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Overview of Vehicle Optical Wireless Communications

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ABSTRACT Effective information transmission between vehicles has become one of the solutions to improve road safety. Based on the huge advantages of optical wireless data transmission technology, this article summarizes the research status of unmanned vehicles in optical wireless communication (OWC). The article not only studies the actual progress of building optical links through an unmanned vehicle, connecting air communication, ground communication, underwater communication into a unified wireless network, and realizing the fast, stable, large-capacity data transmission system. The technical challenges of unmanned vehicle OWC are also discussed and its future development has prospected.

INDEX TERMS Optical wireless communications, communication and networking, unmanned aerial vehicles, ground operated vehicles, autonomous underwater vehicles.

I. INTRODUCTION

A. OPTICAL WIRELESS COMMUNICATION TECHNOLOGIES

For many years, wireless optical data transmission technology has been a research hotspot in the field of optical wireless communication (OWC), whether air or vacuum, data are transmitted by light. OWC technology has many advantages over radio frequency (RF) communication technology. For the time being, the use of optical wireless does not require authorization, reducing costs, relieving the pressure on RF spectrum resources. Also, due to the characteristics of optical wireless line of sight (LOS) transmission, there are no problems such as resource allocation, hidden terminal, multipath in traditional wireless, which can guarantee the low delay and reliability of communication under the condition of high-density users [1], [2]. In different application scenarios, OWC has different names, and the method of transmitting data through light-emitting diodes (LEDs) is called visible light communication (VLC). VLC technology can not only provide indoor users with green lighting and high-speed wireless coverage. At the same time, OWC technology has also made great progress in outdoor scenes. As shown in Fig. 1, unmanned vehicles can be roughly divided into air unmanned aerial vehicles (UAVs), ground operated vehicles (GOVs) and autonomous underwater vehicles (AUVs) based on different spatial positions of unmanned vehicles. Optical wireless technology plays a unique role in UAV real-time monitoring, emergency support, wireless coverage, building smart cities based on vehicles, and wireless sensing arrangement on the seafloor.

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B. VEHICLES OPTICAL WIRELESS COMMUNICATIONS

1) UNMANNED AERIAL VEHICLES

UAVs are widely used in civilian applications because of their ease of deployment, low cost, high mobility, and hover ability [3]. Such as real-time monitoring of road traffic, providing wireless coverage, remote sensing, search and rescue operations, cargo delivery, security and surveillance, precision agriculture and civil infrastructure inspection [4]. It is worth considering that the irregular use of UAVs will bring huge security risks. The application of UAV in supporting public safety communication will be affected by privacy communication technology and the frequency band range of public safety technology used in the United States, the author of [5] has a strict discussion on the above issues. Based on the above conclusions, the authors propose features and requirements for prospective civil applications of UAVs from a communication and network perspective between 2000 and 2015 [3]. They investigate quality-of-service requirements, network-related mission parameters, data requirements, and the minimum amount of data transmitted over civilian networks. They also discuss general network-related requirements such as connectivity, adaptability, security, privacy, security, and scalability. Finally, they presented the experimental results of several projects and investigated the applicability of existing communications technologies to support reliable air networks. In [6], the authors provide a comprehensive study of the use of wireless networks. They looked at two main uses of UAVs: airbase stations and cellular connection users. In most cases, they pose key challenges, applications, and basic open questions. Besides, they describe the mathematical tools and techniques needed to meet the drone challenge, as well as the analysis of the UAV enabled wireless networks. In [7], the authors provide a comprehensive air-to-ground channel measurement survey, including large- and small-scale fading channel models, limitations, and future research directions for UAV communication scenarios. In [8], the authors provide a survey of the use of low-altitude platforms for UAV channel modeling and discuss the efforts of various channel characteristics. In [9], the basic network structure and main channel characteristics of UAV-assisted wireless communication are introduced. They also highlight key design considerations and new opportunities to explore. Second, in terms of energy and deployment, the authors focus on routing, seamless switching, and energy efficiency. First, they distinguish between infrastructure and networks, between applications where the drone acts as a server or client, between star or Mesh UAV networks, and whether the deployment is enhanced by delays and outages. Then, the main problems of routing, seamless handoff, and energy efficiency in the UAV network are studied.

However, considering the high-speed data interaction of UAVs, RF technology cannot fully meet the high-speed communication requirements of UAVs because of the limitations of capacity, interference, confidentiality and spectrum resources. Based on the advantages of OWC, the authors propose to combine the wireless optical communication technology with UAV to ensure high-speed information transmission. In [10], researchers describe the research status and progress of optical wireless communication technology based on UAVs platform, and classifies and analyzes the relationship between UAVs and ground terminals, and between UAVs, there are many technical challenges in achieving reliable and high-speed Optical wireless links between UAV and satellite.

2) GROUND OPERATED VEHICLES

Since Carl Bentz invented it more than 130 years ago, cars have taken a big leap forward. Smart cars, especially those with driverless ones, are receiving unprecedented attention. Wireless communication technology is a key driver of this development. As early as 1992, the American Society Testing Materials (ASTM) proposed dedicated short-range communication (DSRC) to enable external communication of vehicles [11]. In the 21st century, RF communication has developed rapidly. For DSRC technology, which can only be used for short-range communication, people begin to study and use RF technology for vehicle network communication [12]. Traditional RF wireless in-vehicle networks include Wi-Fi networks, IEEE 802.11p networks, and cellular vehicle networks. RF communication technology is characterized by limited wireless bandwidth, high cost and a serious shortage of spectrum resources [13]. As a result, low-cost, low-latency, high-reliability wireless communication technology has become an urgent need for vehicle communications. In the face of this situation, OWC is becoming a promising complementary technology for communication. The technologies of DSRC, 5G and OWC were evaluated in the above, and the advantages and disadvantages of the above communication technology were elaborated, and the solutions were put forward for the existing problems. On the other hand, LEDs are widely used in infrastructure construction, such as traffic lights and street lights. At the same time, the automotive industry is increasingly using LEDs in taillights, headlights and brake lights. Taken together, these two trends open up the possibility of OWC's application in Intelligent Transport Systems (ITS) [14]–[17]. There is no doubt that the demand for wireless capacity will grow more than tenfold over the next five years, thanks to the proliferation of mobile devices and the Internet of Things (IoT) [18]. Using OWC technology can increase the possibility of vehicle-to-vehicle communication (V2V) and vehicle-to-infrastructure (V2I) [19].

3) AUTONOMOUS UNDERWATER VEHICLES

The mysterious underwater field has always attracted experts and scholars to explore, and the harsh underwater environment of information transmission is an important factor that prevents ocean exploration from falling far behind land and even space exploration. Sometimes the use of underwater cables seems to be the only viable means of underwater communication. However, such wired solutions often require complex and expensive wet joints. These connectors, especially in deep water, are usually installed by one or more remotely operated vehicles (ROVs), which must be carefully controlled by trained operators on the mothership. Therefore, the deployment and maintenance of wired underwater communication system is a time-consuming and laborious task.

On the other hand, underwater wireless communication has attracted more and more attention due to its high scalability and flexibility. Due to the low attenuation of acoustic waves in water, acoustic wireless links are traditionally the main

FIGURE 1. Automotive optical wireless communication application scenarios.

choice [20]. However, they are essentially bandwidth-limited, have large time widths and a large number of antennas. Underwater optical wireless communication (UOWC) can also use electromagnetic induction and RF electromagnetic waves. At present, the bandwidth and link distance that can be realized in conductive seawater are still very limited, especially in the case of limited antenna size [10]. Light, a particular type of electromagnetic radiation, could revolutionize the way we communicate in the underwater world. UWOC has gained considerable interest from academia and industry over the past few years for its bandwidth, high security, compact footprint, and low time latency. With the further development of optical wireless technology, Khalighi *et al.* briey reviewed some of the work of UOWC in channel model, modulation and coding schemes and experiments in recent years [21]. In [22], [23], the performance of a typical UOWC system under several simplied assumptions is studied. Johnson *et al.* investigated the UOWC channel mode [22]. Several typical UOWC modeling methods such as Bill Lambert's law, radiative transfer function, and Monte Carlo method are briefly discussed. Johnson *et al.* also introduced UOWC, mainly studying aquatic optical properties [23]. Arnon assessed the link performance of a typical UOWC system and introduced many challenging issues related to the UOWC system [24].

C. ORGANIZATION

The full text is divided into seven parts: Section II introduces the UAVs optical wireless communication system, including the application of UAV wireless communication technology and the research progress of the channel model. Section III introduces the technical application of OWC in GOVs and platoon communication. In section IV, the previous work is briefly summarized. Based on the existing simulation introduction and experiment, the research progress of the new development of AUVs is introduced. section V is based on the different spaces in which the vehicle is located, and introduces the UAV network, UAV-GOV network and UAV-AUV network. Section VI makes a preliminary discussion on the technical challenges faced by the vehicle-based OWC system and proposes prospects for its future development. In section VII, we summarize the full text.

II. UNMANNED AERIAL VEHICLE OPTICAL WIRELESS COMMUNICATIONS

A. UNMANNED AERIAL VEHICLES COMMUNICATIONS TECHNOLOGY APPLICATIONS

The use of UAVs is growing rapidly in many applications, including remote sensing, real-time surveillance, the provision of wireless coverage, search and rescue, cargo delivery,

TABLE 1. List of Abbreviations.

Acronym	Description
AUVs	Autonomous Underwater Vehicles
AOA	Angle of Arrival
ASTM	American Society Testing Materials
BER	Bit Error Rate
DSRC	Dedicated Short Range Communication
DPSK	Differential Phase-Shift Keying
DSSS	Direct Sequence Spread Spectrum
FSO	Free Space Optical
GOVs	Ground Operated Vehicles
IM/DD	Intensity Modulation / Direct Detection
ITS	Intelligent Transport Systems
IoT	Internet of Things
LAP	Low Altitude Platform
LED	Light-Emitting Diode
LD	Laser Diode
LOS	Line of Sight
MIMO	Multiple-Input Multiple-Output
OFDM	Orthogonal Frequency Division Multiplexing
OOK	On-Off Keying
OWC	Optical Wireless Communication
QAM	Quadrature Amplitude Modulation
PDs	Photodiodes
QPSK	Quadrature Phase Shift Keying
RF	Radio Frequency
ROVs	Remotely Operated Vehicles
SNR	Signal-to-Noise Ratio
SISO	Single-Input Single-Output
UAVs	Unmanned Aerial Vehicles
UUVs	Unmanned Underwater Vehicles
UWA	Underwater Acoustic
UOWC	Underwater Optical Wireless Communication
UWSNs	Underwater Wireless Sensor Networks
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
VLC	Visible Light Communication

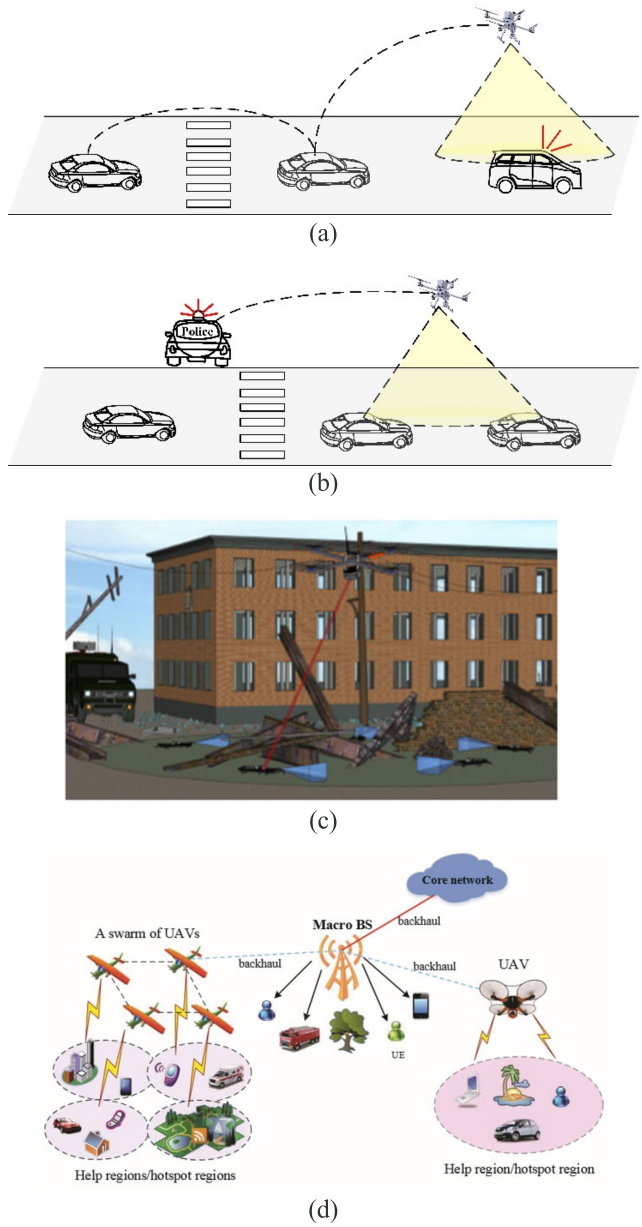

FIGURE 2. Application of OWC in UAV (a) UAV remote sensing system (b) UAV real-time monitoring technology (c) Search and rescue [25] (d) OWC wireless coverage [26].

security and surveillance, precision agriculture and civilian infrastructure inspections. In this article, Fig. 2 shows the scene diagram of UAV in remote sensing systems, real-time monitoring, search and rescue, OWC wireless coverage.

1) UAV REMOTE SENSING SYSTEM

UAV remote sensing system is a new generation remote sensing system after the traditional manned aerospace remote sensing system. At present, the active sensors used in remote sensing systems are lidar and radar. The lidar sensor directs the laser beam to the surface of the earth and determines the distance to the object by recording the time between the emitted and backscattered light pulses. The radar sensor generates a two-dimensional image of the surface by recording the range and magnitude of energy reflected from all objects. The passive sensor commonly used in remote sensing is a spectrometer. Spectrometer sensors are mainly used to detect, measure and analyze the spectral content of incident electromagnetic radiation. The UAV remote sensing system has the characteristics of fast access to space remote sensing information, rapid data collection and processing, low cost, high security, high mobility, high resolution, and the ability to meet the needs of human coordinates and spatial geographic information.

Because military wireless communications require the secure transmission of information on the battlefield, UAV remote sensing can use the technology to disseminate a large number of images and videos to combat forces, mostly in real-time. Near-Earth, observation UAVs can use synthetic aperture radar and light detection and ranging techniques to provide high-resolution images of the Earth's surface. Using OWC technology, the airborne sensor can also transmit the acquired data to the command center through the airborne satellite communication subsystem [27]. UAV remote sensing technology based on field crop surface morphology can provide high-resolution data, which is required to accurately estimate crop parameters. Under certain conditions, the use of UAVs as a platform to derive crop morphology based on spectral reflection information has extremely high accuracy. However, it has shown lower accuracy in nondestructive acquisition studies of complexity indirectly related to spectral information. In transportation networks, UAVs can collect data from ground sensors and transmit the collected data to ground base stations [28], [29]. Taking the UAV as the platform, the collected digital data and high-resolution image processing techniques are used to generate the time digital ground model to realize the real-time tracking of the vehicle.

2) UAV'S REAL-TIME MONITORING TECHNOLOGY

In the traffic environment, UAV's real-time monitoring technology can be used to help rescue when traffic accidents happen. The speed of the rescue personnel arriving at the accident site is directly related to the work efficiency of the rescue personnel and then affects the life safety of the accident personnel [30]. When the nearest rescue team terminal is too far from the accident site, it may take too long for the rescue team to reach the scene. Of course, in some big cities rescue teams can use helicopters to reach accident sites in remote areas. However, the associated costs of this solution are too high and not appropriate for many conditions. In this case, the UAV can be fully utilized to help the rescue team to get to the scene of the accident in time. What's more, rescue teams can quickly acquire detailed information about accidents in the form of pictures and videos from UAVs, for example, the number of people involved and their conditions. The UAVs can also be used to establish a real-time communication channel between the accident scene and the rescue team when the team approaching [31].

Also, UAVs can pay a traffic police role in traffic environments to make traffic on the roads safer [32]. Radar speed tests and video surveillance are still the most common techniques for enforcing traffic rules. If the driver exceeds the speed limit on a speed measuring road, he/she may be caught by a still or moving speed camera. If the driver keeps driving during the red light, he/she may be caught by nearby surveillance. However, with people's understanding of the camera range, the driver adjusts their driving behavior according to the camera Angle, and the monitoring effect becomes worse and worse. Under this condition, the mobile camera is used and installed in different positions. In fact, the UAVs equipped with such cameras which can move while operating, enable themselves to perform all or specific tasks of the traffic police. For example, the UAV can pass through the roads, and judge whether the vehicle violates the regulations, making V2I and V2V communication testing possible. UAVs can also intercept vehicles by turning traffic lights in front of the vehicle red. Additionally, UAVs can fly over highways and catch any vehicle that is speeding or breaking traffic rules. There could be a question that UAVs cannot catch up with the fast cars on the highway, but it can be solved by flying the UAV at high altitude to get a panoramic view.

3) SEARCH AND RESCUE

In modern life, people have more and more understanding of the potential of science and technology, in these areas, especially in public safety, search and rescue operations, and disaster management, people have more and more exploration. In the event of natural or man-made disasters such as floods, tsunamis and terrorist attacks, important infrastructure systems, including hydropower, electricity, transportation and telecommunications, are partially affected by disasters. This requires a quick solution to provide communications cover for rescue operations. When a public communications network is compromised, the drone can provide immediate warning and assist with speech therapy and rehabilitation operations. UAVs can also deliver medical supplies to areas classified as inaccessible. In some catastrophic situations, such as toxic gas infiltration, wildfires, avalanches, and the search for missing persons, UAVs can be used for transportation, communications, and special operations [33]–[39]. Besides, the UAV quickly covers the dangerous area, will not endanger the related personnel's safety.

Search and rescue operations using conventional air systems, such as aircraft and helicopters, are often very expensive. Also, aircraft are required to undergo special training and to obtain a special take-off and landing area permit. However, UAVs can reduce costs, resources, and human risk. In a single UAV system, the UAV initiates a search operation on the target area, and then the real-time aerial video/image of the target area can be sent to the ground control system through the remote sensing system. Rescue teams analyze these videos and images to guide the best search and rescue operations [34]. In a multi-UAV system, airborne imaging sensors are used to locate the location of missing persons. Firstly, the path planning algorithm is used to calculate the optimal trajectory of the task. Each UAV's then begins a search process in which all UAVs scan the target area following their designated trajectory. Second, start the detection process. In the process, one drone detects an object that is above the ground, while the other will facilitate coordination between all UAVs and communication with ground control systems. Finally, the position of the target object and the related video and image are transmitted to the ground control system [35].

At present, RF communication is the most commonly used method for UAV search and rescue system. However, RF has some limitations such as security issues, crowded spectrum, limited availability of data rates, and the ability to generate unnecessary interference in sensitive environments [40], [41]. One possible alternative to overcome these limitations is to supplement the RF with a wireless optical system. In fact, OWC links enhance the capacity and capability of RF networks for large-scale applications. These hybrid wireless optical/RF systems provide temporary point-to-point links in the network and provide wireless access when the RF may be disrupted or may cause unwanted interference.

4) OWC WIRELESS COVERAGE

Due to their high mobility, the latest developments in UAVs have been deployed in wireless cellular networks and mobile base stations [42]. UAV-based wireless communications can provide higher wireless connectivity in areas not covered by infrastructure and achieve higher LOS link capacity with ground terminals. Traditionally, the way UAVs achieve wireless coverage is based on radio frequency transmission technology. However, with the emergence of new wireless applications, RF technology itself is limited by the spectrum resources [43]. Recently, OWC communication has been proposed as a promising technology to overcome the shortcomings of RF [44]–[46]. Compared with the traditional RF-based wireless communication system, the OWC system has the advantages of high-speed transmission in an unconstrained frequency band, spectrum without license, anti-electromagnetic interference and inherent security [47]. The channel capacity of OWC links is negatively affected by two physical phenomena, namely, attenuation due to atmospheric turbulence and pointing error due to the position deviation of high-rise buildings. In fact, the reliability of a wireless optical communication link can be severely affected by a link distance of more than a few kilometers. Recently, the use of UAVs has received much attention in OWC communication environments due to their inherent ability to create LOS Communication links to increase the flexibility of OWC links [48], [49]. In [50], a new wireless access network architecture is proposed for fast event response and flexible deployment, in which OWC front-end and backhaul links are installed on UAVs. In [43], an optical network consisting of a UAV node is proposed, which collects data from sensors based on multiple base stations. An important aspect of assessing the benefits of UAV deployment for OWC communications is accurate channel modeling, which has been addressed in some recent work (see [51], [52]).

However, in addition to the atmospheric turbulence attenuation and pointing errors caused by position deviation, the angle of arrival (AOA) fluctuation caused by the directional deviation of the hovering UAV is a special challenge for UAV deployment. In [52], an accurate channel model for the UAV OWC link is proposed by considering the combined effects of atmospheric turbulence and position and track. In [51], a new alignment model of the OWC link between two hovering UAVs is proposed to support multi-element optical transceiver array with multi-parameters. Therefore, it is of practical significance to select the optimal values for the parameters of the tunable system, such as the transmitter divergence angle or the equivalent beam width and the receiver FOV, to improve the performance of the UAV-based OWC link in terms of the realizable data rate. Also, the ergodic capability of ground-to-ground UAV transmission system is derived by using known elementary functions [43], and the wireless coverage ergodic capability of the adjustable system parameters on the UAV OWC link is studied.

B. UNMANNED AERIAL VEHICLES OPTICAL WIRELESS COMMUNICATIONS CHANNEL MODE

UAV communications consist of two types of channels, UAV-ground and UAV-UAV channels, which exhibit several unique characteristics as compared to the extensively studied terrestrial communication channels.

1) UAV-UAV CHANNELS

The UAV channel is mainly composed of LOS although limited multipath fading may occur due to ground reflection, its impact is minimal compared to the UAV's ground or ground channels. Moreover, because of the potentially large relative speeds between UAVs, the UAV-UAV channel may have higher Doppler frequencies than the UAV-ground channel. These channel characteristics have a direct impact on the spectrum allocation of UAV links. On the one hand, the advantages of the LOS link may indicate that the emerging millimeter-wave (MMW) communication can be used to achieve high capacity UAV-UAV wireless backhaul [53]. On the other hand, the high relative speeds between UAVs, combined with the high frequency of the MMW band, could lead to excessive Doppler effect. Due to its unique channel characteristics, more in-depth research is needed to identify the most suitable technologies for use in UAV links.

2) UAV-GROUND CHANNELS

Although the aeronautical applications of manned aircraft air-to-ground channels are well understood, systematic channels are still ongoing [54]–[56]. Unlike manned aircraft systems, where the ground is usually in an open area with tall antenna towers, UAVs-ground passages are complicated by the more complex operating environment. Although in most cases these channels require a tie-line connection, they are measurements and modeling of unmanned aircraft ground occasionally blocked by obstacles such as terrain, buildings, or the aircraft itself. In particular, recent measurements have shown that the ground access of UAVs may be affected by severe fuselage tracking lasting tens of seconds during aircraft movements, which needs to be taken into account in mission-critical operations. For low altitude platform (LAP), the ground channel may also constitute a series of multi-path components due to the reflection, scattering and diffraction of mountain, ground surface and blade. For UAVs operating over deserts or oceans, the bi-ray model is mostly used because of the dominance of the LOS and surface reflection components. Another widely used model is the stochastic Rician fading model, which consists of a deterministic LOS component and a random scattering component with a specific statistical

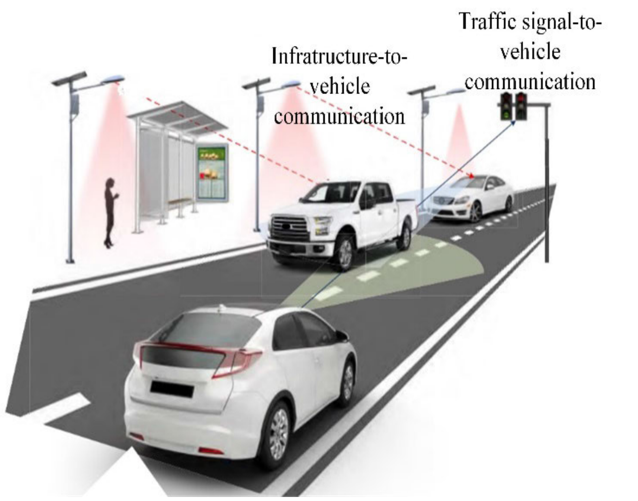

FIGURE 3. Vehicle optical wireless communication scenario [57].

distribution. Based on the environment around the ground terminal and the frequency used, the UAV ground channel exhibits a wide variation of the rice factor (i.e. the power ratio between LOS and the dispersion element), typically about 15 dB in the L-band and about 28 dB in the C-band in hilly terrain [56].

III. GROUND OPERATED VEHICLES OPTICAL WIRELESS COMMUNICATIONS

A. THE COMMUNICATION WAY OF VEHICLE OWC

ITS is based on the research of V2V and V2I. It is a system designed to improve road safety performance, reduce traffic congestion, and solve environmental problems. Fig. 3 shows the ITS scenario based on optical wireless technology and the following two sections will detail introduction the application of OWC in this scenario. Compared with the low-frequency band utilization, large time delay and serious data delay of RF signals, optical wireless technology has the characteristics of fast transmission speed, high security and high reliability.

1) VEHICLE-TO-VEHICLE

In modern urban life, people mostly choose vehicles as the basic means of transportation, which greatly increases the degree of traffic congestion. At the same time, occupying the spectrum resources, cellular network communication makes information transmission mode based on RF signal not only interfere with the environment but has a limited spectrum in traffic. The probability of accidents for vehicles beyond 1000 meters is very low [58], which indicates that shorter communication distances can be considered to improve two-way environments, these links can be used to establish V2V communications to transmit early warning and telemetry data such as emergency braking, forward impact, LOS control, and change of speed [59]. This kind of illumination-based information transmission mode can not only possess a high transmission rate but also cause no harm to the human body. Meanwhile, the pattern of lamp placement provides a variety of ways for communication. In the OWC system, there are multiple communication modes like single input single output (SISO) and MIMO [60], [61]. In SISO mode, when transmitting the same set of data, the inter-vehicle SISO mode can reduce the impact of the external environment, but the communication capacity is not high enough. In order to optimize this kind of transmission, we can adapt the communication mode of MIMO which could offer the opportunity to increase the data rate by transmitting the info on parallel channels. Headlights transmit different information, the headlights transmit different data streams, and multiple photodiodes (PDs) are used to receive the Information.

2) VEHICLE-TO-INFRASTRUCTURE

In the daily life, the traffic environment is various, the road condition information is complex. Now the demand for communication is increasing rapidly and the spectrum resource is limited. The RF signal cannot satisfy people's needs. There are two main categories of OWC applications for vehicles and transportation: (i) LED-based traffic light. Because their main use is not lighting, and they are always open even if there is sunlight, so more suitable for vehicle safety, traffic information broadcast applications. For example, in the dense traffic environment, in the city road intersection, the vehicle density, the disturbance is serious [62], [63]. A typical wireless light intelligent transportation communication system needs only a few modifications to the existing vehicles or infrastructure. Using headlamps, traffic lights, street lights, and billboards as the sending end of information, the headlamp of the vehicle is used as the receiving end to receive the optical signal [64]–[66]. It can transmit position information, safety information, traffic information and so on, and realize integrated communication service without affecting the initial function. (ii) Street lamp. This kind of street lamp can be used for data communication with cars, transmitting location information or traffic information, etc., usually can provide communication coverage within 50-100 m. This mode of communication can improve the average speed during rush hours and reduce the degree of traffic congestion and vehicle delay, while also greatly reducing the number of traffic accidents, ensuring traffic safety, saving fuel and reducing vehicle wear and tear, shorten Transportation Time, reduce pollution, play the expressway fast, safe, comfortable and efficient function. Besides, facilities like LEDs on building screens can be used even in streets without traffic lights and street lamps.

It is well known that experiments are the best way to demonstrate theoretical studies, and Table 2 provides current research on receiver-based vehicle communication. PDs can support higher data rates at lower cost, enabling them to be used as receiving devices for economic systems. In contrast to PD, an image sensor can simultaneously identify all light sources and transmit data in parallel when each signal is modulated separately. Second, the image sensor is more resistant to light interference. Fig. 4 shows a typical experiment using image sensors and OWC technology to achieve distance

TABLE 2. Performance comparison of different receivers of vehicles.

Receiver type	Scenario	Receiver FOV	Data rate	Max distance	Modulation/ coding technique	Reference
Camera based	V2I(static)	22°	10-20 Mb/s	2 m	OFDM/QAM/Manchester code	[68-72]
			10 Mb/s	20 m		
	V2I(mobile)		32 kb/s	70 m		
			2 kb/s	110 m		
	V2V		55 Mb/s	1.5 m	OFDM	[73-77]
PD based+ low-cost camera	V2I	1.3°	4.8 kb/s	90 m	2PPM	
	V2I(mobile)	0.4°	1 Mb/s	60 m	QPSK	
			2 Mb/s		16QAM	
PD based	V2I(static)	20°	15 kb/s	15 m	OOK with Manchester or Miller codding	[78]
	V2I(static)	-	20 kb/s	50 m	DSSS	[79-81]
	V2I/V2V	10°	15 kb/s	23 m	OOK with Manchester or Miller codding	[16]

measurement between vehicles and information transmission in the tunnel and outside. Through the investigation of vehicles, we know that most of the vehicle are equipped with event data recorder, which provide a basis for the use of image sensors in vehicles. The image sensor with a rolling shutter has the advantage of progressive scanning and can improve the data rate. At the same time, the image sensor has good performance even if it is far from the transmitting. Specifically, if the camera is too far away from traffic lights, it will result in pixel reduction and defocusing, making it difficult to distinguish between individual data emitted by LEDs. As a result, the high spatial frequency component of the data is often lost. But the low-frequency component is still in the pixels, which means that even if the camera is far away from the transmitter, the high-speed camera can still pick up the low frequency LED data patterns contained in those pixels.

3) PLATOON

Platoon is an upcoming and promising technology that will improve many aspects of road traffic. It is possible to use a fleet to improve road utilization, safety, fuel efficiency and driving convenience [83], [84]. However, for the platoon, vehicles need to quickly exchange information to understand the driving conditions of the vehicles in the queue. The current proposal is mainly realized by using radio frequency-based communication, such as DSRC based on IEEE 802.11p or cellular V2X [84], [85], the main connection mode is shown in Fig. 5(a) and 5(b). The communication method is shown in Fig. 5(a), cluster-headed cars are mainly used for information transmission. This method will delay the information of other vehicles in the queue. Due to this shortcoming, Fig. 5(b) interconnects the vehicles in the queue two by one. This connection method can effectively reduce the time delay. Even if the cluster head vehicle connection is interrupted, it will not affect the connection of the entire system. For the team to work safely, a higher update rate is required, and therefore a higher message rate [86].

In addition, the closeness of the distance between vehicles can lead to an increase in vehicle density, especially when multiple platoons are closely connected on the same highway. Relying on RF alone will cause serious network congestion, and a large number of vehicles will be affected by congestion. Therefore, this kind of shared network that only relies on RF is not desirable, and it leaves few resources for other applications. On-board OWC is the use of LED headlights and taillights used in automobiles, using a large amount of unauthorized bandwidth in the wireless light spectrum and high-frequency conversion that the human eye cannot detect to achieve information transmission between vehicles. In the study of [87], communication via headlights can travel up to a distance of approximately 120 meters in a narrow beam in front of the vehicle. The specific application of optical wireless technology in platoon is shown in Fig. 5(c). At the same time, because the propagation characteristics of light determine that information transmission mainly depends on the LOS between the sender and the receiver, the optical link makes the transmission faster, which limits network congestion. But in the car queue, it can only reach a relatively small number of nodes, which cannot satisfy long-distance connections. In addition, severe weather conditions, such as fog, heavy rain, or bright sunlight, can severely reduce the reachable range [88]. In severe weather conditions, network congestion may become so great that even stable and

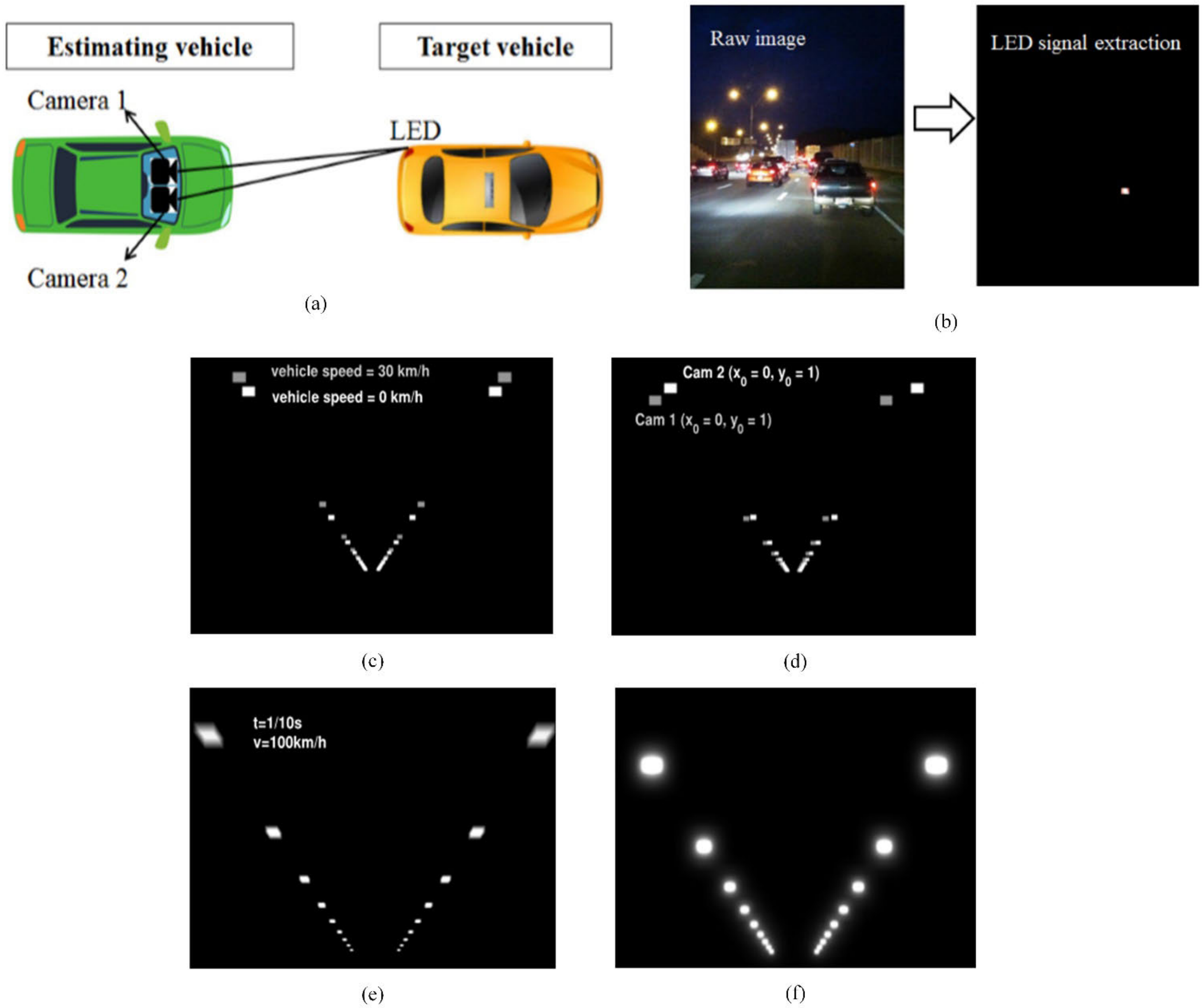

FIGURE 4. Vehicle-to-Vehicle Distance Estimation Using a Low-Resolution Camera Based on Visible Light Communications (a)System architecture (b) Extracting the LED signal from the image [58] (c) Vehicles in the tunnel experiment scene (d) Images from two cameras (e) Images with motion blur (f) Images with blooming effect [67].

therefore safe exclusion can no longer be guaranteed [89]. One way to solve this problem is to deeply integrate the communication protocol design with the control loop used for car operation. Another way is to integrate classic RF and LOS technology in the context of 5G haptic Internet [90]. Initial research has shown that supplementing RF with OWC and using additional parts of the electromagnetic spectrum can help achieve higher communication reliability [91], as shown in Fig. 5(d). Given the different characteristics of RF communication technology and OWC communication technology, this communication method with complementary characteristics will have a very important meaning in the future fleet communication method.

IV. AUTONOMOUS UNDERWATER VEHICLE OPTICAL WIRELESS COMMUNICATIONS

Two-thirds of the earth's surface is covered with water. In the past few thousand years, mankind has never stopped exploring the ocean. In recent years, with the intensification of global climate change and resource depletion, there has been increasing interest in the study of marine detection systems. Underwater wireless communication refers to the use of radio waves, sound waves, light waves in the unoriented water environment to transmit data. It is of great significance in the areas of tactical monitoring, pollution monitoring, oil control and maintenance, marine exploration, climate change monitoring and marine scientific research, and underwater wireless information transmission [82].

As early as the 1960s, the invention of lasers as a light source changed the future of OWC [83]. Since then, many ground OWC applications have been developed. The early development of UOWC lagged far behind ground OWC due to the severe attenuation of visible light in seawater and limited knowledge of water optics.

However, UOWC's research activities have increased in recent years. There is an urgent need for a comprehensive

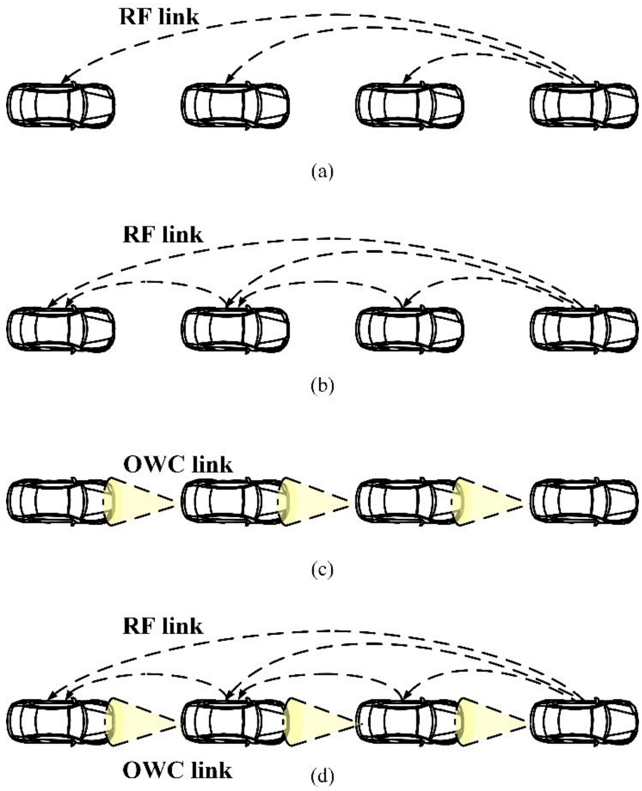

FIGURE 5. Platoon wireless communication (a) only RF by the leader vehicle (b) only RF (c) Only OWC (d) Heterogeneous communication used by all platoon members.

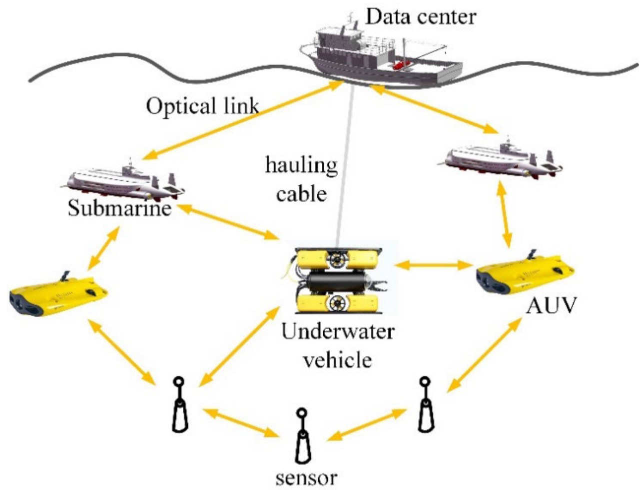

FIGURE 6. Underwater vehicles OWC node link diagram.

survey to provide researchers with a basic understanding of UOWC and the latest research on UOWC. Based on nearly20 years of experiments and theoretical studies on the propagation of light in the ocean, Duntley proposed in 1963 that seawater has a low attenuation characteristic for light with wavelengths of 450 to 550 nm, corresponding to the blue and green spectra [92]. This finding was subsequently confirmed by experiments by Gilbert *et al.* [93]. In recent years, to meet the need for efficient and high-bandwidth data transmission in ocean exploration, researchers have proposed the concept of underwater wireless sensor networks (UWSNs). The introduction of UWSNs greatly promoted the development of UOWC. As a result, the UOWC market is beginning to show the future. Simply put, the underwater wireless sensor network consists of a number of distributed nodes, as shown in Fig. 6, which are usually made up of autonomous underwater vehicles, remotely operated vehicles, sensors and submarines. It provides a higher data transfer rate than traditional hydroacoustic communication systems, greatly reducing power consumption and computational complexity for short-distance link links.

In [94], Milton, the underwater robot used in this work, is a low cost 6-degree of freedom thruster-based UUV revision. Milton has been updated somewhat since the version described in [95] and onboard computation is now provided via a Nvidia Jetson TX2 mounted on an Auvidea J120 carrier board and includes an HDMI display mounted within the robot to provide visual feedback to fellow divers. Fig. 7(a) shows the entity of Milton. More details about the robot can be found in [95]. Based on the development of optical wireless technology, the team developed a waterproof Li-Fi modem and installed the optical modem on the Milton for underwater experiments. In Fig. 7(b), this optical modem is essentially small cylindrical housings with port glands for power and data. Light emission and sensing are performed using emitters and sensors mounted in an octagonal 3D printed structure that isolates the emitters from the receivers to reduce crosstalk and also enables both emitters and receivers to cover a full 360 horizontal field. Each light byte transceiver communicates using five emitters LEDs and five light sensors that act as receivers and a small amount of electronics to drive and monitor the emitters and receiver. Fig. 7(c) shows the Milton robot being controlled by a surface-based operator through light byte and Fig. 7(d) shows Milton in an above ground pool being teleoperated via a floating light byte modem at night. In the subaquatic domain, control of the robot is facilitated through the use of a waterproof tablet-like device (see Fig. 7(e)) that includes two waterproof 2-way switches and an onboard inertial measurement unit. The primary switch provides navigation between some key interface panels (battery, control, calibrate, annotate, record and console). The secondary switch provides a standard operation within each panel (e.g. start/stop recording session, change console log level). More complex user interactions are possible on interface panels that capture the focus of the primary switch. Once the focus of the primary switch has been obtained, the primary switch can be used to select the focus of different interface widgets within the panel. The secondary switch then changes its function based on the current widget within the panel that has focus. Although the terrestrial user interface can exploit standard widget-based user control, the lack of pointer/selection tools and limited input necessitates other solutions underwater. Fig. 7(f) shows

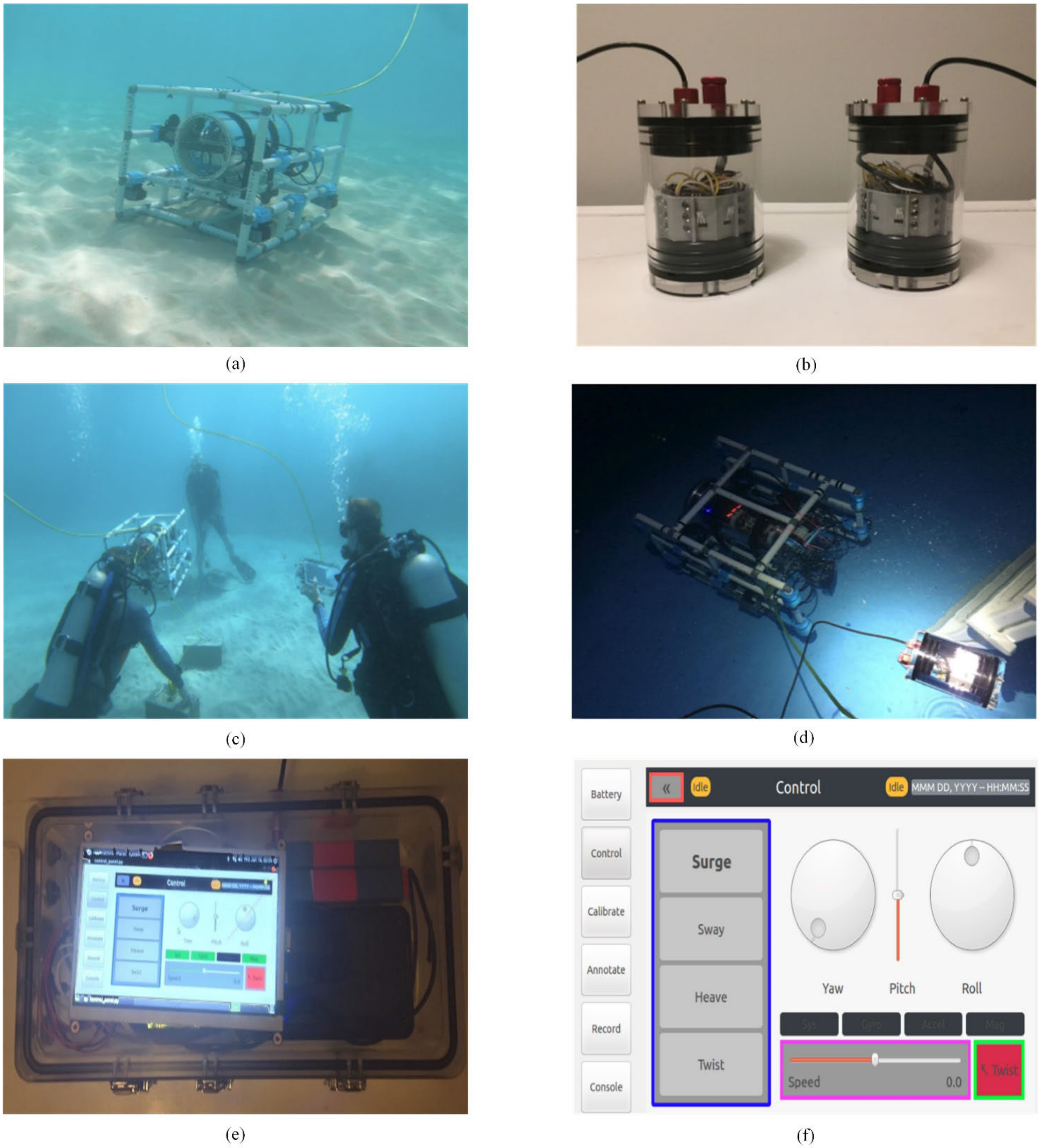

FIGURE 7. **Based on Milton's underwater optical wireless communication experiment (a) The Milton unmanned underwater vehicle (b) Waterproof Li-Fi modems (c) Outdoor underwater experiment scene (d) Indoor underwater experiment scene (e) and (f) Experimental operating platform [94].**

the input display used within the tablet. The two switches are used to select between input widgets and to make selections within that widget.

V. VEHICLES NETWORK COMMUNICATIONS STRUCTURE

A. UAV-UAV NETWORK COMMUNICATIONS

UAVs have been used in many civil fields, including real-time rescue, agricultural and civil infrastructure inspection functions. There are two types of UAV networking, one is single UAV centralized networking, the other is selforganizing UAV network.

1) CENTRALIZED UAV NETWORKING STRUCTURE

UAV centralized network structure, the base station (BS) as the center node of the UAV centralized wireless communication network. All UAVS in the network needs to be connected to this central node to send information, receive commands and control data, there is no direct link to connect the UAVS.

The whole network is centered on the ground station, and the communication between two UAVs needs to be carried out through the ground station as a relay, so the information and data transmitted between the two UAVs will have a long delay. Besides, since long-distance communication between ground stations and UAVs is usually required, high-power wireless optical transmission equipment is needed on UAVs. However, for small and medium-sized UAVs, the size and carrying capacity are limited, and this mode of transmission faces great challenges. In addition, in the centralized UAV communication architecture, the failure of a single network node will lead to the collapse of the whole communication system. This means that if something goes wrong with the station, the entire network will be down. As a result, this communication architecture is not robust. To improve the reliability of the network and reduce the communication delay, a UAVS wireless optical ad hoc network structure is proposed.

2) SELF-ORGANIZED UAV NETWORK

In the UAV wireless self-organized network communication architecture, two groups of information exchange between any UAV do not need routing through the ground station, this means that in addition to sending data to the station network, any UAV can only act as an information exchange station to process its information sending data, greatly reducing the computing and communication load of the ground station, the two UAVs can communicate directly or indirectly. Fig. 8 is a typical self-organizing UAV network communication architecture. Typically, ad hoc networks do not rely on existing ground infrastructure, and each UAV will participate in the forwarding of data from other UAVs in the network. The network only needs a backbone UAV to transmit the data as a gateway to the ground station. The backbone UAV requires two backbone optical communication modules, one for communication with other UAVs and the other for communication with ground stations. In such a self-organizing network, coverage can be significantly expanded because only one UAV is needed to connect to a ground station. Also, because many UAVs fly relatively close to each other, they can be equipped with low-cost, lightweight digital equipment, making them more suitable for small and medium-sized UAVs. At the same time, to keep the network stable, all UAVs need to have similar motion patterns, such as speed and direction. Therefore, this self-organizing communication architecture is particularly suitable for flying a group of UAVs to perform search and surveillance tasks. This network model cannot be brought down by a single node failure, so it has strong robustness and mobility.

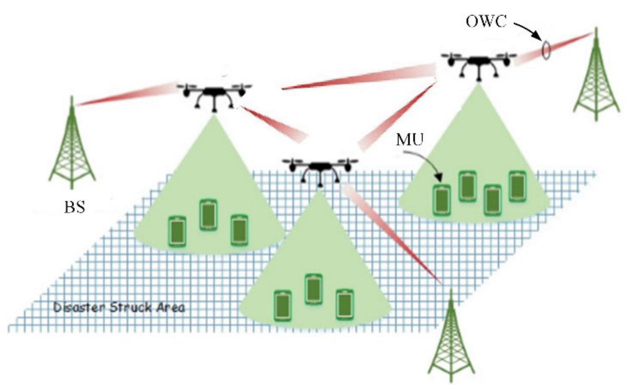

FIGURE 8. UAV network communications [96].

B. UAV-GOV NETWORK COMMUNICATIONS

Vehicle networks based on UAV enabled OWC are an important part of ITS. The OWC link can provide high data rate communication between UAVs and vehicles because of the absence of limitations in comparison to microwave links. The OWC alongside UAVs is a very promising practical direction and can be applied in the vertical backhaul/fronthaul framework for the fifth generation and beyond wireless networks [97].

Another application of UAVs is ITSs which are a crucial part of so-called smart cities. The usage of UAVs in the ITS enables to control the traffic and warn the driver about possible danger. Particularly, three aspects of the UAV utilization such as data routing, cybersecurity, and privacy were examined [98], while the authors in [99] presented a new type of UAV-assisted network which purpose is to enhance the connectivity and minimize the data transfer delay.

Due to various obstacles such as vehicles and buildings, it is usually difficult to find the shortest end-to-end connection path in the city. Besides, the visible light communication between vehicles is short-distance communication, which cannot guarantee the effective transmission of long-distance information. In the absence of a reliable direct communication link, we can deploy UAVs as relays to provide wireless connections between two or more remote vehicles or groups of vehicles. The relay technology can effectively improve the throughput, reliability and communication range of the system [100]. However, limited by fixed nodes, the existing relay technology is short in distance and less flexible. To effectively solve this problem, we can use UAV as the relay node, in which case the flexibility of UAVs can be networked according to the actual needs of different environments. This kind of mobile relay is more cost-effective because it can find the best communication environment through dynamic relay position adjustment. The advantages of UAV relay are not only reflected in the flexible mobility. Compared with the traditional ground relay nodes applied in the traffic environment, the UAV has a certain flight altitude, and the link relaying to the destination node can be regarded as the LOS link.

In the UAV-GOV network system, the vehicle network, as an important part of the entire network structure information exchange, undertakes the data transmission tasks of three important communication links V2V and V2I [101]. The performance of the communication system is directly related to the efficiency of information transmission between vehicles and affects the security of the whole traffic network. In the networking part of UAV, the UAV network can be centralized or self-organized. The centralized UAV networks centers on the ground station and requires the long-distance radio and optical communication between the ground station and each UAV. Self-organizing communication architecture can provide wider network coverage through multi-hop transmission. The UAV self-organizing network is suitable for the formation flight of multiple identical UAVs, while the multi-group UAV network and multi-layer UAV network architecture is more suitable for collecting a large number of heterogeneous UAVs to perform tasks, which can provide higher communication efficiency. This new network mode provides a greater possibility to improve the information transmission rate, to optimize people's travel efficiency, and to ensure travel safety.

As mentioned above, atmospheric turbulence attenuation is considered important and must be expressed statistically because the air-to-ground channel of UAVs is conducted through the air. The intensity fluctuation of received optical signals caused by atmospheric turbulence is usually simulated by the gamma-gamma lognormal distribution, and the small scale and large-scale atmospheric turbulence vortices can also be described by the double gamma and double Weibull statistical models [102]. On the basis of the original model, the OWC channel model based on UAV and ground vehicle is proposed in [43]:

$$f_{RV_i}(r) = \frac{\alpha_i \lambda_i^{\mu_i}}{\Gamma(\mu_i)} r^{\alpha_i \mu_i - 1} \exp\left(-\lambda_i r^{\alpha_i}\right), \alpha_i > 0 \quad (1)$$

where $\lambda_i = \mu_i / \tilde{r}^{\alpha_i}, \tilde{r} = \sqrt[\alpha]{\mathrm{E}[r^{\alpha_i}]}$ is the α_i-root mean value, where E[•] defines the expectation operator. $\Gamma(t) = \int_0^\infty x^{t-1} e^{-x} dx$ is the Gamma function [108]. The μ fading parameter has been determined as the inverse of normalized variance of r^{α_i}, $\mu_i = \mathrm{E}[r^{\alpha_i}] / \mathrm{E}\left[r^{2\alpha_i}\right] - \mathrm{E}^2[r^{\alpha_i}] \geq \frac{1}{2}$. Keeping this in mind, the PDF referred to the product of two independent RVs can be received by following the next steps.

$$f_Z(z) = \int_0^\infty \frac{f_{RR_1}(u) f_{RR_2}(z/u)}{|u|} du = \frac{2\alpha (\lambda_1 \lambda_2)^k}{\Gamma(\mu_1)\Gamma(\mu_2)} z^{k-1} K_v\left(2\sqrt{\lambda_1 \lambda_2 z^\alpha}\right) \quad (2)$$

where $K_v(\bullet)$ represents the v^{th}-ordered modified Bessel function of the second kind, $K = \frac{\mu_1+\mu_2}{2}$, $v = \mu_1 - \mu_2$ and $\alpha = \alpha_1 = \alpha_2$ (this assumption is valid for double distribution). After some algebraic manipulations, the PDF of the double $\alpha - \mu$ distribution can be expressed as:

$$f_{I_i}(I) = \frac{2(\lambda_1 \lambda_2)^k}{\Gamma(\mu_1)\Gamma(\mu_2)\tilde{I}_i} \left(\frac{I}{\tilde{I}_i}\right)^{k-1} \left(2\sqrt{\lambda_1 \lambda_2 \left(\frac{I}{\tilde{I}_i}\right)}\right) \quad (3)$$

where $\tilde{I}_i$ stands for the average irradiance of the i^{th} hop. α_1 and α_2 represent the effective numbers describing small and large scale eddies of atmospheric turbulence. We can express them respectively as:

$$\lambda_1 = \left[\exp\left(\frac{0.49\beta_0^2}{\left(1 + 0.18d^2 + 0.56\beta_0^{12/5}\right) 7/6}\right) - 1\right]^{-1} \quad (4)$$

$$\lambda_2 = \left[\exp\left(\frac{0.51\beta_0^2}{\left(1 + 0.9d^2 + 0.62d^2\beta_0^{12/5}\right) 5/6}\right) - 1\right]^{-1} \quad (5)$$

where according to the theory of scintillation $\beta_0^2 = 0.5C_n^2 k^{7/6} L^{11/6}$ is defined as Rytov variance for a spherical wave and $d = \left(kD^2/4L\right)^{1/2}$ represents diameter of the receiver aperture. Here, $k = 2\pi/\lambda$ denotes the number of an optical wave, λ stands for the wavelength, C_n^2 is the refraction of index parameters, D corresponds to a receiver antenna diameter.

C. UAV-AVU NETWORK COMMUNICATIONS

In networking of UAVs and AUVs, the most important thing is how to integrate the underwater information system into a whole and transmit them to the UAV together. First of all, there are three basic networking methods for underwater information networks. They are based on underwater acoustic link networking, RF link networking and optical link networking [103]–[105]. The longer the distance between the underwater acoustic channel and the RF link, the worse the communication performance. These two communication modes have the characteristics of low data rate, prolonged time and unstable communication performance. A recent numerical study has shown that the use of single-photon avalanche diodes can realize an LED-based VLC with a link distance of 500 meters in pure seawater [23]. Although underwater wireless optical communication can achieve high data rates, it is difficult to carry out long-distance transmission due to the influence of water absorption and scattering by suspended particles. Therefore, they cannot achieve long-distance, high-bandwidth, high-performance information transmission and exchange alone. Since underwater optical fiber can be used as a high-speed, large-bandwidth, and long-distance carrier network, a feasible method is to combine the basic networking mode with underwater optical fiber. Fig. 9 shows an underwater cellular communication network structure integrating underwater acoustic/wireless-optical/optical fiber. Based on the research of the land cellular structure, we can divide the area where ROV, AUV, underwater sensors and frogmen are located into small cells, use hydroacoustic waves and optical wireless for short-distance communication, and then connect them into one through an optical fiber network. For vehicles on the surface, ROV's and AUVs can be connected to the underwater network, and RF can be connected to offshore base station data centers, UAVs, and even satellites. However, due to the complexity of the underwater environment and the huge cost required for optical fiber laying, this hybrid network is mainly considered for use near important straits and islands. Other sea

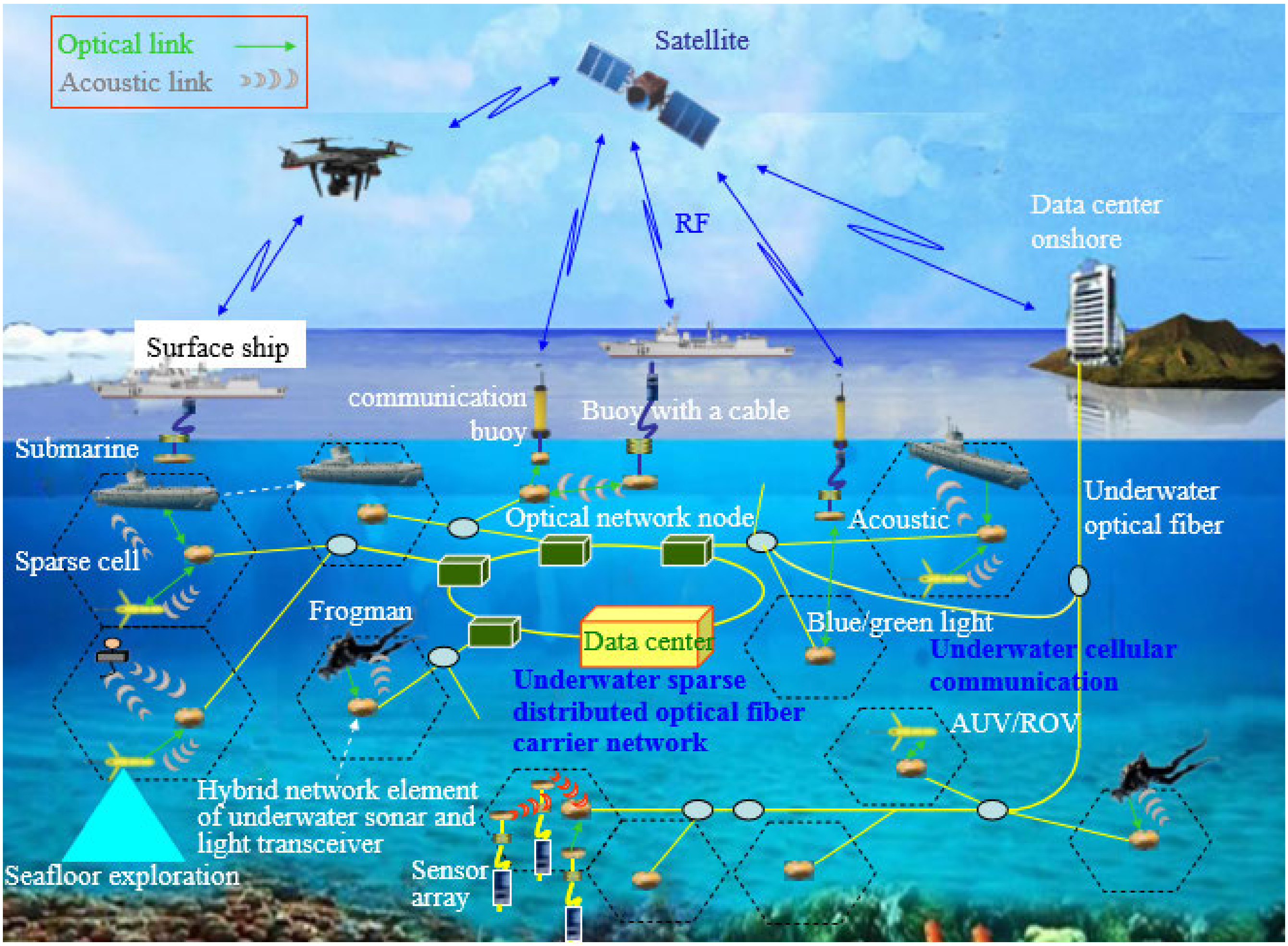

FIGURE 9. UAV-AUV network communication [105].

areas can be connected using a light/sound hybrid networking method [106]–[108].

Secondly, research on UAVs and underwater networking systems began as early as 1976. Karp evaluated the feasibility of optical wireless communication between underwater and satellite terminals [109]. In 1977, researchers at the Lawrence Livermore Laboratory at the University of California proposed a one-way optical communication system from UAV to submarine [110]. As can be seen above, the transmitter of the UOWC system uses blue-green laser light source to generate a light pulse. Due to its compact structure, it can be flexibly carried by underwater unmanned vehicles. The transmitter can also focus its output beam on the UAV and then reflect the beam onto the submarine [111]. UOWC tests such as aircraft to submarine topologies were also established by the US Navy in the early 1990s [112]. For decades, the UOWC's interests remained limited to military applications [111]–[113].

So far, UOWC has not achieved large-scale marketing. In the early 2010s, only a limited number of UOWC products were commercialized. These products include the Blue Comm UOWC system, which enables underwater data transmission of 20 Mbps over a distance of 200 meters [21], [114]. In 2018, Japan's Yokosuka Marine Technology Center and Shimadzu Aircraft Equipment Department developed a modem that can be used for communication between UAVs and underwater vehicles [115]. This kind of demodulator can send light beams in a specific direction and does not require precise alignment devices before communication. The tank has achieved a communication speed of 12.5 Mb/s within a range of 46 m. At the same time, under the interference conditions of sunlight, a stable communication link was established on the water through the UAV and the underwater vehicle. The Ambalux UOWC system can provide data transmission of 10mbps over a distance of 40 m [22], [116].

VI. COMPARATIVE ANALYSIS AND RESEARCH PROSPECTS

In Table 3, we analyzed some typical unmanned vehicle experiments in the field of OWC technology in recent years. The specific analysis will be elaborated in this section.

TABLE 3. Performance comparison of different receivers of vehicles.

Vehicle type	Wavelength/ radiation luminous efficacy	Distance	Data rate	Light source	Receiver type	Ref.
UAV	1550 nm	500 m	~1 Gb/s	-	PD	[52]
	850 nm	4~5 m	3 Mb/s	LED	PD	[117]
	1550 nm	100 m	40 Gb/s	LD	PD	[118]
	1590 nm	50 m	1.25 Gb/s	LD	APD	[119]
	940 nm	6.76 km	1.25 Gb/s	LD	PD	[120]
GOV	-	5 m	6 Mb/s	LED	Camera	[121]
	2.5 W	200 m	Kb/s	LED	Camera	[122]
	250.3 lm/W	100 m	3 Mb/s	LED	PD	[123]
	400-700 nm	20 m	Mb/s	LED	PD	[124]
AUV	520 nm	34.5 m	2.70 Gb/s	Green LD	APD	[125]
	488 nm	10 m	16 Gb/s	LD	PD	[126]
	550 nm	30 m	Gb/s	LD	APD	[127]
	660 nm	10 m	4.17 Gb/s	Red LD	APD	[128]
	520 nm		4.17 Gb/s	Green LD		
	440 nm		1.17 Gb/s	Blue LD		

In addition, based on the research of existing technologies, this section analyzes the unresolved technical challenges and proposes the prospect of future research directions.

First of all, in terms of light sources, the light sources used by vehicles in different locations are different. From Table 3, we can know that UAVs and AUVs have high spatial freedom and relatively long transmission distance. In the UAV link, the laser light source of traditional OWC is still used, and the most selected optical wavelength is 1550 nm. In terms of transmission rate, UAVs can usually achieve Gb/s-level transmission performance due to their advantages in their weight. In terms of meter-level short distance UAV links, factors such as flight flexibility, cost, size, power consumption, etc. are comprehensively considered. At the same time, due to the significant reduction of link distance, the optical signal emitted by the transmitter no longer needs to experience atmospheric turbulence and atmospheric turbulence. Traditional long-distance fading effects such as scattering and beam drift. Therefore, to reduce security risks. To increase the link coverage, the researchers replaced the source of this type of link with LEDs. For ground mobile vehicles, it is no longer limited to using traditional laser light sources and can rely on its own LED light source to load wireless data for the LED light source through a drive circuit. It can achieve Mb/s-level transmission performance, as the communication distance increases, communication performance also decreases, and the lowest kb/s-level transmission can be achieved. In addition, due to the complex underwater environment and the fluidity of water bodies, most of the research on autonomous underwater vehicles is still in the laboratory stage. Similar to UAVs, most AUVs use blue-green lasers as light sources, with light wavelengths mostly 550 nm, which can achieve a transmission rate of up to 16 Gb/s within a range of tens of meters. The laser has good performance over long distances. However, the laser is greatly affected by temperature. Besides, although the efficiency of the laser is high, the total power is not high. The divergence angle of the beam is generally between a few degrees and 20 degrees, so it is poor in directivity, monochromaticity and coherence. For vehicles, their own LED lights will reduce installation costs. Secondly, many LED manufacturers have been able to reshape the light beams emitted by LEDs through packaging and installing secondary optical lenses and other technologies to obtain a directional beam. LED lights have more advantages in terms of stable performance.

Also, the existing research work usually uses a single light source transmitter, SISO of a single PD receiver configuration. In this configuration, once the transceiver link is affected by turbulence, beam drift, masking and other adverse factors, transmission performance will be sharply degraded or even link interruption. One of the effective solutions to the above problems are the introduction of multiple light transmitters at the starting point and multiple PDs at the receiving end, which can objectively build multiple spatial links between the receiving and receiving ends. The advantage of this approach is that even if one link becomes degraded, the overall transmission performance of the other link remains relatively reliable due to the presence of other links, thus largely avoiding link outages. At the same time, by introducing space multiplexing algorithms such as airtime coding and singular value decomposition, different content sending data can be transmitted on different transceiver links, thus improving the spectral efficiency of the UAV's on-board wireless optical link.

For short-distance vehicle wireless light technology, VLC technology will soon use traditional LED Lambertian light source. In fact, many LED manufacturers have been able to reshape the light beams emitted by LEDs with the help of technologies, such as packaging and adding secondary optical lenses to obtain non-Lambertian or even customized light beam effects. According to the above-mentioned industry foundation, in the design process of short-distance vehicle wireless light technology, we can try to introduce non-Lambertian light sources. In order to construct diversified link options in the optical beam dimension. The beam switching technology can also be used to improve the transmission energy efficiency of the link. At this stage, the assumptions in the numerical simulation of some links are still too ideal. A further experimental demonstration is needed. In fact, in the network of UAVs and GOVs, UAVs must use real-time measurement or uplink feedback to learn the location information or channel state information of the ground receiving end. What method is used for measurement, what kind of uplink is used for feedback, and the real-time performance and accuracy of measurement and feedback all need to be discussed in depth. In the next study, the rationalization of the solutions to the above problems will greatly affect the practical process of such systems.

Secondly, for vehicle's OWC systems, mobility can cause channel aging problems similar to those in traditional massive MIMO systems. However, the random speed of the vehicle causes the uncertainty of the time correlation. The channel prediction method considered in the channel aging problem is difficult to implement due to the need for an accurate channel covariance matrix. Therefore, the channel change effect is one of the most serious problems in airborne wireless optical communication, and it is necessary to perform fast channel estimation for highly mobile communication systems. In order to overcome the serious channel variation problem, other channel characteristics can be used to help reduce the channel estimation overhead. In the MIMO system under LOS conditions, there are fewer channel paths due to the limitation of the scattering environment. Therefore, the channel covariance matrix reduces the rank, which can make full use of the sparsity of the channel. Since the number of training pilots and feedback bits is proportional to the effective dimensionality of the transmitter, the reduction in channel dimensionality results in a significant reduction in training and feedback overhead. At the same time, a fast channel estimation method with low complexity and high efficiency is also needed. One potential method is to apply fast Kalman filtering to the UAV's cellular system to predict the vehicle's channel.

One problem we have to face is that UOWC technology faces greater challenges. Wireless light allows high data rates, but will be limited by distance. The bandwidth of underwater acoustic communication is very limited, but it allows long-distance data transmission. With the widespread application of underwater robots in underwater operations and networking, hybrid networking may become the first choice for communication. In particular, some underwater applications require accurate location information of sensor nodes. When we want to use an optical network to communicate with sensor nodes, we need to accurately locate and approach it first. For precise positioning, AUV navigation systems usually require a large number of virtual anchor points. As a result, the computational complexity will be several orders of magnitude greater than traditional architectures. Therefore, it is very important to develop low-complexity algorithms. For example, the low-complexity algorithm proposed in [129] performs rough estimation, while using more complex algorithms to refine the results. At the same time, the calculation process can be further optimized at the hardware level because the nonlinear equations obtained from the initial measurement are all in the same format.

Also, although the existing research work has solved the problem that the path of the underwater vehicle and the sending time of the beacon information have a great influence on the value of the underwater vehicle [130], [131], the path planning of the underwater vehicle positioning still needs further the study. Due to the lack of accurate node location information, it is unrealistic to determine the path of the AUV in advance to provide location services for all sensor nodes. This requires real-time dynamic adjustment of the AUV, and precise positioning algorithms for path planning [132]. If the underwater robot can access all the sensor nodes in the network, the life cycle of the network will be maximized. However, in the vast marine environment, timely execution of these tasks becomes very challenging. In such a scenario, another feasible solution is data aggregation. Simply put, when only a few sink nodes (or cluster heads) need to be accessed, AUV can be very efficient. However, how to determine the access point of the AUV and realize the energy consumption balance between the AUV and the sensor node requires further research. Also, the number of underwater robots has a significant impact on path planning. The effective cooperative relationship between underwater robots and the path design of underwater robots should be the focus of the next UOWC research.

VII. CONCLUSION

Optical wireless communication links can be deployed in air, ground, ocean and other environments. According to different environments, the OWC link will experience different damages, thereby affecting its performance. In this article, we discuss the research progress of vehicle-based OWC in three different environments. Besides, we also briefly discussed the difficulties faced by vehicle OWC technology in different scenarios, possible solutions and future research directions. It can be concluded that OWC communication is increasingly becoming a mainstream technology in 5G and 5G evolution communication systems. This technology can integrate the ''space, earth and sea'' communication system into a whole, significantly improve the communication link data transmission rate, so that the entire communication network becomes more robust.

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