

Towards 6G-V2X: Aggregated RF-VLC for Ultra-Reliable and Low-Latency Autonomous Driving Under Meteorological Impact

Gurinder Singh, Anand Srivastava, Vivek Ashok Bohara, Md Noor-A-Rahim, Zilong Liu, and Dirk Pesch

Abstract—We are witnessing a transition to a new era where driverless cars are pervasively connected to deliver significantly improved safety, traffic efficiency, and travel experiences. A diverse range of advanced vehicular use cases including connected autonomous vehicles will be made possible with the emerging sixth generation (6G) wireless networks. Among many 6G wireless technologies, the mission of this paper is to introduce the potential benefits of the hybrid integration of Vehicular Visible Light Communication (V-VLC) and Vehicular Radio Frequency (V-RF) communication systems by studying the impact of interference as well as various meteorological phenomenon viz. rain, fog and dry snow. In particular, we show that regardless of any meteorological impact, a properly configured link-aggregated hybrid V-VLC/V-RF system is capable of meeting stringent ultra high reliability (>99.999%) and ultra-low latency (<3 ms) specifications, making it a promising candidate for 6G Vehicle-to-Everything (V2X) Communications. To stimulate future research in the hybrid RF-VLC V2X space, we also highlight the potential challenges and research directions.

I. INTRODUCTION

CONNECTED and automated vehicular (CAV) technologies are expected to support improved road safety and driving comfort in future intelligent transportation systems (ITS). To fully support CAV, next generation vehicles will be equipped with a wide range of sensors and thus there is a strong demand for reliable near-real-time exchange of sensing and control data. Such a demand will be filled by vehicle-to-everything (V2X) communication which comprises a wide range of communication technologies such as vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications [1]. The most salient V2X communication technologies are dedicated short-range communication (DSRC)-aided V2X and cellular-V2X (C-V2X). While DSRC-V2X represents a mature cost-efficient V2X technology, C-V2X has attracted much attention in recent years due to its significantly improved coverage, throughput, and latency. Thanks to sophisticated cellular infrastructure, C-V2X outperforms due to centralized resource allocation as well as enhanced communication/sensing

Gurinder Singh, Anand Srivastava, and Vivek Ashok Bohara are with Centre of Excellence on LiFi, IIIT-Delhi, New Delhi 110020, India (e-mail: gurinders@iiitd.ac.in; anand@iiitd.ac.in, and vivek.b@iiitd.ac.in). This work was supported by Ministry of Electronics and Information Technology (MeitY), Government of India, implemented by Digital India Corporation.

Md Noor-A-Rahim and Dirk Pesch are with the School of Computer Science & IT, University College Cork, Cork, T12 K8AF Ireland (e-mail: m.rahim@cs.ucc.ie, d.pesch@cs.ucc.ie).

Zilong Liu is with the School of Computer Science and Electronic Engineering, University of Essex, Colchester CO4 3SQ, U.K. (e-mail: zilong.liu@essex.ac.uk).

capabilities. Several 3GPP V2X initiatives (such as LTE-V2X and 5G New Radio (NR)-V2X) have contributed to the prominence of C-V2X. With an abundance of both advanced sensors and communication devices, however, new challenges arise for the emerging next generation V2X networks [2]. More explicitly, stringent system reliability (>99.999%), end-to-end latency (<5 ms), coverage-quality, spectral efficiency, energy rating, networking, and privacy/security specifications should be met to support various C-V2X use case requirements [3]. Although the current C-V2X technology (such as 5G-NR-V2X) offers substantial performance gains over its predecessor, the improved performance is achieved at the cost of requiring additional spectral/hardware resources, while utilizing LTE-based system architectures and mechanisms. Thus, V2X networks based on 5G NR may not be able to meet the above-mentioned rigorous requirements and use cases of the emerging intelligent autonomous vehicles. A paradigm shift from conventional communication networks in favor of more flexible and diversified approaches is necessary. In fact, this transformation is beginning to take shape with the intensifying research into 6G wireless communication networks aiming for incorporating disruptive concepts [4]. In addition to intelligent and ubiquitous V2X systems, 6G is expected to provide significant data rate increases (e.g., up to Tbps), extremely fast wireless access (e.g., in the range of sub-milliseconds) and massive increase in wireless connections (e.g., billions of connected devices) as well as more extensive, more energy-efficient, and more environmentally friendly three-dimensional (3D) communications.

To realize the above vision of 6G-V2X, this paper advocates the intrinsic amalgamation of Radio frequency (RF) and Visible Light Communication (VLC) solutions, which are complementary to each other due to their respective benefits and trade-offs. Autonomous driving requires close monitoring of the surrounding area around the vehicle by deploying various sensors such as LIDAR, RADAR, camera, ultrasonic sensor, etc. In particular, a camera can not only allow the vehicle to recognize its surrounding objects, it can also be used as a receiver for VLC. Such a camera can then communicate via VLC with a large number of devices because of its spatial separation feature, thereby facilitating object recognition around the vehicle, obstacle location estimation, and even communication. By intelligently combining VLC-aided V2X communications with classic RF-based communications, our objective is to increase the data rates, reduce the transmission latency, improve reliability, reduce power

	Our Paper	[5]	[6]	[7]	[8]	[9]
Hybrid RF-VLC based V2X	✓	✓				
Link Aggregation	✓		✓			
Meteorological Impact	✓			✓		
Optical RIS Technology	✓				✓	
UAV-to-Vehicle (U2V) systems	✓					✓
System Reliability and Latency concerns	✓	✓				
Trends, Opportunities and Research challenges	✓					

TABLE I: Our novel contributions compared to state-of-the-art.

consumption, and enhance safety. However, one of major challenges for vehicular-VLC (V-VLC) arises from its outdoor operation. Meteorological phenomenon such as fog, rain, snow etc influences the reliability as well as range of V-VLC [7]. In terms of commercialization progress, there has been renewed industry interest in implementing and commercializing VLC technology to create new value chains, and in the meantime several pilot projects have been launched to promote research in this new field. For instance, pureLiFi is the global leader in bringing to market the world's first commercial light antennas making LiFi possible—for all kinds of applications, from industrial to consumer, and from smart cars to smartphones. Oledcomm is a French telecommunications company that began its research into LiFi systems that can be used extensively in the automotive sector.

Table I compares our novel contributions to previously published works. More specifically, we show how the judicious link aggregation of V-VLC and V-RF improves the network performance as compared to standalone RF or VLC based V2X communication systems under different meteorological factors. Briefly, link aggregation results in more efficient use of physical resources as well as improves reliability and availability. The paper has been organized as follows: In Section II, the RF-VLC communication system model is introduced. Several case studies specifically relevant to link aggregated hybrid RF-VLC V2X applications under various meteorological conditions are presented in Section III. In Section IV, we outline a range of promising research directions, challenges and opportunities associated with RF-VLC in vehicular environments and conclude in Section V.

II. HYBRID RF-VLC V2X SYSTEMS

Pure RF links may suffer from excessive RF interference in scenarios of high road-traffic density, which increases the communication latency owing to packet delivery failures and aggressive ARQ retransmission attempts. This in turn increases the spectrum congestion in dynamic vehicular environments. As a possible solution, the non-interfering unlicensed VLC band may be harnessed in unison with the RF

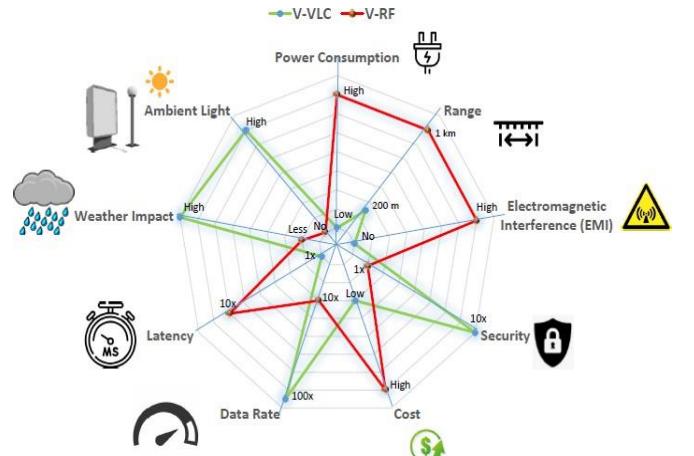


Fig. 1: Performance trade-offs of conventional VLC and RF based V2X communication systems.

band for improved V2X communications, while supporting enhanced security [10]. Furthermore, a VLC-enabled V2X system will need minimal setup costs as VLC-based V2X can use light emitting diodes (LEDs) or laser diodes (LDs) that are already present in the vehicular head- and tail-lights or in street/traffic lights. Despite the above benefits, standalone VLC networks also have their drawbacks, including their limited coverage distance, sensitivity to background light and line-of-sight (LOS) blockage. These impediments are conveniently circumvented by the classic RF wireless networks, which exhibit wider coverage and higher transmission integrity in the absence of LOS. By intelligently combining, we show that the integration of VLC and RF improves the overall system performance to meet the stringent requirements of 6G-V2X networks. As depicted in Fig. 1, hybrid RF-VLC based V2X systems have the potential to deliver significantly improved vehicular message disseminations by exploiting the complementary advantages of standalone VLC and RF systems. There are two main categories of hybrid RF-VLC based vehicular

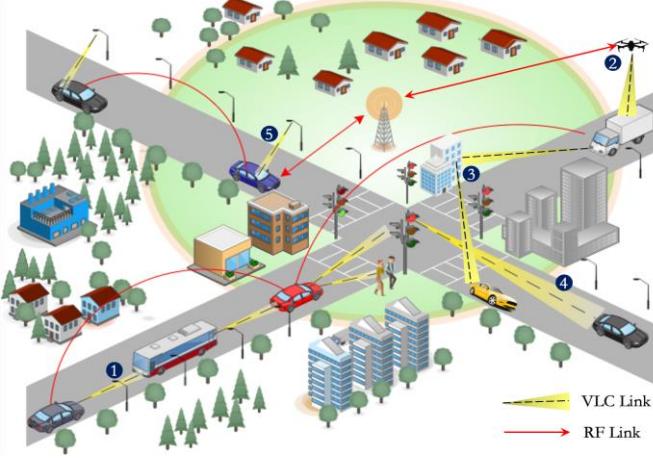


Fig. 2: Illustration of a generic hybrid RF-VLC communication in a vehicular network.

communication systems [11]:

a. Link-Aggregated (LA) Hybrid RF-VLC V2X systems:

In order to improve the achievable data rate and connection reliability, the vehicular nodes employ both VLC and RF links simultaneously.

b. Non-Link Aggregated (non-LA) Hybrid RF-VLC V2X systems:

In this case, the vehicular nodes utilize either VLC or RF technology at a given time instant to optimize the network parameters.

As shown in Fig. 2, there are five primary scenarios in which VLC can complement and strengthen RF communication in V2X networks: (1) V2V communications via front lights or back lights, (2) U2V (UAV-to-Vehicle) communication, (3) V2V communication via Re-configurable Intelligent Surfaces (RIS¹), (4) V2X communications via traffic lights, and (5) V2X communications via street lights. The latter may be viewed as a second layer of ubiquitous small-cell VLC BSs. In addition to increasing data rates, VLC has the potential to address some of the limitations of traditional V2X communication based on RF. For example, in the left bottom corner of Fig. 2, the RF-based V2V communication of two cars separated by a large bus may suffer from severe packet loss due to the shadowing effect. In this case, the transmitting car may use VLC to communicate with the bus; subsequently, the bus could forward the messages to the receiving car in the shadowed region. Moreover, the data packets can also be relayed using traffic/street lights at urban intersections, allowing vehicles to interact across perpendicular streets, where classical V-RF solution is often plagued by severe packet loss. Further, the use of optical-RIS (O-RIS)² can further combat packet loss, enhancing signal quality and providing wider coverage in a VLC aided V2X systems. Apart from the above, VLC enabled

¹RIS refers to reconfigurable metasurfaces consisting of numerous passive antenna-elements having adjustable phases. In fact, in advance RISs, one can effectively control not only the phase, but potentially even the frequency, amplitude and the polarization of the incident wireless signals to overcome the deleterious effects of natural wireless propagation [2].

²O-RIS can be envisioned as an extension of RIS for THz optical wireless signals and eventually for VLC [8].

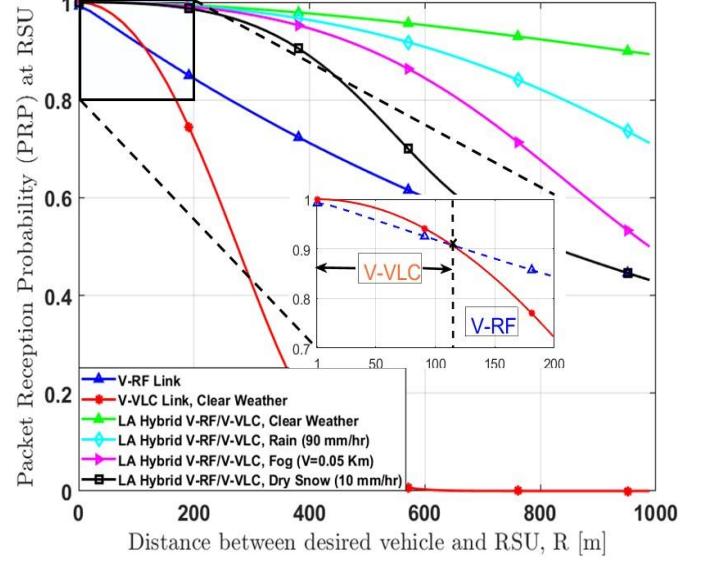


Fig. 3: PRP at RSU for pure V-RF, pure V-VLC and LA hybrid RF-VLC V2X communication system under rain, fog and dry snow conditions.

unmanned aerial vehicle (UAV) based U2V communication [9] can be utilized for smart traffic monitoring system to monitor, track and control allowed speed, other traffic violations and suspicious behavior of vehicles moving on the road. Although RF-based relaying in context of vehicular communication has been widely explored in the literature, resultant interference has to be mitigated in high-density vehicular environments.

III. CASE STUDY

Hybrid RF-VLC is capable of significantly improving the safety at road intersections, where frequent accidents tend to occur. At road intersections, the surrounding high-rise buildings, road-side installations or sign-boards may block the LOS communication among vehicles. Consequently, traffic safety can be enhanced by improving the opportunistic exchange of the V2X-specific cooperative awareness messages (CAMS)/basic safety messages (BSMs) among vehicles. In order to increase the reliability of a communication link, a relay can be placed at an intersection relying upon the existing vehicular-RF (V-RF) communication technologies. However, with increase in vehicular density, V-RF assisted relaying experience higher interference, lower packet reception rates, and increased communication delays due to severe channel congestion and retransmission attempts [2]. To this end, the co-deployment of vehicular-VLC (V-VLC) and V-RF communication systems is capable of improving the safety message dissemination at road intersections. Specifically, we propose to use VLC based V2I communication, where the RSU mounted on lamp-posts or traffic lights receive BSMs in the VLC uplink. It has been shown in [5] that non LA hybrid RF-VLC V2X networks lead to substantial reduction of outage along with improvements of throughput and latency as compared to pure V-VLC or pure V-RF networks. For sake of analysis, we consider a typical road intersection scenario as

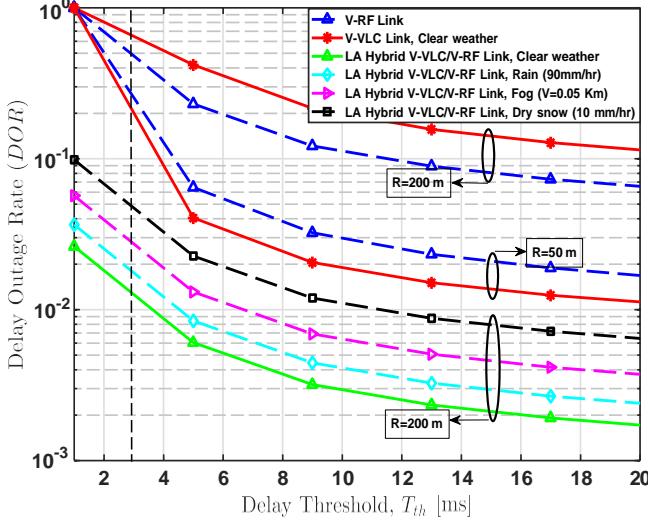


Fig. 4: Delay outage performance for pure V-RF, pure V-VLC and LA hybrid RF-VLC V2X communication system as a function of delay threshold, T_{th} .

shown in Fig. 2, in which vehicles equipped with both VLC and RF transceivers are assumed. For the sake of illustration, we consider a LA hybrid RF-VLC V2X uplink scenario and compare its performance to that of the pure V-VLC and pure V-RF uplink taking into consideration the impact of interference and various meteorological phenomenon such as rain, fog and dry snow conditions with an aid of stochastic geometry tools. The LA technique enhances not only the total available bandwidth, but also leads to more reliable network performance, and reduction in the end-to-end latency. We take into account that the communications between the RSU and desired vehicle are subject to interference from the same lane as well as from vehicles in the perpendicular lanes. The system parameters were chosen in accordance with a practical vehicular communication scenario as in [5]. The attenuation coefficient under rain (rain rate=90 mm/hr), fog ($V=0.05$ Km) and dry snow (snow rate=10 mm/hr) are taken to be 21.9, 78.8 and 131 dB/km respectively as given in [7, Table 2]. Unless otherwise stated, we assume having the vehicular density λ and channel access probability ρ to be 0.01 and 0.01, respectively. Observe from Fig. 3 that depending on the transmitter's location, the pure V-VLC and V-RF systems exhibit complementary roles in terms of packet reception probability (PRP). In particular, the PRP for standalone V-VLC links is better as compared to V-RF links, when the distance between the RSU and desired vehicle is not higher than 120 m. However, pure V-RF is a more reliable option for longer-range communication. Interestingly, regardless of the distance between the desired vehicle and the RSU and any prevailing weather conditions, the LA hybrid RF-VLC V2X systems outperform the pure V-VLC or V-RF links. Notice that the performance of LA systems are mainly influenced under dry snow condition. This is primarily due to high attenuation in the pure V-VLC link under dry snow condition.

Many warning/safety specific messages are life-critical,

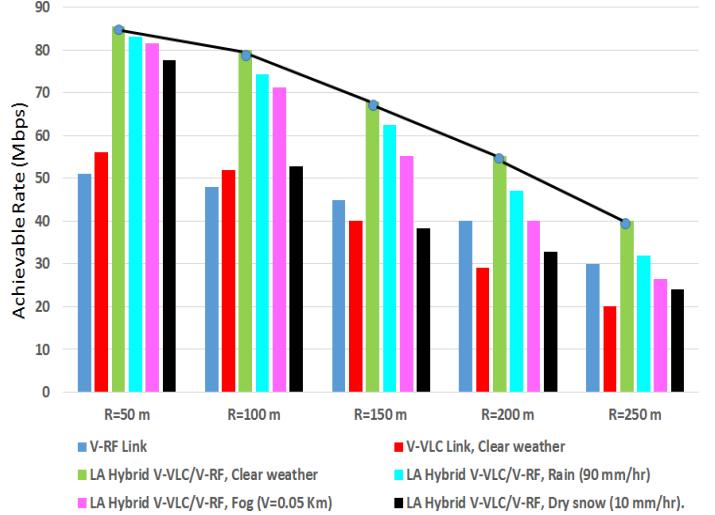


Fig. 5: Achievable data rate for different network configuration for different values of distance between RSU and desired vehicle.

hence a high latency is unacceptable, especially in accident-prone situations. It is anticipated that the hybrid RF-VLC V2X systems can offer ultra-reliable low latency communication (URLLC) among vehicles, while meeting 6G key performance indicators (KPIs) vehicular network requirements. According to [5, Eq.(28)], we consider the metric of delay outage rate (DOR), which represents the probability that the minimum transmission time (MTT) required for sending a certain amount of data is higher than the tolerable duration. We plot the DOR of standalone V-RF, LA hybrid RF-VLC V2X, and pure V-VLC ensuring different maximum delay requirements for both 50m and 200m distances in Fig. 4. Here, we assume that the system bandwidth for pure RF and VLC system to be 20 MHz³. Again, depending on the transmitter's location, pure V-VLC and V-RF exhibit complementary roles, as evidenced by Fig. 4. Additionally, for data traffic having stringent delay requirements of < 3 ms, the LA-aided hybrid RF-VLC V2X under any weather condition ensures having the minimum delay in transmitting data size, $H=50KB$ from the desired vehicle to the RSU as compared to pure V-VLC or V-RF systems. In light of the above results, it can be inferred that irrespective of any meteorological phenomenon, the LA-aided hybrid RF-VLC V2X system achieves ultra high reliability (~99.999%) and ultra-low latency (<3 ms) up to $R=200$ m. For an interference-limited scenario, the LA-aided hybrid RF-VLC V2X system meets stringent reliability and latency requirements for advanced vehicular scenarios [3].

Fig. 5 shows the achievable data rate for different network configurations of $R \in \{50m, 100m, 150m, 200m, 250m\}$. In an interference-limited scenario, the maximum achievable data rate associated with LA-aided hybrid RF-VLC V2X can be as high as 83.2 Mbps at $R=50$ m, which reduces to 39.8 Mbps at $R=250$ m under clear weather conditions. Note that the achievable rate of a non-LA hybrid RF-VLC V2X system

³RF spectrum is generally licensed and expensive, whereas VLC spectrum is free, hence it more cost effective.

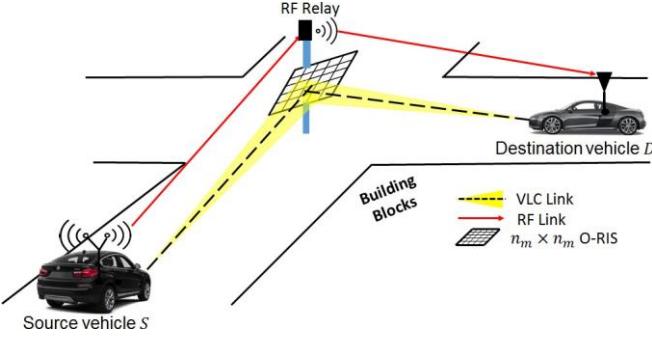


Fig. 6: O-RIS/metasurface can be deployed on RSU/buildings at road intersection to relax the LOS requirement between source and destination vehicles in hybrid RF-VLC V2X systems.

relies on the maximum throughput offered by either pure V-VLC or pure V-RF systems. Here, we assume that the desired vehicle accesses the channel at a transmission probability of $p_A=0.9$ and link aggregation overload of $\theta_{ov}=0.8$ [6]. The results presented meet the data rate requirements of advanced vehicular scenarios that have been investigated in [3]. Note that the advanced driving scenario includes semi-automated or fully-automated driving use-cases for longer inter-vehicle distances, supporting data rates ranging from 10-53 Mbps among vehicles or RSUs in close proximity.

IV. CHALLENGES AND FUTURE DIRECTIONS

A. Reconfigurable Intelligent Surfaces (RIS) Enabled Hybrid RF-VLC V2X Systems

Recently, RIS has attracted much research attention owing to its salient feature of transforming hostile wireless channels into benign ones. It has emerged as a disruptive communication technology for enhancing signal quality and transmission coverage in wireless vehicular networks. Significant gains may be gleaned by incorporating RISs into hybrid RF-VLC V2X systems, thanks to the enhanced resilience to LoS blockages, especially, when striking a flexible tradeoff between lighting and communications, quality-of-service, interference mitigation, enhanced localization services, and improved energy harvesting. In particular, 6G-V2X can benefit from RISs in situations where coverage is constrained. For instance, in urban areas, road intersections constitute an ideal use case for deploying RIS-aided RF-VLC V2X systems, where the exchange of safety messages between vehicle lights may be blocked by buildings, walls, surrounding vehicles and other obstructions, as shown in Fig. 6. By enabling an RIS controller to actively relay the information from the source to the destination vehicle, the RIS can not only potentially help improve the transmission rate for standalone V-VLC systems, but also provide wide coverage range using RIS controller. As soon as the quality of VLC link degrades (e.g. long range communication case), the communication between source and destination vehicles can still be accomplished using conventional V-RF systems employing relaying. Nonetheless, several distinctive research challenges such as channel estimation in

highly dynamic scenarios, optimal RIS deployment, reliable energy management schemes, optimal resource allocation and reflection optimization have to be carefully addressed before the practical integration of RIS into hybrid RF and VLC vehicular communication systems.

B. ML-assisted System Design

Machine learning (ML) assisted 6G is expected to unlock the promise of future ITS [4]. These features are desirable in vehicular networks to accommodate diverse and advanced use cases and their technical requirements. Due to the inherent heterogeneity and mobility of vehicular networks, communication environments are highly complex resulting in varying wireless or optical channels. On the other hand, different layers of the current RF and VLC communication systems are optimized independently. Such a design paradigm may not be ideal when dealing with diverse quality of service (QoS) requirements (e.g., throughput, delay, reliability, and spectrum efficiency), particularly when dealing with complex and dynamic vehicular environments. There is a need to configure different functional blocks of VLC/RF communication systems in a joint and adaptive manner according to the dynamically varying vehicular network. For example, ML-assisted adaptive coding and modulation (ACM) is expected to improve the robustness whilst reducing the communication latency. ML can also be applied to optimize multiple configurations simultaneously. An end-to-end hybrid communication architecture needs to be considered when an ML-based joint optimization is developed. A hybrid RF-VLC V2X system would also face resource allocation issues such as bandwidth allocations and access point selection based on the requirements of the network, availability of resources, and mobility of the vehicles. In addition, dynamic decision making on whether to use LA or non-LA hybrid techniques can be crucial for effective and energy-efficient V2X communications. Using traditional methods of resource allocation would mean re-running the simulation for every small change, resulting in significantly large overhead [12]. In such case, ML-based techniques can be an effective tool for data-driven decision making in order to improve the performance of resource allocation in RF/VLC vehicular networks. In particular, a reinforcement learning solution for hybrid RF-VLC V2X systems can be helpful to tackle the challenge arising due to dynamic environments and shortage of relevant datasets for vehicular networks. Future research may be devoted to developing ML-based resource allocation algorithms for RF/VLC V2X network with the goal of ensuring maximum network performance and decrease in control overhead and handover latency.

C. Deployment Issues

Despite the huge potential of hybrid RF-VLC V2X systems, their widespread deployment can be hampered by availability of VLC links under meteorological phenomena such as rain, fog, snow and hazy conditions [7]. In addition, solar irradiance and artificial light sources (e.g. roadside illumination, sign boards, fluorescent lamps) also impose challenges for such hybrid systems in the real world. In addition, the intensity of

the signal received in VLC can vary widely due to the mobility of the vehicle. Thus, channel variations caused by mobility and ambient light-induced noise must be carefully addressed before implementing VLC in the 6G-V2X ecosystem. Compared with V-RF, V-VLC are subject to light-path blockages, which can drastically reduce the data rate in such hybrid vehicular applications. The authors of [13] overcome this challenge by proposing omnidirectional and ubiquitous coverage in VLC. Furthermore, the specific bandwidth aggregation in LA-aided hybrid RF-VLC V2X systems constitutes an open research challenge, given for example 1Hz RF bandwidth in the sub-6GHz band and 1Hz VLC bandwidth in the 800 THz band. In light of the above discussions, it is clear that these challenges have to be tackled before the practical deployment of such hybrid systems.

D. Coexistence of mmWave, THz and VLC

Both VLC and TeraHertz (THz) techniques constitute promising candidates for realizing the vision of 6G V2X. It is anticipated that operation of 6G V2X will rely on usage of a wide range of transmission frequencies including RF, VLC, THz, and mm-wave frequencies. There exists a trade-off among coverage area, ergodic rate, mobility and latency when dealing with variety of spectrum. There can be two ways to realize the presence of multiple frequencies namely; flexible spectrum coexistence and hybrid deployment. In the flexible spectrum coexistence approach, the base stations (BSs) with different frequencies are deployed separately and each BS at a certain time can operate on only one of RF, VLC, and THz frequency bands. For flexible multi-band utilization, the multiband C-V2X system needs advanced front-end hardware. In addition, the coexistence of different network spectrum leads to new interference problems [14]. In the hybrid approach, each BS relies on more than one frequency band. Optimizing user-side opportunity spectrum selection, network activation mechanisms considering traffic load, BS implementation, and multichannel solutions will be the key challenges for such multiband vehicular networks (MBVNs).

E. NOMA and its variants

Multiple access plays a pivotal role in vehicular communication and networking. In DSRC, carrier sense multiple access (CSMA) is adopted, whereby all vehicles that have messages to send must constantly sense the availability of the channel. CSMA is simple, however may lead to large communication overhead and high collision rates in dense vehicular networks. LTE-V2X and 5G-NR-V2X, on the other hand, use OFDMA for multiple access, but they could suffer the same problem due to its orthogonal nature. In view of the explosive growth of communication sensors and connected vehicles, tremendous research activities have been carried out in recent years on non-orthogonal multiple access (NOMA) for supporting a massive number of concurrent communication links. Both power-domain NOMA and code-domain NOMA may be applied to hybrid RF-VLC based V2X communication systems. In this line of research, it is interesting to optimize the user pairing, power allocation, codebook design, and

multiuser detection algorithms in order to meet the diverse QoS requirements in future vehicular networks [15]. Further, it is of practical interest to carry out user grouping such that some are supported by NOMA and some by orthogonal multiple access (e.g., OFDMA).

V. CONCLUSION

In this article, we have shown that the potential benefits of hybrid RF-VLC based vehicular communication systems by exploiting the complementary advantages of both technologies. In particular, Figures 3-5 have demonstrated that regardless of any meteorological phenomenon, link aggregation aided hybrid RF-VLC V2X systems are capable of achieving considerable performance improvement in successful packet reception probability, data rate and latency compared to pure RF and VLC counterparts, making it a promising technology for various 6G-V2X applications. We have also discussed the challenges and promising future research directions of such hybrid systems in the 6G-based V2X era. In conclusion, a significant increase in the real-time deployment of such hybrid systems may be anticipated in support of advanced 6G V2X features.

REFERENCES

- [1] S. Chen, J. Hu, Y. Shi, Y. Peng, J. Fang, R. Zhao, and L. Zhao, "Vehicle-to-everything (V2X) services supported by LTE-based systems and 5G," *IEEE Commun. Standards Mag.*, vol. 1, no. 2, pp. 70–76, 2017.
- [2] M. Noor-A-Rahim, Z. Liu, H. Lee, M. O. Khyam, J. He, D. Pesch, K. Moessner, W. Saad, and H. V. Poor, "6G for vehicle-to-everything (V2X) communications: Enabling technologies, challenges, and opportunities," *Proceedings of the IEEE*, vol. 110, no. 6, pp. 712–734, 2022.
- [3] D. P. Moya Osorio, I. Ahmad, J. D. V. Sánchez, A. Gurtov, J. Scholliers, M. Kutila, and P. Porambage, "Towards 6G-enabled internet of vehicles: Security and privacy," *IEEE Open J. Commun. Soc.*, vol. 3, pp. 82–105, 2022.
- [4] E. Calvanese Strinati, S. Barbarossa, J. L. Gonzalez-Jimenez, D. Ktenas, N. Cassiau, L. Maret, and C. Dehos, "6G: The next frontier: From holographic messaging to artificial intelligence using subterahertz and visible light communication," *IEEE Veh. Tech. Mag.*, vol. 14, no. 3, pp. 42–50, 2019.
- [5] G. Singh, A. Srivastava, V. A. Bohara, Z. Liu, M. Noor-A-Rahim, and G. Ghatak, "Heterogeneous visible light and radio communication for improving safety message dissemination at road intersection," *IEEE Trans. Intell. Transport. Syst.*, pp. 1–13, 2022.
- [6] N. M. Karoti, S. Paramita, R. Ahmad, V. A. Bohara, and A. Srivastava, "Improving the performance of heterogeneous LiFi-WiFi network using a novel link aggregation framework," in *Proc. IEEE Wireless Communications and Networking Conference (WCNC)*, 2022, pp. 2322–2327.
- [7] G. Singh, A. Srivastava, and V. A. Bohara, "Impact of weather conditions and interference on the performance of VLC based V2V communication," in *Proc. IEEE Intl. Conf. Transparent Optical Net. (ICTON)*, 2019, pp. 1–4.
- [8] S. Aboagye, A. R. Ndjiongue, T. Ngatchou, O. Dobre, and H. V. Poor, "RIS-assisted visible light communication systems: A tutorial," *arXiv preprint arXiv:2204.07198*, 2022.
- [9] N. Agrawal, A. Bansal, K. Singh, and C.-P. Li, "Performance evaluation of RIS-assisted UAV-enabled vehicular communication system with multiple non-identical interferers," *IEEE Trans. Intell. Transport. Syst.*, vol. 23, no. 7, pp. 9883–9894, 2022.
- [10] A. Memedi and F. Dressler, "Vehicular visible light communications: A survey," *IEEE Commun. Surveys Tut.*, vol. 23, no. 1, pp. 161–181, 2021.
- [11] H. Abuela, M. Elamassie, M. Uysal, Z. Xu, E. Serpedin, K. A. Qaraqe, and S. Ekin, "Hybrid RF/VLC systems: A comprehensive survey on network topologies, performance analyses, applications, and future directions," *IEEE Access*, vol. 9, pp. 160 402–160 436, 2021.
- [12] L. Liang, H. Ye, and G. Y. Li, "Toward intelligent vehicular networks: A machine learning framework," *IEEE Internet of Things Journal*, vol. 6, no. 1, pp. 124–135, 2019.

- [13] H. B. Eldeeb, S. M. Sait, and M. Uysal, "Visible light communication for connected vehicles: How to achieve the omnidirectional coverage?" *IEEE Access*, vol. 9, pp. 103 885–103 905, 2021.
- [14] T. Xu, M. Zhang, Y. Zeng, and H. Hu, "Harmonious coexistence of heterogeneous wireless networks in unlicensed bands: Solutions from the statistical signal transmission technique," *IEEE Veh. Tech. Mag.*, vol. 14, no. 2, pp. 61–69, 2019.
- [15] Z. Liu and L.-L. Yang, "Sparse or dense: A comparative study of code-domain noma systems," *IEEE Trans. Wireless Commun.*, vol. 20, no. 8, pp. 4768–4780, 2021.



Zilong Liu (zilong.liu@ess.ac.uk) is currently a Lecturer (Assistant Professor) with the School of Computer Science and Electronics Engineering, University of Essex. His research lies in the interplay of coding, signal processing, and communications, with a major objective of bridging theory and practice as much as possible. Recently, he has developed an interest in applying machine learning for wireless communications. He is an Associate Editor of IEEE Transactions on Neural Networks and Learning Systems, IEEE Transactions on Vehicular Technology, IEEE Wireless Communications Letters, and IEEE Access. More details of his research can be found in the link here: <https://sites.google.com/site/zilongliu2357>



Gurinder Singh (gurinders@iiitd.ac.in) is a Ph.D. degree candidate at Indraprastha Institute of Information Technology (IIIT), Delhi, India. His research interests include vehicular-visible light communication, hybrid VLC-RF architecture, non-orthogonal multiple access (NOMA), and reconfigurable intelligent surfaces (RIS)-aided vehicular communication systems.



Anand Srivastava (anand@iiitd.ac.in) did his Ph.D. from IIT Delhi. He is currently Professor at IIIT Delhi and an Adjunct Professor at IIT Delhi. Earlier, he had 20 years of experience with the Center for Development of Telematics (CDOT), a telecom research center of Govt. of India where he was involved in the development of national-level telecom projects. His research work is in the area of optical networks, vehicle-to-vehicle communications, Fiber-Wireless architectures, and Visible Light Communications.



Vivek Ashok Bohara (vivek.b@iiitd.ac.in) is an Associate Professor with Department of Electronics and Communication Engineering, Indraprastha Institute of Information Technology (IIIT), Delhi, India. His research interests include next-generation communication technologies, such as device-to-device communication, carrier aggregation, and visible light communications.



Dirk Pesch (dirk.pesch@ucc.ie) is a Professor with the School of Computer Science and Information Technology, University College Cork, Cork, Ireland, and was previously the Head with the Nimbus Research Centre, Munster Technological University. His research interests include problems associated with architecture, design, algorithms, and performance evaluation of low power, dense, and vehicular wireless/mobile networks and services for Internet of Things and cyber-physical system's applications in building management, smart connected communities, independent living, and smart manufacturing.



Md. Noor-A-Rahim (m.rahim@cs.ucc.ie) is currently a senior researcher with the School of Computer Science and IT, University College Cork, Cork, Ireland. His research interests include Wireless Networks, Intelligent Transportation Systems, Machine Learning, and Signal Processing.