Towards 6G-V2X: Hybrid RF-VLC for Vehicular Networks

Gurinder Singh*, Anand Srivastava*, Vivek Ashok Bohara*, Md Noor Rahim*, Zilong Liu*, Dirk Pesch*, and Lajos Hanzo†

*Indraprastha Institute of Information Technology, Delhi (IIIT-Delhi), India
*University College Cork, Ireland
†University of Essex, UK
^University of Southampton, UK

With the advent of connected autonomous vehicles, we are expecting to witness a new era of unprecedented user experiences, improved road safety, a wide range of compelling transportation applications, etc. A large number of disruptive communication technologies are emerging for the sixth generation (6G) wireless network aiming to support advanced use cases for intelligent transportation systems (ITS). An example of such a disruptive technology is constituted by hybrid Visible Light Communication (VLC) and Radio Frequency (RF) systems, which can play a major role in advanced ITS. Hence we outline the potential benefits of hybrid vehicular-VLC (V-VLC) and vehicular-RF (V-RF) communication systems over standalone V-LC and standalone V-RF systems. In particular, we show that the 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 ITS. To stimulate future research in the hybrid RF-VLC V2X area, we also highlight the potential challenges and research directions.

Introduction

Connected and automated vehicular (CAV) technologies are expected to support improved road safety and driving comfort, hence they are expected to play a critical role in 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. Vehicle-to-everything (V2X) communication - which is a key enabler of data exchange in CAV - 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, the more sophisticated C-V2X has attracted much attention in recent years due to its significantly improved coverage, throughput, and latency. This is a benefit of the sophisticated cellular infrastructure, which permits centralized resource allocation as well as enhanced communication/sensing capabilities. Several 3GPP V2X initiatives (such as LTE-V2X and 5G-NR-V2X), which are supported by the telecommunication sector, have contributed to the prominence of C-V2X.

Again, intelligent autonomous vehicles will be supported by an abundance of both sophisticated sensors and advanced communication devices, but their tight control will impose new communication challenges on the emerging V2X networks [2]. More explicitly, stringent throughput, latency, coverage-quality, spectral efficiency, energy rating, networking, and privacy/security specifications have to be met. While 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. While adopting the underlying mechanisms and system architectures of LTE-based V2X. Thus, V2X networks based on 5G New Radio (NR) may not be able to meet the above-mentioned radical 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. This transformation is beginning to take shape with the intensifying research into 6G wireless communication networks aiming for incorporating disruptive concepts [3]. 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 RF and VLC solutions, which are complementary to each other due to their respective benefits and trade-offs. 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 consumption, and enhance safety. Therefore, the principal objective of this treatise is to harness the potential of RF-VLC in support of 6G-V2X. 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 vehicular communication systems. Briefly, link aggregation results in more efficient use of physical resources as well as improving reliability and availability.

In Section II, the RF-VLC communication system model is introduced. Several case studies specifically relevant to RF-VLC V2X applications are presented in Section III. In Section IV we then 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 radio frequency (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 these demanding vehicular environments. As a remedy, the non-interfering unlicensed VLC band may be harnessed in unison with the RF band for improved V2X communications, while supporting enhanced security [4]. Additionally, 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 beneficially combining the advantages of both, 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 dissemations by exploiting the complementary advantages of standalone VLC and RF systems. There are two main categories of hybrid RF-VLC based vehicular communication systems [5]:

a. Link-Aggregated (LA) Hybrid Systems:

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

b. Non-Link Aggregated (non-LA) Hybrid Systems:

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

As shown in Fig.2, there are three main scenarios in which VLC can complement and strengthen RF communication in V2X networks: V2V communications via front lights or back lights, V2X communications via traffic lights, and 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-bodied bus may suffer from severe packet loss due to the shadowing effect. In this case, the transmitting car could use VLC to communicate with the bus; subsequently, the bus could forward the messages to the receiving car in the shadowed region. Additionally, data packets can also be relayed using traffic/street lights at urban intersections, allowing vehicles to interact across...
perpendicular streets, where traditional RF-based solution is often plagued by severe packet loss. Although RF-based relaying by vehicles or roadside units (RSUs) has been widely explored in the literature, resultant extra 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, traffic safety can be enhanced by exploiting the opportunistic exchange of the V2X-specific cooperative awareness messages (CAMs)/basic safety messages (BSMs) among vehicles. At road intersections the surrounding high-rise buildings, road-side installations or sign-boards may block the LOS communication among vehicles. In order to enhance the reliability of a communication link, one can place a relay at an intersection relying upon the existing V-RF communication technologies. However, with increase in vehicular density, V-RF assisted relaying tends to suffer from higher interference, reduced packet reception rates, and increased communication delays due to the potentially severe channel congestion and retransmission attempts [2]. To this end, the co-deployment of V-LC and V-RF communication systems is capable of improving the safety message dissemination at road intersections. Specifically, we propose to use VLC based vehicle-to-infrastructure (V2I) communication, where the RSU mounted on lamp-posts or traffic lights receive BSMs in the VLC uplink. It has been shown in [6] that hybrid RF-VLC V2X networks lead to substantial reduction of outage along with improvements of throughput and latency as compared to pure V-LC or pure V-RF networks. A typical road intersection scenario has been depicted in Fig. 2, in which vehicles equipped with both VLC and RF transceivers are assumed. For the sake of illustration, we consider a hybrid RF-VLC V2X uplink scenario and compare its performance to that of the pure V-LC and pure V-RF uplink. 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 [6]. Unless otherwise stated, we assume having the vehicular density of $\lambda$ and channel access probability $\phi$ to be 0.01 and 0.1, 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, the LA as well as non-LA hybrid RF-VLC V2X systems outperform the pure V-LC or V-RF links.

![Fig 3: PRP at RSU for pure V-RF, pure V-LC and hybrid RF-VLC V2X communication system.](image)

Many warning/safety specific messages are life-critical, 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 [7]. According to [8, Eq.(3.2)], 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 as well as non-LA hybrid RF-VLC V2X, and pure V-VLC ensuring different maximum delay requirements for both 50m and 200m distances in Fig. 4. 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 ensures having the minimum delay in transmitting $H=50$KB of data from the desired vehicle to the RSU as compared to pure V-VLC or V-RF systems. In light of the above results, 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 [9].

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

In particular, 6G-V2X can take advantage of RISs in coverage-limited scenarios. 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 optical-RIS (O-RIS\(^1\)) controller to actively relay the information from the source to the destination vehicle, the O-RIS can potentially help improve the transmission rate for standalone V-VLC systems. 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 [7]. 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

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\(^1\) O-RIS can be envisioned as an extension of RIS for THz optical wireless signals and eventually for VLC.
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 [3]. 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 [11]. In this case, ML-based approaches can be an efficient tool for making data-driven decisions to enhance the resource allocation performance 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 [12]. 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. Further, the received signal strength in VLC may dramatically vary due to the vehicles’ mobility. Hence, mobility induced channel variations and ambient lighting induced interference need to be carefully addressed before deploying VLC in 6G-V2X ecosystems. 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, operating the C-V2X system at multiple frequency bands needs advanced front-end hardware. Additionally, spectrum coexistence of different networks leads to new interference problems [14]. In the hybrid approach, each BS leverages on more than one frequency band. Optimizing the opportunistic spectrum selection at the users’ end, traffic-load aware network activation mechanisms, deployment of BSs, and multi-connectivity solutions will be primary 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 delay 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) in order to support 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

The potential benefits of hybrid optical and RF vehicular communication systems can be unlocked by exploiting the complementary advantages of both technologies. In particular, Figures 3-5 demonstrated that link aggregation aided hybrid RF-VLC V2X systems are capable of achieving considerable performance improvement in successful packet reception probability, data rate and latency, making it a promising technology for 6G ITS 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.

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Author Information

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 a 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@iitd.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.

Md. Noor-A-Rahim (mrahim@cs.ucc.ie) is currently a Research Fellow with the School of Computer Science and IT, University College Cork, Cork, Ireland. His research interests include control over wireless networks, intelligent transportation systems, information theory, signal processing, and DNA-based data storage.

Zilong Liu (zilong.liu@essex.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 WIRELESS COMMUNICATIONS LETTERS, IEEE ACCESS, and Frontiers in Communications and Networks.

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.

Lajos Hanzo (hanzo@soton.ac.uk) is Professor and Chair of Telecommunications at the University of Southampton, and a former Editor-in-Chief of IEEE Press. He has published more than 2000 contributions at IEEE Xplore, 19 Wiley-IEEE Press books, and has helped fast-track the career of 123 Ph.D. students. He has served several terms as the Governor for both IEEE ComSoc and VTS. He was bestowed upon the Eric Sumner Field Award.