6G-EWOC: Optical Wireless Communication in Support of Autonomous Driving

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Abstract: **The road towards an efficient transport infrastructure, which safely operates fully autonomous vehicles in congestion-free traffic flows, is subject to several technological challenges that reach also into the realm of telecommunications. Future 6G networks are required to handle huge amounts of sensor information, both in terms of low-latency communication and real-time data processing. The 6G-EWOC project contributes to this challenge through a concerted use of optical wireless communication and sensing with radio-frequency based cellular technology. Three optical-wireless scenarios are discussed, including (*i*) instant data exchange between vehicles leveraging their lighting assets for low-latency communication, (*ii*) the provision of vehicular data off-loading to a fiber-based 6G infrastructure through beamsteering-assisted optical remote radio heads to enable data fusion at the edge cloud, and (*iii*) the seamless wireless extension of fiber-grade capacity to isolated network segments situated in fiber-scarce brownfields, which is accomplished through transparent optical air interfaces that ensure fiber-grade continuity by preventing a translucent electro-optic termination of the single-mode fiber channel. Another important contribution aims to advance light- and radio-based sensing technologies towards networked versions that offer simultaneous communication and detecting capabilities.**

I. Introduction

As the sixth generation of communication technology, 6G is considered a key facilitator for a wide range of applications that depend on extensive and instantaneous data exchange, as it applies to the segments of industrial production, utilities, augmented reality and education, or transportation [1]. Research towards these directions concentrate their effort in fusing modern communication technologies with advanced concepts that derive from the field of information processing. By capitalizing on a quiver that blends traditional radio-frequency (RF) based wireless communications with highly efficient photonic technology that is well-known for its unprecedented bandwidth offerings [2], data rates can be once more scaled up. At the same time, network-wide operation and resource management can be optimized by means of artificial intelligence [3]. The 6G-EWOC project aims to explore the offerings of 6G technology for the specific challenge of autonomous driving, with the overarching aim to enhance transport efficiency and safety. It does so by investigating optical wireless communication (OWC) and sensing technology that underpins a seamless and transparent connection for vehicular users to the fiber-based and compute-enhanced 6G network segment, while at the same time gathering the necessary data to acquire situational awareness for all traffic participants through network-wide road-side perception that is further enabled through instant and unrestricted access to data processing facilities integrated at the edge of the 6G network.

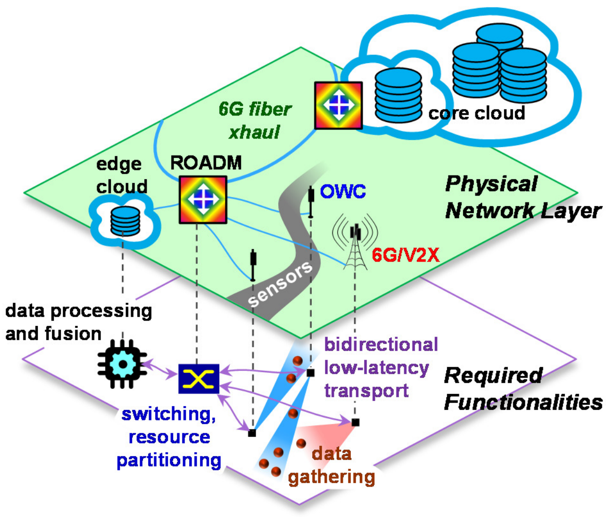

Fig. 1. 6G addressing the challenge of autonomous driving, which requires the extensive deployment of communication and computation resources to facilitate the "collective perception" paradigm.

In this paper, we highlight the peculiarities of OWC technology for various scenarios in the context of connected mobility, including vehicular-to-vehicular (V2V) communication for an instant relay of road-side data such as LiDAR point clouds, vehicular-to-infrastructure (V2I) connectivity to off-load huge amounts of data while acquiring situational updates through the processing and data fusion assets integrated with the 6G infrastructure, and support for infrastructure-to-infrastructure (I2I) communication to bridge network islands that are not connected to optical fiber media, in order to ensure a seamless continuum of fiber-grade capacity to the very far edge of a road-side 6G network where fiber might be scarce.

II. The Need for 6G in Support for Large-Scale Traffic Optimization

Road safety and optimization of road traffic are serious concerns as the lack thereof results in more than 1 million fatalities every year, while further greatly burdening economics and our daily lives through inefficiencies along the transport infrastructure. Although real-time information can be gathered through a multitude of sensor technologies, including high-resolution camera or radio- / light-based detection and ranging (RaDAR / LiDAR) concepts, information needs to be fused in real-time and on a larger scale in order to generate notable efficiency gains. In this context of "collective perception", the provision of instant access to a processing infrastructure becomes paramount as it enables a district-scale optimization of traffic towards congestion-free flows, while further safeguarding fast and uninterrupted travel for emergency response vehicles and while further protecting vulnerable road users in challenging road situations such as colluded overtakings. In addition, the enrichment of the digital horizon for every individual vehicular user unleashes the paradigm of collision-free fully-autonomous driving, which is touted to contribute through its superior driving skills when compared to human drivers.

Advanced sensor technologies offering a high sensitivity and a high resolution have been demonstrated in this context. As one of the promising sensor technologies, chip-scale LiDAR technology is able to acquire a clear digital picture of the environment at high update rates [4]. The offerings in terms of resolution and sensing distance then allow, together with dedicated signal processing engines, a clear understanding of the road-side processes in the proximity of the host vehicle. This allows the individual traffic participant to identify and comprehend objects, vehicles and people along the road-side scenery, including the perception of difficult challenges such as the prediction of paths pedestrians will choose or the identification of child-age pedestrians who might not follow a logical behavior along the road-side scenery.

However, for a wide-scale optimization of transport infrastructure, a much larger situational picture is required – one that necessitates the distribution of road-side data gathered in a much more distributed fashion, involving many traffic participants. This is where advanced 6G technologies are expected to provide the required communication pipes suited to transport raw multi-modal sensor data at elevated multi-Gb/s/user data rates, while providing the required edge infrastructure that can process and fuse the collected data before it is findings are fed back to the traffic participants at ultra-low latencies (Fig. 1). While this also involves RF-based V2X technologies and fiber-based xhaul solutions that support antenna remoting – ideally by means of coherent digitized [5] or analogue [6] radio-over-fiber transmission, the following chapters will exclusively discuss OWC aspects under this umbrella of connected mobility.

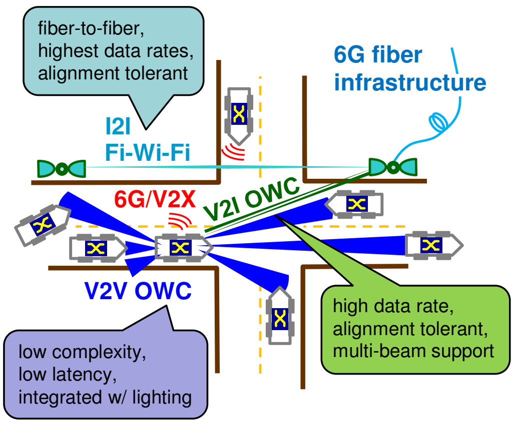

Fig. 2. Flavors and requirements for optical wireless communication in the context of connected mobility, involving vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I) and infrastructure-to-infrastructure (I2I) scenarios.

III. Optical Wireless Communication in the Context of Connected Mobility

First, OWC provides a low-latency high-datarate pipe to instantaneously off-load data gathered through vehicular traffic participants to an edge computing facility. The data collected by several traffic participants can then be processed and communicated back to the vehicular users to enrich their digital horizon. By exploiting unlicensed optical spectrum, OWC can operate in environments that are contaminated by excessive electro-magnetic interference (EMI) while leveraging the bandwidth of photonic communications.

Co-existence with RF-based cellular V2X technology can ensure support for non-line-of-sight communication, which in turn is indirectly supported by the presence of line-of-sight OWC technology through off-loading vast amounts of data to the license-free optical spectral range and thus moving capacities out of the quickly exhausted RF-based wireless communication spectrum. There are multiple approaches for the joint integration of cellular V2X and OWC: In a *hybrid* scenario, both technologies coexist simultaneously and support connectivity in parallel by exploiting the unique advantages of the constituent communication channels to realize the best-achievable throughput, building also on assets such as high link capacities over shorter reach (over OWC), or increased robustness to unfavourable weather conditions and support for non-line-of-sight links (over RF). Adaptive switching can then opt between them to maximize the throughput. In a *cooperative* approach the technologies are dedicated to certain tasks linked to the peculiarities of the use-cases and service requirements identified for autonomous driving. For example, OWC will be advantageous at busy road intersections or when ultra-low latencies are required, while cellular V2X ensures larger-scale situational awareness. The two technologies can further complement each other in a way that they serve as *backup* for each other. Although this redundancy mitigates outage, it does not increase the data throughput on the wireless segment.

Three constituent OWC technologies shall be in focus (Fig. 2), including (*i*) V2V communication in busy road intersections, where data is to be locally exchanged between vehicles and their integrated far-edge computing assets – without being restricted by crosstalk deriving from the use of RF-based V2X technology, (*ii*) V2I communication to off-load road-side data collected by the vehicles to the 6G infrastructure for further data processing at the edge, and (*iii*) a fiber-wireless-fiber (Fi-Wi-Fi) scenario where the lightpath within the xhaul segment is extended by means of OWC in order to avoid an early termination of lightpaths when bridging the xhaul with local 6G network islands in fiber-scarce brownfield domains. Additionally, active sensing devices like RaDAR and LiDAR technologies are nowadays only used for sensing. However, further developments to provide them with communication capabilities achieving Joint Communication and Sensing (JCAS) are of high interest due to their impact in reducing system and integration complexity.

The following chapters will discuss the peculiarities of these three OWC applications and connected RaDAR/LiDAR technologies.

IV. Wide-Beam V2V OWC

When information needs to be exchanged among the traffic participants, point-to-point communication between road users is the preferred option under one strict requirement: Simplicity shall prevail for the involved communication terminals, since no cost sharing among users applies in this V2V context. Moreover, the density of road users, which can reach ~50 cars per intersection, calls for EMI-robust and low-latency communication – essentially without the need to retransmit data. OWC, though being restricted to line-of-sight schemes, can re-use existing technology assets such as used for lighting. OWC can facilitate light emitting diode (LED) based 100 Mb/s (or laser-sourced multi-Gb/s) transmission in a maximally transparent way: Through integrating V2V OWC in the head/rear-lamp of vehicles, information can be instantly transported through wide-beam OWC schemes to adjacent traffic participants, while occluded network users can be reached through multi-hop packet forwarding. This "see-through" effect in cars is supported through the minimization of latency in the OWC link, which is accomplished through the use of simple baseband signalling that allows OWC to omit digital signal processing (DSP) sub-systems such as required for multi-carrier modulation schemes.

While V2V OWC can build on mature high-power LED technology, exploiting the benefits of high-datarate communication yet requires support for high electro-optic modulation bandwidths. In stark contrast to high-speed micro-LED [7] or Gb/s-capable SMD LED technology [8], the modulation bandwidth of high-power LEDs is challenged by the large active area of LED devices that facilitate a powerful photon flux for lighting applications [9]. Although LED technology intended for lighting inherently suffers from this limitation, its electro-optic (e/o) modulation bandwidth can be boosted through a two- to three-fold bandwidth extension by means of analogue equalization [10]. This renders 100 Mb/s on-off keyed (OOK) transmission over a reach of 100 m as feasible. Towards this direction, Fig. 3(a) compares the e/o bandwidth of a commercial high-power LED and a visible-light laser source. A bandwidth of 85.5 MHz is proven feasible, which is sufficient to permit 100 MbE connectivity without DSP support. At the same time, the bandwidth of 1.65 GHz for the laser-sourced emitter indicates the possibility to realize data rates towards and beyond 10 Gb/s through simple multiplexing of coherent R/G/B light sources in combination with subsequent optical beam diffusors [11].

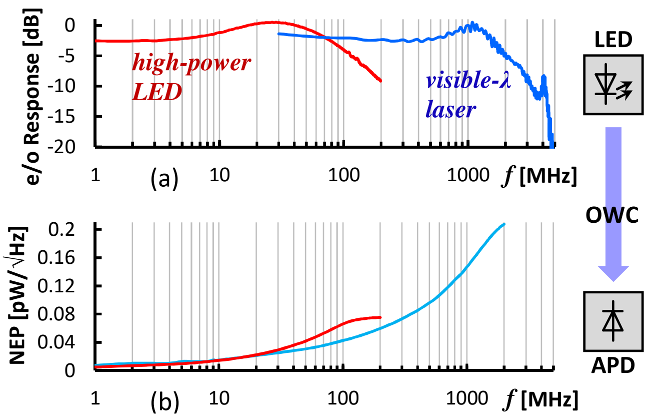

Fig. 3. Applicability of low-cost OWC technology for V2V applications: (a) electro-optic bandwidth of high-power LED and visible-light laser emitters, (b) noise equivalent power for APD-based receivers.

At the same time, wide-beam communication requires highly sensitive receivers, for which silicon photo-multipliers (SiPM) [12] or avalanche photodetectors (APD) are suitable candidates. Figure 3(b) proves the low noise equivalent power (NEP) of silicon APD-based receivers for targeted bandwidths of 100 MHz and 1 GHz. The corresponding integrated NEP is 64 and 164 fW/√Hz, respectively. Together with the high-power incoherent light emission of headlamps, the optical budgets for V2V applications can be overcome at reasonable light collection cross-sections implemented through 1” lenses at the receiver.

Finally, Figure 4(a) proves 125 Mb/s OOK transmission over a link sourced by high-power LED and sunk by an APD-based OWC receiver. The eye is clearly open, which evidences a good signal-to-noise ratio. This OWC link has then been used to transmit a LiDAR point cloud over a 100 m long out-door 100 MbE V2V OWC link. As Fig. 5(a) shows, there are no sectors missing in the point cloud, meaning that the data is reliably transmitted over the OWC link.

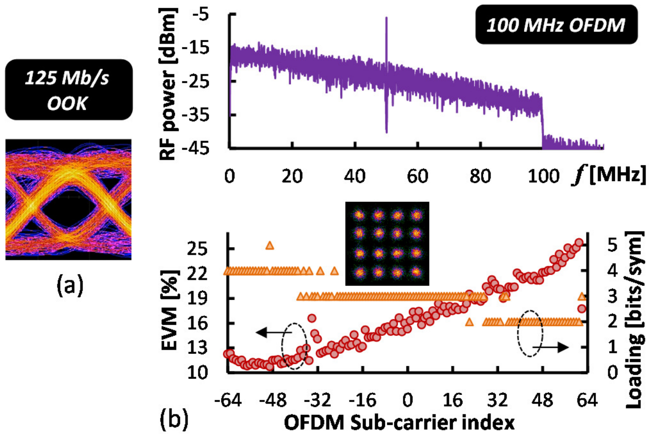

Fig. 4. V2V OWC with high-power LED and an APD receiver (a) 125 Mb/s OOK eye diagram and (b) 100 MHz OFDM transmission performance.

Moreover, Fig. 4(b) includes the received RF spectrum and error vector magnitude (EVM) when changing the modulation format to multi-carrier orthogonal frequency division multiplexed (OFDM) data transmission with adaptive bit-loading for its 128 sub-carriers over a bandwidth of 100 MHz. A data rate of 275 Mb/s can be supported over this low-cost OWC link, though at the expense of involving DSP. The OWC data rates can be further extended through wavelength-bonding of R/G/B emitters when realizing the required chromaticity for (white) lighting applications.

This aspect of joint visible-light communication and lighting squarely fits to the application of high-power LEDs. Figure 5(b) presents the chromaticity characteristics resulting from the use of co-packaged R/G/B high-power LEDs (for which Fig. 3(a) has earlier reported the e/o modulation characteristics regarding the red channel). As can be seen, the summed light (Σ in Fig. 5(b)) of all three colour channels with center wavelengths of 460, 520 and 634 nm resembles rather well the characteristics sought for white light, yielding a color temperature of 5710 K.

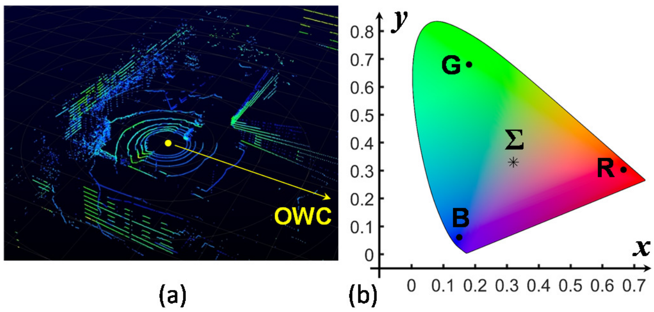

Fig. 5. (a) LiDAR point cloud transmitted over 100-m long V2V OWC link before its visualization. (b) Chromaticity for the employed high-power LED.

V. Pencil-Beam V2I OWC

Apart from direct user-to-user communication, road-side data collected through the network users is intended for joint processing through the edge cloud infrastructure integrated with the 6G network. To accomplish this, the required data exchange between the street furniture along the fiber-based 6G infrastructure and road-side vehicles can be supported through multi-Gb/s/user V2I OWC employing pencil-beam schemes. In such a setting, alignment-tolerant reception is considered a main implementation challenge.

Pencil-beam OWC systems are typically sourced by coherent light emitters to ensure a good beam quality when forming the beam. Suitable optical antenna designs, whose antenna elements operate in the 182-238 THz range and are spaced by just a few to tens of µm, enable the generation of very narrow beams with exceptionally small (few mrads) divergence. At the same time, tunability and agile steering are provided through electro-optic feed control for all constituent antenna element. There are various implementations for optical beamformers, building on concepts such as optical phased arrays [13] or focal plane arrays (FPA) [14]. The FPA features a simple architecture that can operate with rather simple control and does not require phase calibration, making it an attractive candidate for low-cost OWC applications. Pencil-beam V2I links then employ chip-scale beamformers at the mobile user and the remote radio head (RRH) to provide a transparent fiber-grade pipe between the vehicular user and the 6G network.

An example for an FPA beamformer is shown in Fig. 6. Here, a photonic lantern with multiple hexagonally-arranged single-mode fiber cores over its cross-section acts as the optical antenna, with the location of the cores determining the offset from the center of the beam-collimating lens that completes the overall optical antenna, and thus the emission angle of the OWC beam. By provisioning a high number of cores, the emission angle can be finely tuned, which together with a slightly widened beam ensures coverage within the field-of-illumination. Several options can be exhausted to “tune” the FPA, including space or wavelength switching for the light source that feeds the FPA, while multiple feeds can generate tailored beam profiles specific to the application.

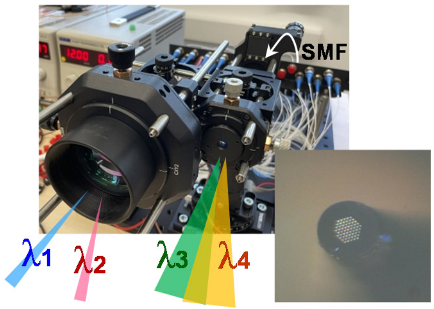

Fig. 6. Remote radio head setup for V2I OWC, including a photonic lantern as optical antenna (inset) for the lens that defines the focal plane of the optical radio head. The wideband nature of the single-mode fiber (SMF) feed enables beamsteering at multiple wavelengths λ_i, serving different users and/or OWC beam profiles.

Moreover, the spectral wideband support of standard ITU-T G.652B-compatible single-mode fiber (SMF) technology between 1260 nm and 1650 nm allows us to combine simultaneous pencil- and wide-beam OWC to further support communication-independent pointing, acquisition and tracking of mobile road-side users, following a make-before-break notion for their hand-over. O- to L-band support further provides sufficient spectral resources to accommodate multiple independently switched beams dedicated to multiple individual network users.

The characteristics for a space-switched FPA architecture [15] are exemplarily reported in Fig. 7, which shows the received power profile for 32 connected optical antenna elements upon reception of a pencil-beam subject to an angle of arrival $\alpha > 0$ sourced by a 10 Gb/s directly modulated laser at the opposite OWC link end. The received power is coupled off the center of the optical antenna lens (denoted as core ‘1’ in Fig. 7), meaning that for an optical RRH without support for beamforming it would not be possible to receive any signal. For the FPA beamformer, however, the data can be fully recovered from the signal received at core 27. This is shown in terms of signal-to-noise ratio (SNR), which improves by 16 dB and eventually renders OWC despite sub-optimal beam launch conditions ($\alpha \neq 0$) as still accomplishable. The corresponding open 10 Gb/s eye diagram appended to Fig. 7 evidences the high SNR.

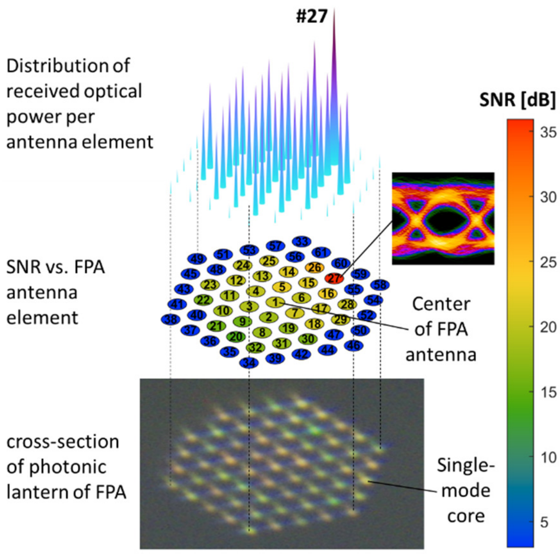

Fig. 7. Reception of an OWC pencil-beam signal under an angle of arrival, as it would correspond to a V2I OWC scenario with sub-optimal coupling. The signal can be recovered off the center (antenna element #1) of the optical antenna, through antenna element #27.

VI. Fi-Wi-Fi Bridge Ensuring Fiber-Grade 6G Continuity Through I2I OWC

OWC can further assist I2I connectivity by linking 6G network segments in fiber-scarce scenarios. In such a case, a low-loss interconnect between two SMF-based demarcation points needs to be established by means of free-space optical (FSO) communication. These free-space bridges are typically bound to complexity and thus cost, since they require active means of pointing, acquisition and tracking [16] – mostly implemented through opto-mechanics [17]. The availability of FPA-based RRHs can greatly simplify the involved air interfaces. Placing FPAs in a face-to-face configuration with coarse initial pointing enables the OWC system to minimize its losses without involving mechanically moving parts. In this way, a long-term stability of the OWC link between two single-mode ports can be guaranteed.

The setup for such a Fi-Wi-Fi bridge for evaluation in an out-door environment is sketched in Fig. 8. The corresponding histogram for the received optical power (ROP) over a free-space transmission distance of 63 m is appended to Fig. 8 and proves the low spread in end-to-end coupling loss across the bridge: For a measurement period of slightly more than 8 hours, the coupled power over the out-door bridge shows a peak-to-peak deviation of 4.1 dB for 95% of data points. Moreover, the coupled power provides a sufficiently high margin for high-data rate transmission. Towards this direction, OOK transmission at 10 Gb/s/λ (see eye inset in Fig. 8) showed no spurious artifacts or power drops deriving along the out-door Fi-Wi-Fi bridge.

As the fiber continuum is extended by virtue of the good coupling efficiency, so is its potential capacity. The availability of an OWC-based Fi-Wi-Fi bridge thus alleviates the 6G infrastructure from an early termination of the lightpath, thus ensuring transparent fiber-grade connectivity till the very last meter of the 6G network, close to the far edge.

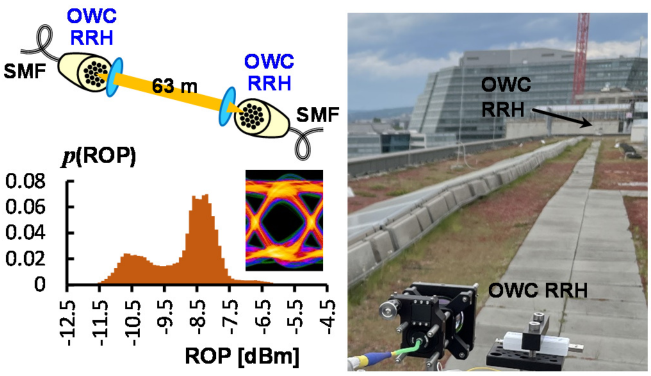

Fig. 8. OWC for I2I connectivity, featuring a Fi-Wi-Fi bridge furnished by FPA beamformers as air interfaces between single-mode fiber ports. The histogram shows the spread in coupled power for a long-term measurement over more than 8 hours, indicating a good coupling efficiency suitable for high-data rate transmission.

VII. Connected RaDAR/LiDAR Technologies

The abovementioned JCAS is gaining momentum as it reduces hardware costs and can be adopted for a broad application range [18]. Allowing both sensing and communication functions will yield more efficient wireless systems concerning their use of spectrum and their mobilisation of hardware and information processing resources. Many important applications in 5G and beyond (6G) such as autonomous vehicles, Wi-Fi sensing and extended reality, require both high-performance sensing and wireless communications [19]. Within this context, LiDAR and RaDAR devices are of high interest due to their non-contact ranging solution based on free-space propagation, and are widely used in many advanced applications, including autonomous vehicles, robotics, smart cities and security.

However, up to now, there are limited or no demonstrators of JCAS LiDAR devices, though research has already focused on the application of LEDs for V2V visible ranging and communicating applications [20]. This serves as a reference for future JCAS developments in more complex systems such as LiDAR devices, which are nowadays becoming more available yet remain primarily dedicated to imaging and sensing. LiDAR-integrated FSO communications can be accomplished involving flash-like pulsed emission or modulation of a continuous wave [21-23].

Furthermore, RaDAR has been suggested as an additional JCAS technology [24]. Despite the lower resolution, radio signals offer a suitable foundation for system architecture, signal processing, and the design and optimization of the employed waveforms. While it is not an optical technology, it serves as a convenient platform for the initial implementation of advanced techniques such as multiple-input/multiple-output (MIMO) concepts, which are later adopted in LiDAR implementations [25].

RaDAR is considered a crucial component in the overall detection system of autonomous driving, along with cameras and LiDAR [26-33]. It plays a crucial role in determining the distance to objects captured by cameras and in detecting other vehicles or obstacles under challenging weather conditions, such as heavy rain or fog. During such circumstances, cameras and LiDAR experience a significant decrease in their efficacy, or may even become completely ineffective.

The latest 5G standards have already suggested utilizing 5G networks to provide support for user localization. The 5G Rel-17 specification [34] aims to achieve a horizontal positioning accuracy of less than 1 m for 90% of User Equipments (UE) in commercial use-cases, and less than 0.2 m for 90% of UEs in Industrial Internet-of-Things (IIoT) applications. Additionally, it sets a vertical localization requirement of less than 3 m for 90% of UEs in commercial use-cases, and less than 1 m for 90% of UEs dedicated to IIoT.

As standards for 5G are progressing towards JCAS, RaDAR can also have a significant impact on JCAS applications for vehicles that are driving in areas where 5G coverage is not available. Similarly, just as OWC is being suggested to assist upcoming 6G networks that need to manage vast quantities of sensor data, RaDAR can also play a significant role in supporting optical JCAS technologies such as LiDAR, by offering fully complementary capabilities.

VIII. Outlook and Future Directions

The advent of chip-scale optical beamformers is seen as a critical step to enable V2I communications. In addition, these beamformers are paramount for LiDAR-based systems, which in a wider application setting can propel cost-reduced JCAS technologies for future autonomous driving.

The high optical budgets inherent to optical non-line-of-sight communication will undoubtedly require coordinated OWC / cellular-V2X schemes, where simplified short-reach (sub-)mm-wave links enhanced by frequency-/phase-agnostic photonic up-conversion techniques supported through the xhaul segment can be a viable option. OWC indirectly supports this scenario by reducing EMI in such a scenario, since the entire line-of-sight communication can be handed over to the optical domain, thus clearing out the RF spectrum from any interrelated cross-talk or congestion.

Robustness to unfavourable weather conditions (such as dense fog) over longer reach would require the adoption of mid- (and far-)infrared OWC [35], for which first electro-optic components such as directly modulated quantum-cascade lasers and photomultipliers have been demonstrated [36]. These presently yet cost-ineffective mid-infrared transceivers can be blended with the earlier introduced concepts following a dual-band scheme, especially for critical V2I OWC links such as required to connect vehicles to the edge cloud.

Acknowledgement

This work has received funding from the Smart Networks and Services Joint Undertaking (SNS JU) under the European Union's Horizon Europe research and innovation programme under Grant Agreement No. 101139182.

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