Information Revealed by Vision: A Review on the Next-Generation OCC Standard for AIoV

Nhu-Ngoc Dao, Trong-Hop Do, Sungrae Cho, and Schahram Dustdar

***Abstract*—The artificial intelligence of vehicles (AIoV) paradigm defines an AI-empowered computational and communication platform in which vehicles, pedestrians, roadside units, and network infrastructures interact with each other to fashion transportation ecosystems. However, the communication technologies that are currently available continue to be plagued by practical problems such as high-cost implementation and upgrade, thereby constraining this development. In this regard, optical camera communication (OCC) is emerging as a promising technology with excellent compatibility. In particular, OCC utilizes the light sources and cameras that are already incorporated with existing devices to act as transceivers, obviating the need for additional specialized hardware. In this article, we describe the current status of OCC standardization and applicable AIoV scenarios. Then, the characteristics of OCCs are analyzed, including channel modeling, adaptive modulation, region-of-interest anchoring, and image enhancement. Finally, open challenges are presented to drive future research on improving OCC performance realizing the AIoV paradigm.**

***Index Terms*—Intelligence of vehicles, intelligent transportation system, optical camera communication**

I. Introduction

A. Intelligence of Vehicles

Recent years have witnessed an increase in the development of Internet of Vehicles (IoV) toward intelligent transportation systems (ITSs). However, the integration of Internet capability is considered insufficient to promote the rapid evolution of these systems. In other words, realizing the maturity of ITSs requires all transportation components such as vehicles, pedestrians, roadside units, and network infrastructures to be connected via an artificial intelligence (AI)-empowered ubiquitous platform with both computational and communication abilities. Such a paradigm defines the next generation of IoV, a.k.a. the AI of vehicles (AIoV) [1].

AIoV paradigms constitute the exploitation of AI technologies to improve the performance of ITSs, especially in terms of user experience and safety. In the AIoV paradigm, vehicle-centric communications are envisioned to not only support efficient autonomous driving but also to actively absorb as much information from the surrounding environment as possible to meet user service requirements. Enriching knowledge by actively absorbing information is critical to guarantee user experiences and safety in ITSs because this approach significantly reduces communication overhead and latency. Although most available wireless technologies can disseminate information through multicast and broadcast transmissions, they do not offer affordable implementation or upgrades, which is especially problematic with respect to backward compatibility with low-tech vehicles.

B. Optical Camera Communications

Motivated to address the aforementioned practical problems, optical camera communication (OCC) technologies are emerging as out-of-the-box solvers. OCCs utilize the existing light sources and cameras on the devices to act as transceivers and thus have no additional specialized hardware requirements [2]. The transmitters are detected using computer vision techniques to analyze the images captured by the cameras. Meanwhile, information such as the intensity, on-off states, frequencies, and phases, are encoded in the characteristics of the light, and this information is subsequently recognized by the image sensor of the cameras. In layman's terms, OCCs are software-based solutions that enable vehicles to reveal information based on what they visually perceive in their surroundings. With this distinctive feature, OCCs have been proven potential to support application in multiple AIoV scenarios [3]. Several reviews on OCCs from various perspectives have been conducted in [2]–[5] to investigate current advancements and applicability of the technologies. However, a dedicated investigation on the next-generation OCC standard for AIoV was out of the focus. Especially, a comprehensive understanding of novel characteristics of the next-generation OCC and their exploitation to efficiently serve AIoV applications is of importance.

From a technological perspective, OCC and emerging wireless vehicular communications, such as dedicated short-range communications (DSRC) and cellular vehicle-to-everything (C-V2X) are not in conflict but complement each other [6]. Specifically, DSRC and C-V2X operate at radio frequencies, whereas OCC exploits the optical spectrum. Regarding the base technologies, DSRC, C-V2X, and OCC have been developed on the basis of Wi-Fi, cellular, and optical wireless communications (OWC), respectively. As a result,

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TABLE I
COMPARISON OF DIFFERENT TECHNOLOGIES FOR AIOV COMMUNICATIONS.

Criteria	**DSRC**	**C-V2X**	**OCC**
Reference standards	IEEE 802.11p/bd	3GPP Release 14/15 (LTE C-V2X) and 3GPP Release 16 (5G NR V2X)	IEEE 802.15.7-2011/-2018/a
Base technology	WiFi	Cellular	OWC
Frequency	5.9 and 60 GHz	Cellular sub-6 and mmWave	IR, VL, and UV (300 GHz–30 PHz)
Bandwidth	40 MHz	400 MHz (CC)	Hundreds of MHz
Transceiver	RF antenna	RF antenna	Tx: LED and screen Rx: Image Sensor
Modulation	Up to 256-QAM OFDM	Up to 256-QAM OFDM	OFDM, OOK, PPM, PSK, etc.
Interference	Higher	Higher	Lower
Distance	Hundreds of meters	Up to thousands of meters	200 m
Data rate	Hundreds of Mbps	Up to Gbps	Up to 100 Mbps
Latency	3–100 ms	3–100 ms	< 100 ms
Reliability	99–99.999 %	99–99.999 %	90–99 %
Mobility	500 km/h	500 km/h	350 km/h
Localization	Meters	Meters	Centimeters
Safety of human body	Lower	Lower	Higher
Implementation cost	Higher (hardware installation)	Higher (hardware installation)	Lower (software installation)
Compatibility	Lower (new hardware requirements)	Lower (new hardware requirements)	Higher (software updates)
Applications	Automated driving assistance, aerial transportation, basic safety messages, observed information sharing, in-car infotainment, low latency service offloading, service and information localization, etc.	Automated driving assistance, aerial transportation, basic safety messages, observed information sharing, in-car infotainment, low latency service offloading, suburban and rural transportation, etc.	Automated driving assistance, basic safety messages, observed information sharing, service and information localization, vehicle-to-vehicle (V2V) communication, indoor 3-D positioning and navigation, aerial traffic monitoring, etc.

Abbreviation—3GPP: the 3rd Generation Partnership Project; IEEE: Institute of Electrical and Electronics Engineers; IR: Infrared Radiation; LED: Light-Emitting Diode; LTE: Long-Term Evolution; NR: New Radio; OFDM: Orthogonal Frequency-Division Multiplexing; OOK: On-Off Keying; PPM: Pulse Position Modulation; PSK: Phase Shift Keying; QAM: Quadrature Amplitude Modulation; RF: Radio Frequency; UV: Ultraviolet; VL: Visible Light.

their communication characteristics, including carrier bandwidth, modulations, access schemes, interference levels, and propagation models, are distinct from each other. Regardless the implementation cost, DSRC and C-V2X have been considered more potential for unicast and bidirectional services whilst OCC is more suitable for multicast/broadcast and unidirectional services. A comprehensive comparison of the mentioned technologies is presented in Table I. Notably, OCC technologies have unique advantages in terms of their larger bandwidth at a higher spectrum, lower interference, line-of-sight (LoS) propagation, harmlessness to the human body, lower implementation cost, and higher compatibility, compared with other technologies.

C. Standardization Milestones

OCCs have been developed and managed as members of the family of optical spectrum standards by the Institute of Electrical and Electronics Engineers (IEEE) Standards Association, and released under the official name IEEE 802.15.7-2018 [7], which is a revision of the original IEEE 802.15.7-2011 standard for VLC. The IEEE 802.15.7-2018 standard has successfully specified foundational concepts and techniques at the physical (PHY) and medium access control (MAC) layers of OCCs. In particular, five novel PHY modes were proposed along with their specific modulation schemes to facilitate different service categories. Among them, three PHY modes (IV, V, and VI) based on image sensors are considered appropriate for vehicular communications [8]. In particular, the IEEE 802.15 Working Group has recently initiated Task Group 7a to produce an amendment to IEEE 802.15.7-2018. The envisioned strategic majors are to exploit the advantages of multiple-input multiple-output (MIMO) transmissions and AI techniques for the next-generation OCC optimization to increase the data rate (to as high as 100 Mbps), long-range transmission (to as far as 200 m), and high mobility (to as fast as 350 km/h), mainly focusing on promoting AIoV scenarios toward the age of ITS.

II. ENABLING AIOV PARADIGMS USING THE NEXT-GENERATION OCC

The potential incorporation of the next-generation OCC in the AIoV paradigm is a manifold for emerging scenarios. Primary examples consist of bidirectional communications (e.g., V2V and vehicle-to-infrastructure (V2I) communications) and unidirectional communications (e.g., indoor 3-D positioning, navigation, and aerial traffic monitoring), as illustrated in Figure 1.

Bidirectional communications: As the transmitter (the light sources) and the receiver (the image sensors) are typically separate and located in different positions on devices, mutual communication channels require two pairs of these components to be inversely equipped on both sides for transmitting and receiving data in OCC. For instance, V2V communications consist of two directional links (taillights of the car

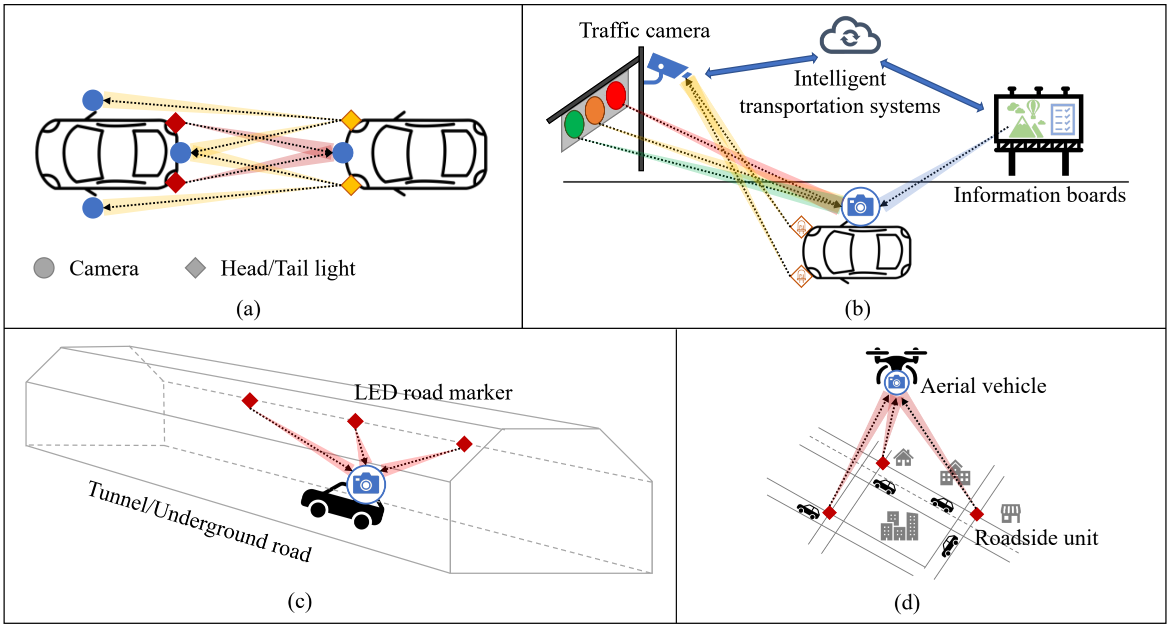

Fig. 1. Emerging scenarios of the next-generation optical camera communications in the AIoV paradigm: a) V2V communications; b) V2I communications; c) Indoor 3-D positioning and navigation; d) Aerial traffic monitoring.

ahead → front cameras of the car behind) and (headlights of the car behind → mirror mounted and rearview cameras of the car ahead); see Figure 1(a). In V2I communications, the head- and taillights of cars transmit data to roadside networking infrastructures via traffic cameras designed to monitor these light sources, whereas messages delivered from the networks to cars are carried on the links between traffic lights and car-mounted cameras (see Figure 1(b)). These communications augment and complement existing services such as road illumination, driving indication, and traffic monitoring, and they additionally offer environmental details to enhance vehicle security, driver and passenger safety, and convenience.

Unidirectional communications: Bidirectional OCC topologies are relatively complicated, whereas unidirectional OCCs are considered to be based on a simple transmission scheme. In unidirectional OCCs, the transmitters frequently encode information bits containing characteristics of the light emitted by light sources regardless of acknowledgment of receipt, and the receiver cameras freely capture and extract information on demand. By demonstrating excellent localization accuracy of the order of centimeters, unidirectional OCCs substantially assist cars with indoor 3-D positioning and navigation services by combining the coordinates of LED road markers in proximity. This feature is especially useful in the case of tunnels or underground roads and in parking garages in modern cities, as shown in Figure 1(c). For traffic monitoring purposes, aerial vehicles are deployed on a predefined trajectory to periodically collect traffic reports from dedicated roadside units at particular locations (see Figure 1(d)). To summarize, OCCs facilitate the extension of knowledge about the driving conditions of vehicles by obtaining and sharing the information these vehicles visually detected.

III. The Next-Generation OCCs

A. *Learning-based Channel Model*

As information is modulated by symbols representing pixel attributes such as transparency and color values (e.g., red/green/blue/alpha–RGBA), the pixel signal-to-noise ratio (SNR) is used as a metric to evaluate the quality of communication channels in OCC. Based on the definition of the pixel SNR in the IEEE 802.15.7-2018 standard [7], the pixel SNR is proportional to the amplitude of the light frequency and the relative camera exposure time during a sampling period. In other words, adaptively adjusting the illumination and exposure time according to particular environmental conditions is of great importance for obtaining the desired pixel SNR. In this regard, AI technologies have recently been increasingly used to refine theoretical channel models and algorithms for optimizing wireless communications. Suppose that environmental conditions (e.g., the weather and ambient light) are observed using local sensors, then AI techniques could be utilized to fine-tune the noise coefficients of the channel model, increase the accuracy of light source detection, determine appropriate modulation schemes, and improve demodulation error correction [9], [10]. It is worth noting that, even under similar environmental conditions, channel optimization distinguishes between downlink and uplink communication in bidirectional communications owing to the different spatiotemporal capabilities of their transceivers.

B. *Enhanced Cooperative MIMO*

As the single-channel data rates (in Mbps) provided by the current OCC standard (i.e., IEEE 802.15.7-2018) are typically insufficient to serve multimedia infotainment services in the AIoV paradigm, AI-enhanced cooperative MIMO technologies are considered an effective solution to improve the communication throughput multifold. Practical AIoV scenarios utilizing cooperative MIMO are presented in Figure 1(a) and 1(b), where both the cars and the ITS infrastructure are equipped with various sources of light and cameras. Cooperative MIMO exploits the benefits of distributed transmitters and receivers in macro-diversity (e.g., the different cameras mounted on cars) as well as micro-diversity (e.g., the different LEDs in the head light of a car) to significantly improve the communication capacities [11]. Here, cooperative multiple-input single-output (MISO) and single-input multiple-output (SIMO) are considered special cases of cooperative MIMO applications.

The current OCC standard has successfully demonstrated the reliable performance of MIMO in terms of micro-diversity with spatiotemporal modulations (e.g., twinkle variable pulse position modulation, Twinkle VPPM, and hybrid spatial phase shift keying, HS-PSK) [8]. The the next-generation OCC in IEEE P802.15.7a aims to exploit and enhance the MIMO in macro-diversity using emerging AI techniques in two ways. First, low-frame-rate cameras utilize deep learning techniques in light source detection and tracking to capture control and management flows as well as redundancy messages for error correction [12]. High-frame-rate cameras concentrate on demodulating the main data streams from the tracked light sources using the redundancies provided by the low-frame-rate cameras. Second, novel spatiotemporal modulations and scheduling schemes can be developed to exploit the correlations between different communication channels to adaptively transmit data [13]. The former and latter strategies complement rather than conflict with each other.

C. Automatic Modulation Decision

In most wireless communication systems, optimal modulation schemes are decided by using negotiation procedures or automatic recognition by the receiver. As IEEE 802.15.7-2018 does not cover modulation decision methods, automatic recognition is preferred owing to its appropriateness for directional communications. Although the current OCC standard allows a shortlist of effective modulation schemes that correspond to different PHY modes (e.g., the on-off keying (OOK), VPPM, and HS-PSK) [8], selecting the optimal modulation under particular circumstances remains an open challenge. The latency of modulation recognition significantly impacts the system capabilities, especially in terms of throughput and mobility support.

However, IEEE P802.15.7a envisions novel approaches toward automatic modulation decisions at both transmitters and receivers. In collaboration with the enhanced cooperative MIMO, a dedicated pilot light source is assigned to transmit control messages, informing modulation schemes of every transmitter that has been identified. In this regard, deep learning techniques can provide robust detection performance for detecting pilot light sources and transmitters [14]. In practice, reinforcement learning may assist transmitters in deciding optimal modulation schemes by jointly considering observed environmental coefficients and data traffic features.

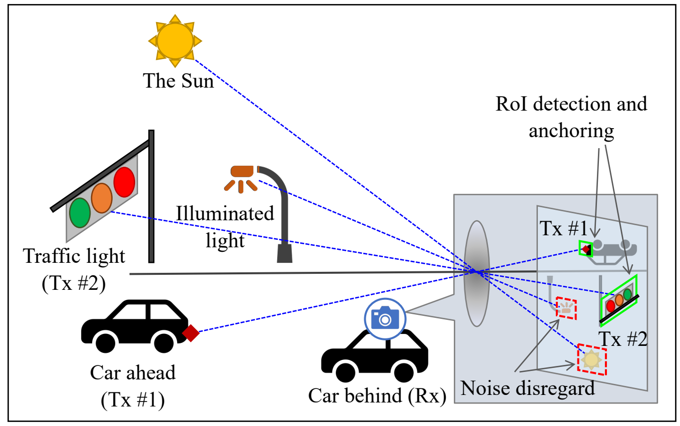

Fig. 2. RoI detection and anchoring in the next-generation OCC.

D. Region-of-Interest Anchoring

The region-of-Interest (RoI), a well-known concept in computer vision, defines the borders of a specific area in an image under consideration for a particular purpose. In OCC, the RoI includes the light source by selecting a sufficient number of pixels (i.e., an RoI of sufficient dimensions) to represent the transmitter. As OCC incorporates cooperative MIMO and simultaneous transmissions, multiple RoI elements may exist in consecutive image frames. Hence, effective RoI detection and anchoring are crucial for improving the communication performance from several perspectives, such as stably maintaining communication channels, eliminating noise from ambient light, minimizing pixel processing overhead, and reducing the demodulation latency [12]. In addition, accurate RoI anchoring results are required to enable location-based services in AIoV paradigms, such as augmented reality and directional sounds. Figure 2 illustrates a scenario of RoI detection and anchoring for vehicles traveling on the road.

Experimental studies [12], [14] revealed that a low frame rate (e.g., 40–50 fps) is sufficient to detect and anchor RoI elements within a highway scenario (approximately 60 km/h) in real time. To accommodate mobility as high as 350 km/h, as targeted by IEEE P802.15.7a, advanced motion tracking techniques can be exploited to assist with the RoI anchoring operation. In this regard, deep learning and neural networks may provide reliable training facilities to efficiently predict RoI motions. For instance, the rapid evolution of the You Only Look Once (YOLO) platform with the latest version, YOLOv3, and its variants such as YOLOv4 and PaddlePaddle-YOLO based on parallel distributed deep learning (PP-YOLO) is increasingly delivering high performance in terms of fast and accurate real-time object detection.

E. Simultaneous Multirate Transmission

To achieve simultaneous multirate transmission, IEEE P802.15.7a enables various channel coding and modulation schemes for processing separate RoI elements. Recently, pioneering studies [14] proved the feasibility of simultaneously transmitting low-rate vehicular identifications and high-rate data streams by two separate LED arrays. In particular, low-rate stream coding and AI-based error-correction methods are utilized in these two OCC channels. Accordingly, the RoI elements that contain the light from these LED arrays were detected and anchored via the same image frames at the receiver cameras. The light attributes of the LEDs were extracted and demodulated to reveal the information. Notably, a cooperative MIMO architecture can orchestrate multiple cameras with different frame rates to provide flexible adaptive multirate transmission capabilities. In this context, the OCC channels can be dedicated to specific services or aggregated into the system throughput capacity.

F. Image Deblurring

Blurriness is considered an inevitable problem when a LED image is captured on the road. The image is corrupted by several blur kernels (e.g., Gaussian white noise radiating from ambient light sources such as the sun and illuminated streetlights) and spatially variant kernels (e.g., the motions of RoIs and cameras). As the image quality directly and significantly impacts the demodulation efficiency in OCC, image enhancement is critical to improve the channel throughput. In this regard, to mitigate the blurriness, image-deblurring techniques are used to determine the blurring behavior and effects to resharpen the image. In the IEEE 802.15.7-2018 standard, a pixel noise model was developed by assuming Gaussian white noise and for SNR calculation. However, such a theoretical estimation faces several constraints to represent the complex effects of real scenarios. Hence, IEEE P802.15.7a anticipates the development of advanced methods based on machine learning to adequately process real-world blurry LED images. In particular, deep learning methods, especially convolutional neural networks (CNNs) and generative adversarial networks (GANs), have achieved remarkable success in this field [15]. Blurriness is mimicked by comparing blurry and sharp versions of the original LED images under various environmental conditions. Conversely, the deblurring process recovers sharp LED images from the captured images and blurriness training. Such image enhancement significantly mitigates the noise in OCC channels, resulting in improvements in demodulation accuracy [16].

IV. Open Challenges

Link blockage: Most of the reported OCC studies were concerned with LoS transmission [17]. However, the stability of LoS propagation from light sources to cameras varies owing to link blockages caused by object movement and obstruction. For instance, vehicles moving into road corners and crossroads may lose their vision within the field of view of the camera to vehicles traveling in the opposite direction and roadside units because of trees, buildings, and traffic congestion. In such cases, the optical attributes and image integrity sensed by the receiver cameras would decrease dramatically, resulting in significant OCC performance reduction. The next-generation OCC would have to detect link blockage problems early and estimate their negative effects by using environmental proximity learning. Consequently, the OCC parameter configuration and vehicle movement control can be appropriately adapted to optimize the communication performance.

Light source density: As cooperative MIMO and simultaneous multirate transmission are envisioned for the next-generation OCC, fast RoI detection even in complex scenarios is a must-have technique to efficiently anchor multiple light sources throughout a series of captured contiguous images. The detection complexity is proportional to the light source density, including noise in the image, which consequently affects the detection accuracy and latency. Improving the RoI detection performance in dense scenarios with potential light sources and ambient light is a significant challenge for the next-generation OCC to yield a high data rate and communication reliability. Although emerging AI-based image processing technologies have recently had impressive successes, several problems relating to these advanced technologies would still have to be solved to enable OCC to be employed toward AIoV paradigms. Examples thereof are the tradeoff between performance and resource consumption, as well as maintaining a balance between detection accuracy and latency.

Modulation efficiency: Although the next-generation OCC intends to standardize novel automatic modulation decision techniques by using deep reinforcement learning, there are still several obstacles in the way of achieving this target. First, the high mobility requirements of the new OCC standard may generate unexpected noise and blurry effects on the images captured by the receiver cameras. Consequently, pixel attributes may not be accurately discovered, resulting in possible high bit error rates and, therefore, a reduction in the modulation efficiency. Second, joint micro- and macro-diversity exploitation assisted by cooperative MIMO for spatiotemporal modulations is considered a complex procedure that requires significant research attention to address various technical problems such as synchronization between transmitters and receivers, transmission schedule, control overhead, resource consumption, and modulation latency.

Security and privacy: Notwithstanding the fact that these concerns are not major targets of the next-generation OCC, V2V and V2I communication in the AIoV paradigms should be protected and secured. The difficulties associated with the secure and private deployment in OCC have their origins in the initial synchronization between transmitters and receivers to negotiate authentication and generate secret keys. In addition, a clear vision of the information obtained from every camera within the field of view makes it vulnerable to man-in-the-middle eavesdropping in silence. Furthermore, OCC channels may be easily attacked by jamming signals from high-intensity ambient light in the proximity of the transmitters. These critical issues need to be addressed to secure the success of OCC.

Reliable simulation tools: Performance evaluations in previous OCC studies were mostly designed using either real experiments or general communication simulation platforms such as MATLAB and NS3. Although real experiments can provide real observations to prove the practical applicability of the research, these evaluation methods require supportive dependencies, such as setups based on the environmental conditions and experimental consistency. These factors may have introduced bias in the observations. Moreover, time and resources are consumed to develop experiments, as required by the studies. Apart from this, general communication simulation platforms may not offer sufficient infrastructure and facilities to characterize OCC, as expected. These limitations of both the aforementioned evaluation methods imply that reliable standard simulation tools for OCC are urgently required.

V. Concluding Remarks

The aim of this article is to provide engineers and researchers in the field with cutting-edge knowledge regarding the latest developments in OCC. The potential of the next-generation OCC to realize AIoV paradigms was comprehensively analyzed. First, multiple criteria are connected with each other to distinguish the unique features of OCC for AIoV communications compared with related technologies, such as DSRC and C-V2X. Moreover, OCC standardization strategies and enabling technologies were presented to clarify the technical feasibility of achieving the targets set by the standard. Open challenges were then drawn to direct future research on the next-generation OCC maturity. Despite several obstacles that would need to be overcome, the next-generation OCC could be considered a complementary solution to efficiently promote and accelerate AIoV realization in upcoming years.

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