sensitive devices, already installed in vehicles such as LEDs could be exploited as photodetectors, i.e., employing LEDs as both transmitters and receivers would create a full-duplex bi-directional channel and its wavelength selectivity would get rid of extra optical filter or barrier structures. Specific photodiodes for VLC are not typically installed in vehicles, but their low-cost, small form factor and affordability make their installation viable, without meaning an extra effort for the automotive industry. To enable BIA in V-VLC, some photodiodes must be installed in vehicles, and their arrangement must be done considering the characteristics of the vehicular environments.

C. *Specific BIA schemes for V-VLC*

Several BIA schemes have been developed for cellular or cognitive scenarios. Thus, motivated by the benefits of BIA applied to V-VLC, specific BIA schemes must be developed in order to optimize the achievable rate and latency subject to reliability conditions such as low probability of error considering specific modulation/coding designs and management of the frame structure. Moreover, the introduction of machine learning techniques in V-VLC [4] opens the door to dynamically adapting the BIA scheme as the conditions of the vehicular environment change.

VI. Conclusions

The challenges of 6G wireless systems are even more difficult to address for vehicular communications, in which VLC are proposed as a promising technology. This article has discussed the implementation of BIA in vehicular communications based on the concept of reconfigurable photodetector. In this sense, BIA allows us to get rid of the closed-loop and to remove the negative effects of channel correlation of MIMO precoding techniques, while providing multiplexing gain. This leads to ensuring high data rate and a extremely low latency required by 6G. We have also discussed the availability of light diversity in current vehicles and its benefit for BIA in VLC. Finally, we have introduced the open research challenges on the implementation of BIA in V-VLC, which must be solved for developing these novel transmission schemes oriented to vehicular environments.

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