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A Review of UV Communications for UAVs

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ABSTRACT As an important branch of free-space optical (FSO) communication technology, ultraviolet (UV) communication is mainly applied to mobile communication platforms represented by unmanned aerial vehicle (UAV). With the development of LEDs and UV detector devices, UAV UV communication technology has shown great potential in related fields. But at the same time, it also faces some challenges. As the communication distance increases, the path loss of the UV communication system can reach 0.12dB/m, and the variation in bit error rate (BER) can rapidly deteriorate from the order of 10^{-8} to 10^{-1}. Additionally, the UV communication system mounted on a UAV platform can emit radiation into the environment, which may have negative effects on human health when the radiation intensity exceeds 0.5μW/cm^2. These issues can be summarized as the availability, stability, and effectiveness of UAV-based UV communication technology. This paper aims to comprehensively address both UAVs and UV communication, providing a detailed introduction to the challenges and solutions facing UAV-based UV communication technology. Focusing on the specific aspects of these three issues, the paper first introduces the research background, value, and challenges of UAV-based UV communication technology, and investigates the current research status of UV communication channel models and positioning techniques. In order to solve the problem of UV environmental radiation, the article goes on to introduce beamforming and power control in UV optical communication technology. To solve the problem of reducing signal attenuation and increasing the communication range, the article introduces diversity technology and networking technology. In order to balance the communication quality and communication rate during UAV movement, the article introduces adaptive modulation and adaptive coding technology. Finally, the future development direction of UAV UV communication technology is summarised.

INDEX TERMS Beamforming, channel model, coding, diversity and combining, modulation and demodulation, networking, positioning techniques, power control, ultraviolet communications.

NOMENCLATURE

AOA	Angle of Arrival
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BF	Bit-Flip
BP	Belief Propagation
CRC	Cyclic Redundancy Check
CSI	Channel State Information
DPIM	Differential Pulse Interval Modulation
DPPM	Differential Pulse Position Modulation
DSTBC	Differential Space-Time Block Coding
EGC	Equal Gain Combining
FAA	Federal Aviation Administration
FOV	Field of View
FSO	Free-Space Optical Communication
GNSS	Global Navigation Satellite System
HD	Hardware Dimming
LDPC	Low-Density Parity-Check
LED	Light-Emitting Diode
LLRBP	Log-Likelihood-Ratio Confidence Propagation
LOS	Line-of-Sight
MAC	Multiplexed Access Control
MIMO	Multiple Input Multiple Output
MISO	Multiple Input Single Output
ML	Maximum Likelihood Combining
ML	Maximum Likelihood

MRC	Maximum Ratio Combining
MS	Minimum-Sum
NLOS	Non-Line-of-Sight
OOK	On-Off Keying
PDOA	Phase Difference of Arrival
PMT	Photomultiplier Tube
PPM	Pulse Position Modulation
RF	Radio Frequency
RS	Reed-Solomon
RSS	Received Signal Strength
SC	Selection Combining
SCL	Successive Cancellation List
SD	Software Dimming
SIMO	Single Input Multiple Output
SISO	Single Input Single Output
SMRC	Selection Maximum Ratio Combining
SNR	Signal-to-Noise Ratio
SOP	Secrecy Outage Probability
SSC	Switching-Dwell
STC	Space-Time Coding
TDOA	Time Difference of Arrival
UAV	Unmanned Aerial Vehicle
UV	Ultraviolet
VLC	Visible Light Communication
VMPPM	Variable Multi-Pulse Position Modulation
VMQAM	Variable Quadrature Amplitude Modulation
VOOK	Variable On/Off Keying Modulation
VPPM	Variable Pulse Position Modulation
ABER	Average Bit Error Rate
ACM	Adaptive Coding and Modulation
AI	Artificial Intelligence
AINM	Alternative Iterative Newton Method

I. INTRODUCTION

UAV HAS a wide range of applications in the military, agriculture, forestry, animal husbandry and service industries, and has gradually spawned the 'drone +' industry model, which has had a profound impact on the development of the world economy [1]. According to the Federal Aviation Administration's (FAA) estimates, the global production of drones will be about 2.7 billion, and by 2025, the production of civilian drones will increase to 10.9 billion. The drone industry will grow by an average of 15%-20% per year over the next decade and by more than 100% in 10 years [2]. The growth of the UAV industry relies on reliable product performance, and communication technology is a major limiting factor in UAV performance. Traditional UAV communications generally use radio frequency (RF) communications, but RF communications suffer from band congestion and are susceptible to eavesdropping and jamming, which limiting the application of UAVs in certain fields. Free space optical (FSO) communication has the advantage of not being subject to electromagnetic interference. It is a feasible solution for UAV communication, such as the UAV-satellite optical communication system [3] and the optical communication system using UAVs as auxiliary relays [4]. Meanwhile, the development of FSO communication technology is of great significance to the development of UAV low altitude economy [5].

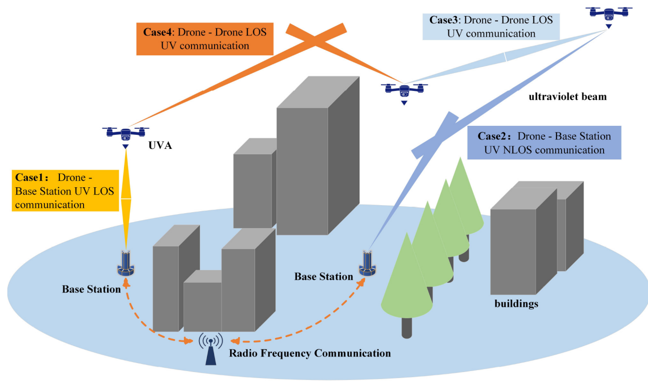

FIGURE 1. Different Link Types for UAV UV Communication.

In recent years, in the field of UAV space optical communication, UV communication technology has received more and more attention. UV communication uses UV light with a wavelength of 200nm to 280nm as a carrier wave, and mainly relies on the scattering of UV particles for signal transmission. With the development of UV LED light source and detector technology [6], [7], [8], [9], the practical value of UV communication has gradually emerged [10], [11], [12]. The basic UAV UV communication scenario is shown in Fig. 1.

Fig. 1 presents the basic scenarios of UAV UV communication according to the link structure, which is divided into UAV-UAV NLOS communication, UAV-UAV LOS networking, ground station-UAV LOS communication, and ground station-UAV NLOS communication. It is worth stating that UAV UV communication is not an alternative technology, but a supplement and improvement of the existing technology. Although UV communication is utilized in the airspace, traditional methods such as RF communication and fiber optic communication remain applicable for connections between ground stations. The reason for this choice is determined by the advantages and shortcomings of UV communication. Compared with traditional communication methods, UV communication has the following three advantages:

- Non-line-of-sight (NLOS) communications. UV particles are prone to interact with atmospheric particles and a NLOS communication link can be established through scattering. This property is suitable for communication over short distances and in complex terrain [13].
- Good confidentiality. The characteristic of UV light being easily scattered makes its signal-to-noise ratio (SNR) decay rapidly when the distance increases, and it is difficult to effectively eavesdrop information outside

the effective communication range, which is suitable for the safe networking of UAVs.
- Low background interference. UV communication uses UV light with a wavelength of 200nm to 280nm. In nature, the light in this wavelength is fully absorbed by the atmosphere, and there is little background interference, which makes it suitable for communication at any time of the day [14].

The above advantages of UV communication technology make it suitable for UAV-assisted communication, and it has a large scope in military, industrial and agricultural applications of UAVs. From a performance perspective, UV communication offers the following advantages over traditional methods such as RF communication and laser communication in terms of reliability, throughput, and performance under adverse conditions:

- Reliability: UV communication leverages its unique wavelength range (200 nm to 280 nm), which is absorbed by the atmosphere in the natural environment, effectively reducing environmental interference and the risk of signal eavesdropping [15]. This characteristic enhances the confidentiality and security of UV communication compared to RF communication. Furthermore, the use of diversity techniques and beamforming enables UV communication to maintain high signal quality in the presence of multipath effects and significant environmental noise, thereby improving communication reliability.
- Throughput: UV communication can achieve higher throughput through adaptive modulation and coding techniques that dynamically adjust the data transmission rate based on channel conditions. This flexibility allows UV communication to perform exceptionally well in scenarios with high data transmission demands. By combining multi-beam methods and appropriate MIMO coding, UV communication can achieve greater diversity gain, thus enhancing system throughput and demonstrating superior data transmission capabilities compared to traditional RF and laser communication methods.
- Performance under Adverse Conditions: In adverse environmental conditions (such as high noise and signal attenuation), UV communication can effectively control signal degradation by optimizing transmit power and adjusting beam radiation distribution, thereby maintaining good communication quality. This is particularly effective in complex terrains and short-range communication.

Despite the numerous advantages of UV communication for UAVs, it also faces several issues, including the trade-off between data rate and error rate, the detrimental effects of UV environmental radiation, and limited communication range (as detailed in Section II). For example, the enhancement of UAV UV communication distance needs to take into account not only the communication quality but also the communication rate. But they can't be realised by unlimited increase of the transmitting power, so technologies such as beamforming, adaptive modulation and coding are also needed to realize the potentials of the existing systems. However, few comprehensive discussions on the above issues have been reported in the field of UAV UV communications. As shown in Table 1, [16], [17], [18], [19] gave an introduction to the characteristics and advantages of UV communication and related technologies, [14] described the application of UV communication technology in UAV networking, starting from the advantages of UV communication technology. These articles focus on UV communication technology and do not focus on the problems that mobile platforms represented by UAVs may encounter when combined with UV communication technology. Regarding the integration of space-based optical communication with aerial platforms, [20] has established a new hovering UAV-FSO channel model, taking into account atmospheric disturbances, turbulence effects, jitter, misalignment, reception errors, and wind resistance effects. Through the reception of incoherent signals at multiple positions, the spatial diversity-assisted non-FSO communication system significantly increased the system's redundancy and connection stability. Additionally, the study investigated UAV-FSO communication channel models under different performance metrics, considering the effects of engine vibration, tilt angle, and horizontal wind resistance on the UAVs. This provides a reference for the analysis of airborne UV communication from a performance analysis perspective.

In this paper, we will focus on the key technologies involved in applying UV communication technology to UAVs from the perspective of airborne UV communication technology. Focusing on the three issues mentioned above, we will provide an account of the current state of UAV UV communication, and introduce the problems and challenges in this field.

This paper will first describe the challenges faced by UAV UV communication technology. It will then introduce channel modeling and positioning techniques, which form the theoretical foundation for UAV UV communication. Then, power control and beamforming techniques in the field of UV communication will be introduced around the problem of background radiation in FSO communication scenarios. In order to solve the problem of limited communication distance, the introduction about diversity technology and networking technology will be carried out sequentially. On this basis, we hope to maximize the information rate under the premise of guaranteeing the communication quality in dynamic communication scenarios, so adaptive modulation and adaptive coding will be introduced. At the end of the article, we will present the future trends of UAV UV communication technology.

As shown in Fig. 2, the structure of this paper is as follows. Section II explains the challenges faced by UV communication technology. Section III introduces the channel model for UV communication including analytical

TABLE 1. Main content of existing research work.

Category	Main Content	References
UV Communication	The latest advancements in NLOS UV communication systems include applications of artificial intelligence, artificial neural networks, game theory, and orbital angular momentum.	[19]
	The development history of UV communication, characteristics related to UV transceivers, and methods for improving UV communication system performance.	[16]
	The research history and current status of UV communication, including the three main issues of channel models, system analysis and design, and optical sources and detectors, as well as future research directions in UV communication.	[17]
	The latest advancements in the technology and implementation of short-range UV communication links.	[18]
UV communication for UAV swarms	Network topology of UAV swarms based on UV communication, system Bit Error Rate (BER) performance, data rate, and communication range, as well as the challenges faced in UV drone network communication.	[14]

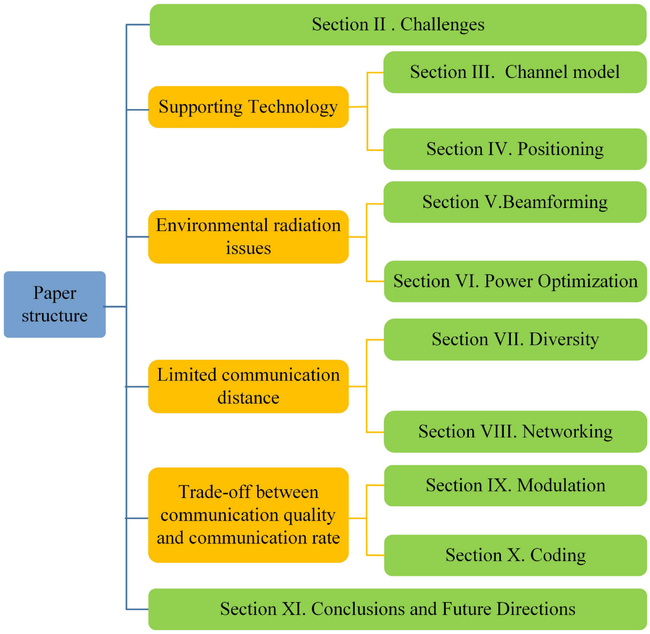

FIGURE 2. Structure of the paper.

model and Monte Carlo model, and Section IV shows the positioning techniques in UAV UV communication. Based on the two basic technologies, channel model and ranging and localization, more key technologies can be realized. Beamforming technology is introduced in Section V, power optimization technology is introduced in Section VI, diversity technology is introduced in Section VII, networking technology is introduced in Section VIII, modulation technology is introduced in Section IX, and coding technology is introduced in Section X. After completing the introduction of the above techniques, Section XI summarizes the main contribution of this paper with the development trend of UAV UV communication technology.

II. CHALLENGES

UV communication technology has garnered significant attention for its advantages in UAV auxiliary communication. It offers substantial benefits in data transmission rates due to its higher spectrum resources and bandwidth. This technology can provide UAVs with stable and high-speed data transmission channels, thereby enhancing their operational efficiency and data processing capabilities in complex environments. However, the development of this field still faces some issues. As shown in Fig. 3, UV communication is used for transmitting information between UAVs and ground stations, as well as between UAVs. For the link between UAVs and ground base stations, the uplink transmits command information, while the downlink transmits status information and media information such as audio and video. Between UAVs, UV communication can transmit status information, media, and command information. During this information transmission, variations in environmental and system parameters can negatively impact communication distance, rate, and error rate. Overall, these negative impacts mainly include three aspects:

- Environmental radiation issues. Natural environments have limited resistance to UV radiation, so the UV energy radiated into the environment by the communication system needs to be controlled, which can be solved from three aspects. The first aspect is the selection of UV bands that are harmless to the human body [21], [22], [23], [24]. The second aspect is to optimise the transmit power and reduce it as much as possible under the premise of ensuring the communication rate and communication quality. The third aspect is to change the radiation distribution of the beam to concentrate the radiation region with the strongest SNR in the vicinity of the detector, which needs to be considered in the overall design of the performance indexes such as confidentiality, BER and communication rate.
- Limited communication distance. As the communication distance increases, the energy of the UV LED outgoing signal rapidly decays, and the SNR of the system rapidly decreases, making the effective communication distance of the single input single output (SISO) UV system limited [25], [26], [27]. In order to overcome this defect, three measures can be considered. The first is to increase the transmit power of the system

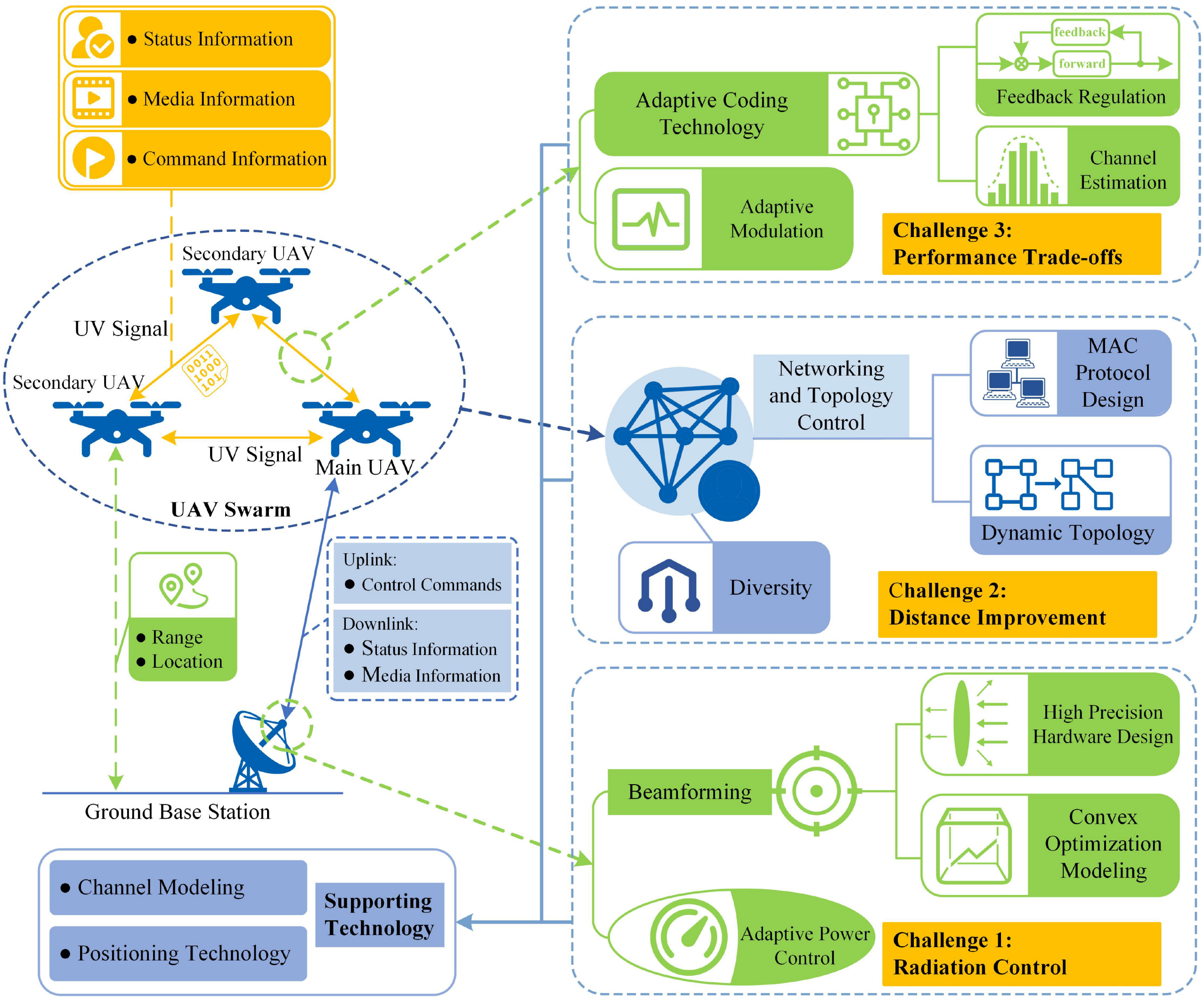

FIGURE 3. Key Technologies in UAV UV communication.

and try to establish line-of-sight (LOS) communication links with relatively low path loss and avoid NLOS links with high path loss. The second aspect is to use diversity and merging techniques to provide multiple independent fading channels in multiple dimensions, such as time, space and frequency, to increase the diversity of signals and thus reduce the impact of multipath effects and fading on the signals. The third aspect is the use of multi-hop communication or networking communication to improve signal coverage [28], [29].

- Trade-off between communication quality and communication rate during dynamic changes in UAV position. Due to the movement of the UAV, the communication link will vary between the shortest and the longest. But the path loss of the UV signal will increase rapidly with the increase of communication distance, which means the communication quality will also vary between the worst and the best. In order to optimise the communication rate while ensuring the communication quality, a coding and modulation method with higher information rate can be selected when the link distance is short. And a coding and modulation method with lower information rate but better BER performance can be selected when the link distance is long, which can be achieved by adaptive coding and modulation.

The division of the above issues doesn't have strict boundaries, and they are linked to each other. Adaptive coding and modulation are primarily used to balance BER and communication rate, while diversity and networking can enhance communication distance. Adaptive power control and beamforming techniques are used for controlling environmental interference. These technologies cover different areas but are all based on channel models and positioning technologies, as the latter provide essential status information for the practical application of other technologies. Next, this paper will begin with an introduction to the two fundamental technologies and proceed accordingly.

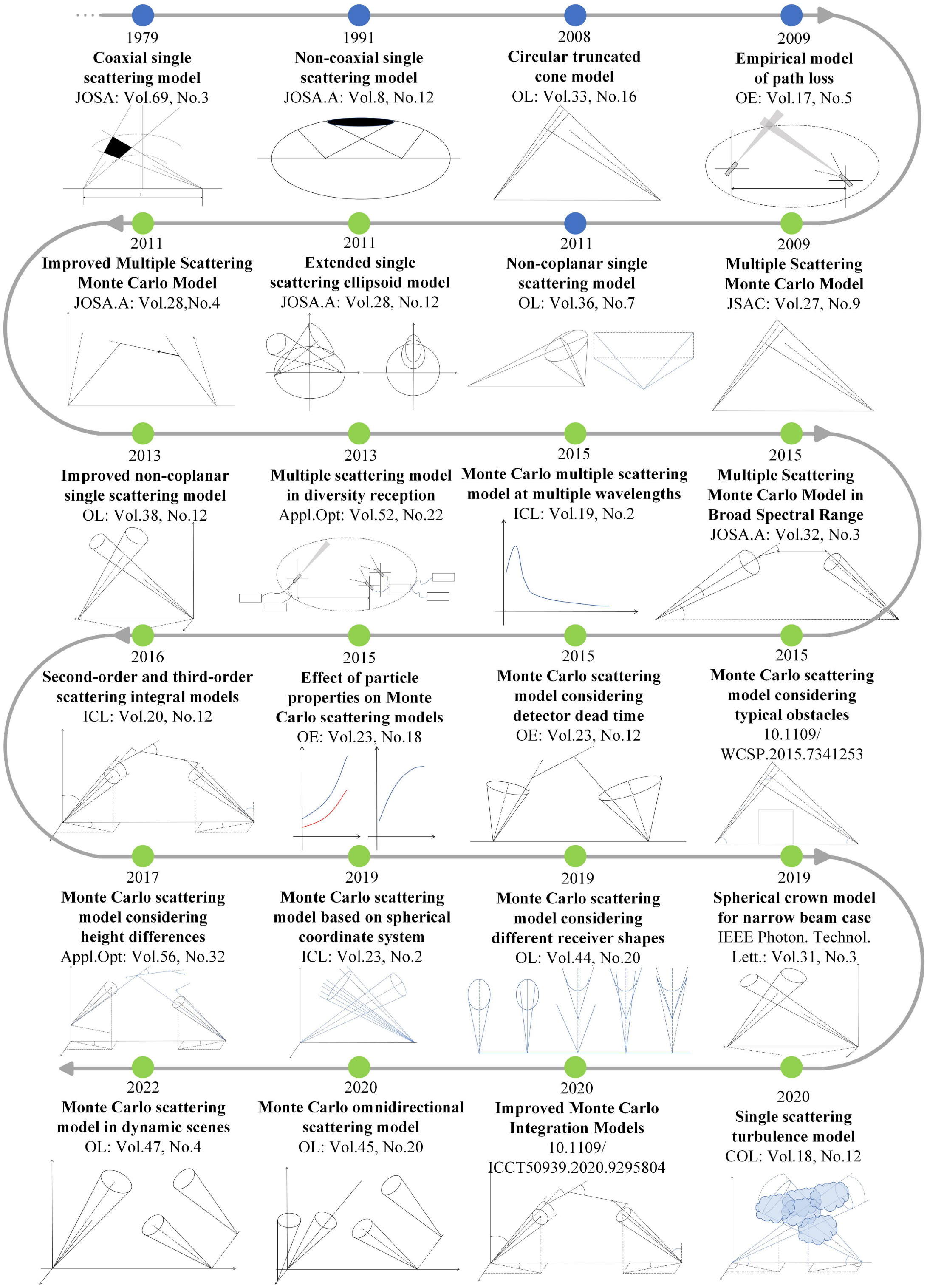

FIGURE 4. Development of channel models for UV communication.

III. CHANNEL MODELS

The channel model is the basis of UV communication research. Based on the UV channel model, the system's BER performance, upper limit of communication rate, and parameters such as transmit power can be estimated. Therefore, the establishment of an accurate and effective channel model is the basis for the study of techniques such as channel estimation, channel coding and adaptive modulation and coding. There have been a large number of research on channel models under short-range, long-range, coplanar and non-coplanar conditions in UV communications, and some related research works are shown in Fig. 4. However, the

TABLE 2. Classification of channel models.

Classification	Content	References
Analytical model	Coaxial single scattering model	[30]
	Non-coaxial single scattering model	[25]
	Circular truncated cone model	[31]
	Empirical model of path loss	[32]
	Non-coplanar single scattering model	[33]
Monte Carlo integration model	Extended single scattering ellipsoid model	[34]
	Improved non-coplanar single scattering model	[35]
	Multiple scattering Monte Carlo model	[36]
	Improved multiple scattering Monte Carlo model	[37]
	Multiple scattering model in diversity reception	[38]
	Multiple scattering Monte Carlo model in broad spectral range	[39]
	Monte Carlo multiple scattering model at multiple wavelengths	[40]
	Effect of particle properties on Monte Carlo scattering models	[41]
	Monte Carlo scattering model considering detector dead time	[42]
	Monte Carlo scattering model considering typical obstacles	[43]
	Monte Carlo scattering model considering height differences	[44]
	Monte Carlo scattering model based on spherical coordinate system	[45]
	Monte Carlo scattering model considering different receiver shapes	[46]
	Spherical crown model for narrow beam case	[47]
	Second-order and third-order scattering integral models	[48]
	Single scattering turbulence model	[49]
	Monte Carlo omnidirectional scattering model	[50]

communication system in the context of UAVs still faces new challenges, such as the relative flight of UAVs, the effects of airframe vibration and altitude changes on the quality of communication, which are potential research directions for UV communication channel modeling.

According to the classification shown in Table 2, in Fig. 4, the green markers are the studies of analytical models of UV communication channels, and the blue markers are the studies of Monte Carlo scattering models. According to the existing studies, UV channel models can be classified into the following categories: coplanar models, non-coplanar models, approximate models and Monte Carlo models. In 1979, Reilly et al. established a single scattering model for the first time based on the ellipsoidal coordinate system, and analysed the time-domain characteristics of the single-scattering information transmission as well as the effects of Rayleigh scattering and Mie scattering. But the model was limited to the case of co-axiality of the transceiver and the transmitter/receiver [30]. To remove this limitation, in 1991, Luettgen et al. extended the single scattering model to the case of non-coaxiality at the receiver and transmitter and investigated the angular spectrum of the received energy, the impulse response and the path loss [25]. Both models [25], [30] contain multiple integrals, which are more complex in form and bring difficulties in studying the laws of the UV channel and in practical applications. In 2008, Xu et al. obtained a closed-form expression for calculating the path loss based on the single scattering theory of [31] by approximating the effective scattering volume as a circular table, and analysed the relationship between data transmission rate and distance. In order to obtain a simple and accurate channel model, in 2009, Chen et al. established an empirical model of path loss by fitting based on outdoor experimental data and analysed the relationship between the communication performance and the transmit power, the communication distance, the pitch angle and the data transmission rate based on the model [32]. In terms of non-coplanar models: in order to extend the single scattering model to the non-coplanar case, in 2011, Elshimy et al. derived a single scattering model for the non-coplanar case based on the ellipsoidal coordinate system [33]. In the same year, Wang et al. proposed a closed-form expression for the single-scattering model considering the non-coplanar case based on the spherical coordinate system. The results showed that the results were compatible with those of [32] when the angle between the axes of the transceiver and the transmitter were small [34]. In 2013, Zuo et al. obtained a closed-form expression for the non-coplanar approximation model based on the non-coplanar exact model, which is more accurate compared to [33], [35].

The above UV channel model only considers the role of single scattering, with the increase of transmission distance, the role of multiple scattering becomes more obvious, and the law of multiple scattering is more complex, it is difficult to analyse it with analytical models. In 2009, Ding et al. used the idea of light tracing to establish a Monte Carlo simulation model for UV scattering communication, which takes into account the role of multiple scattering [36]. In 2011, Ding et al. improved the model of [36], and the improved model converges faster and is more robust, and it is able to efficiently capture the received energy contributed by different scattering times as well as the impulse response [37]. Due to the flexibility of the Monte Carlo model in application, the researchers also studied the diversity reception [38]; scattering communication performance at different wavelengths [39], [40]; the effect of aerosol density and particle size on UV scattering communication based on the model [41]; the effect of photon counter dead time [42]; the effect of typical obstacles [43]; and the effect of height difference between receiver and transmitter [44].

In 2019, Wu and Shen et al. proposed a single scattering integral model based on the spherical coordinate system, including the structure of the effective scattering volume closed and open, and the geometrical rules for the division of communication scenarios [45], [46]. In order to reduce the computational complexity, Wu et al. established a single scattering approximation model for the case of small divergence angle [47]. In 2016, Yuan et al. developed the first integral model for secondary and tertiary scattering [48]. In 2020, based on the approximate model, Shan et al. investigated the effect of turbulence on the UV channel [49]. Since the analytical model is limited by a specific geometric structure, Yuan and Shen et al. improved the Monte Carlo integral model in 2019 and 2020, respectively, to improve the computational efficiency [51], [52]. In order to promote the practicality of UV communication, in 2020, Shen and Shan et al. investigated the receiver-transmitter jitter model for UV communication [53] and the omnidirectional communication model [50], which further improved the channel model for UAV UV communication. Reference [54] studied the path loss of non-line-of-sight (NLOS) UV communication systems in monodisperse and polydisperse aerosol systems, and found that the state of aerosol mixing has a significant impact on the performance of the communication system. Reference [55] has proposed an experimental system for precise measurement of UV channel and communication characteristics. The system comprises a transceiver system with a gimbal, UV light-emitting diode array, and photomultiplier tube detector, along with a LabVIEW-based data acquisition subsystem. Additionally, the article introduces novel techniques for accurately characterizing the radiation pattern of the UV LED array, absolute transmit power, and the field-of-view (FOV) of the detector.

For representing the model of UV communication channels, whether using analytical models or Monte Carlo models, the key to performance improvement lies in approximating irregular spatial geometries. For example, in the analysis of three scattering models in [56], their differences lie in the approximation methods of the scatterer. When the scatterer is approximated as a truncated cone, the path loss is given by:

$$L \approx \frac{96r \quad sin\theta_1 \quad sin^2\theta_2\left(1-cos\frac{\phi_1}{2}\right)exp\left[\frac{k_e r(sin\theta_1+sin\theta_2)}{sin\theta_s}\right]}{k_s P(u) A_r \phi_1^2 \phi_2 sin\theta_s\left(12sin^2\theta_2+\phi_2^2 sin^2\theta_1\right)}. \quad (1)$$

When the scatterer is approximated as a cuboid, the path loss is:

$$L \approx \frac{2\pi r \quad sin\theta_1\left(1-cos\frac{\phi_1}{2}\right)exp\left[\frac{k_e r(sin\theta_1+sin\theta_2)}{sin\theta_s}\right]}{k_s P(u) A_r \phi_1^2 \phi_2 sin\theta_s}. \quad (2)$$

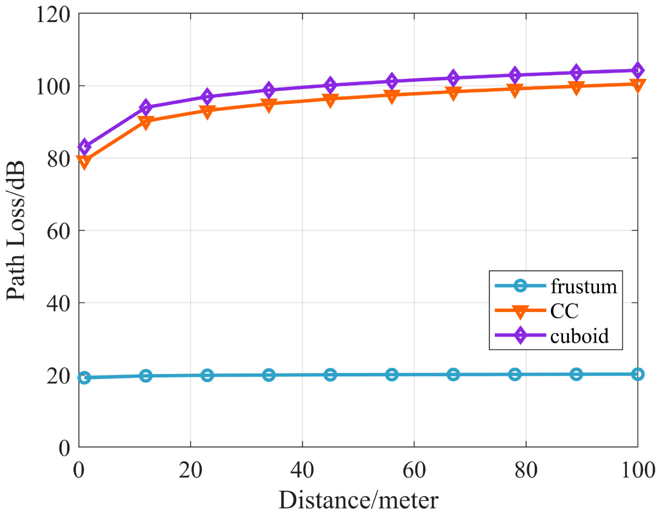

FIGURE 5. Three Approximations of Path Loss.

When the scatterer is approximated as cut and complement, the path loss is:

$$L \approx \frac{2\pi r^4 \quad sin^2\theta_1 sin^2\theta_2\left(1-cos\frac{\phi_1}{2}\right)exp\left[\frac{k_e r(sin\theta_1+sin\theta_2)}{sin\theta_s}\right]}{k_s P(u) A_r V sin^4\theta_s}, \quad (3)$$

r represents the distance between the transmitter and receiver, θ_1 and $\theta_2$are the elevation angles of the transmitter and receiver, ϕ_1 and ϕ_2 are the elevation field-of-view angles of the transmitter and receiver, and $k_e = k_a + k_s$ is the scattering coefficient. $A_r$is the area of the receiving detector, and $P(u)$ is the scattering phase function, determined by the following formula:

$$\begin{cases} p(cos\theta_s) = \frac{k_s^{Ray}}{k_s} p^{Ray}(cos\theta_s) + \frac{k_s^{Mie}}{k_s} p^{Mie}(cos\theta_s), \\ p^{Ray}(cos\theta_s) = \frac{3\left[1+3\gamma+(1-\gamma)cos^2\theta_s\right]}{16\pi(1+2\gamma)}, \\ p^{Mie}(cos\theta_s) = \frac{1-g^2}{4\pi}\left[\frac{1}{(1+g^2-2gcos\theta_s)^{\frac{3}{2}}} + f\frac{3cos^2\theta_s-1}{2(1+g^2)^{\frac{3}{2}}}\right]. \end{cases} \quad (4)$$

Simulations of path loss for the three aforementioned scenarios are shown in Fig. 5. From Fig. 5, it can be seen that the path loss when the scatterer is approximated as a cuboid is greater than when the scatterer is approximated as cut and complement, and the path loss when approximating the scatterer as cut and complement is greater than when approximating it as cuboid. This indicates that the closer the approximation method and mathematical representation of the common scatterer are to the actual situation, the higher the accuracy of the resulting model.

Research on UV static channel modelling is now relatively well developed, and the underlying logic of much of the work described in this chapter is based on the scattering theory of UV particles. Incorporating the UV communication channel model into a specific real-world scenario, considering more channel details, and aiming to improve the accuracy of the model are the general ideas of channel modelling research.

IV. POSITIONING

In Section III, we introduced the development of the basic theory of UV communication channel model. This section will introduce the current research status of the basic technology, UV communication positioning technology. In techniques such as beamforming, power optimisation and adaptive modulation and coding, position information are the basis for algorithm execution. In UAV swarm network communication scenarios, accurate position and distance information is the basis for achieving efficient, safe and reliable formation operations. Positioning technology plays a key role in achieving efficient cooperative operations, avoiding collisions, and optimising resource utilisation [57]. The positioning of the communication system is based on a specific channel structure, regardless of visible light communication (VLC) or UV communication, the energy of NLOS channel is much lower than that of LOS channel, so most of the current mainstream positioning methods are based on LOS channel, and only some research in the field of UV communication will focus on considering the positioning technology under the condition of NLOS channel.

In the field of VLC, which is dominated by LOS channels, the accuracy of positioning techniques has reached centimetre-level [58], [59], [60]. LOS link-based positioning methods mainly achieve positioning through measurements of received signal strength (RSS), time difference of arrival (TDOA), phase difference of arrival (PDOA), and angle of arrival (AOA), which require multiple LOS links to estimate the user's location [61], [62]. The basic principle of the RSS method is that the received signal power decreases as the distance between the receiver and transmitter increases. According to this principle, it is possible to measure the distance in one-dimensional space and the position in two-dimensional space [63], [64]. However, the effects of obstacles and reflected signals mean that the relationship between distance and RSS is difficult to determine, which limits the accuracy of the RSS method. TDOA or PDOA utilise the time difference or phase difference of multiple received signals to make position measurements, and both they require the transmit signals to be perfectly synchronised in order to achieve a high level of accuracy in the measurement [64]. Currently, AOA is a more feasible method because it can achieve high positioning results through a relatively simple optical system [65].

However, the above studies are based on two-dimensional localization, and UAVs need three-dimensional spatial localization information. Generally speaking, three-dimensional localization is based on two-dimensional localization to determine the height of the receiver. In [66], researchers divided the three-dimensional space into several two-dimensional planes, and determined the receiver's position in each two-dimensional plane based on the difference of the angular gain. The three-dimensional localization algorithm proposed in the paper achieved an average localization accuracy of 3.5 cm. In [67], Yang et al. proposed an indoor 3D localization system combining a single transmitter with multiple tilted receivers, using the AOA method for 2D localization and RSS for 3D localization. The method achieved a positioning accuracy of within 6 cm in an indoor environment of 2m×2m×2.5m. In [68], Wang et al. proposed a 3D uplink indoor positioning system based on distributed receivers, which uses acceleration sensors to obtain angular information and does not require positioning assumptions about the mobile user's height or orientation angle. In [69], Gu et al. proposed assuming the height in the prediction stage and using nonlinear estimation in the correction stage to realize the 3D coordinate estimation of the height from 0.7 m to 1.7 m. In [70], Yin et al. used an angle diversity transmitter associated with an accelerometer for uplink 3D localization. In [71], Xu et al. used two ring receivers mounted with multiphotodiodes to localize the led light source. The design uses multiphotodiodes to calculate the angle, while the RSS method is used to calculate the distance, and the localization error is within 0.2 m. Regarding the positioning error, the current reports are mostly based on the GNSS-based UAV ranging and positioning accuracy level division: positioning accuracy within 5m is Healthy, positioning accuracy within 5m-13m is Slightly shifted, positioning accuracy within 13m-23m is inaccurate, and positioning accuracy more than 23m is dangerous [72].

The above is the localization technique in VLC based on LOS link, at present, there are fewer reports related to UAV UV communication localization technique on LOS link, and most of the studies are based on UV NLOS link. However, this does not mean that the performance of UV NLOS positioning technology is superior to LOS positioning technology, as the latter has smaller path loss at the same distance and can achieve higher accuracy. We can take an example of positioning in one-dimensional space to see how UV NLOS communication and LOS communication perform under different atmospheric extinction coefficients and different distances. The expression for the received optical power in the UV communication link is:

$$P_{r,LOS} = \frac{P_t A_r}{4\pi r^2} e^{-K_e r}. \tag{5}$$

By manipulating this formula, we obtain the distance calculation formula for LOS conditions:

$$r = \frac{2lambertw\left(\frac{1}{4}\sqrt{\frac{P_t A_r K_e^2}{\pi P_{r,LOS}}}\right)}{K_e}. \tag{6}$$

Similarly, the expression for the received power in NLOS communication is:

$$P_{r,LOS} = \frac{P_t A_r K_s P_s \phi_1^2 \phi_2 sin(\theta_1 + \theta_2)}{32\pi^3 r \quad sin\theta_1 \left(1 - cos\frac{\phi_1}{2}\right)} e^{\frac{K_e r(sin\theta_1 + sin\theta_2)}{sin(\theta_1+\theta_2)}} \tag{7}$$

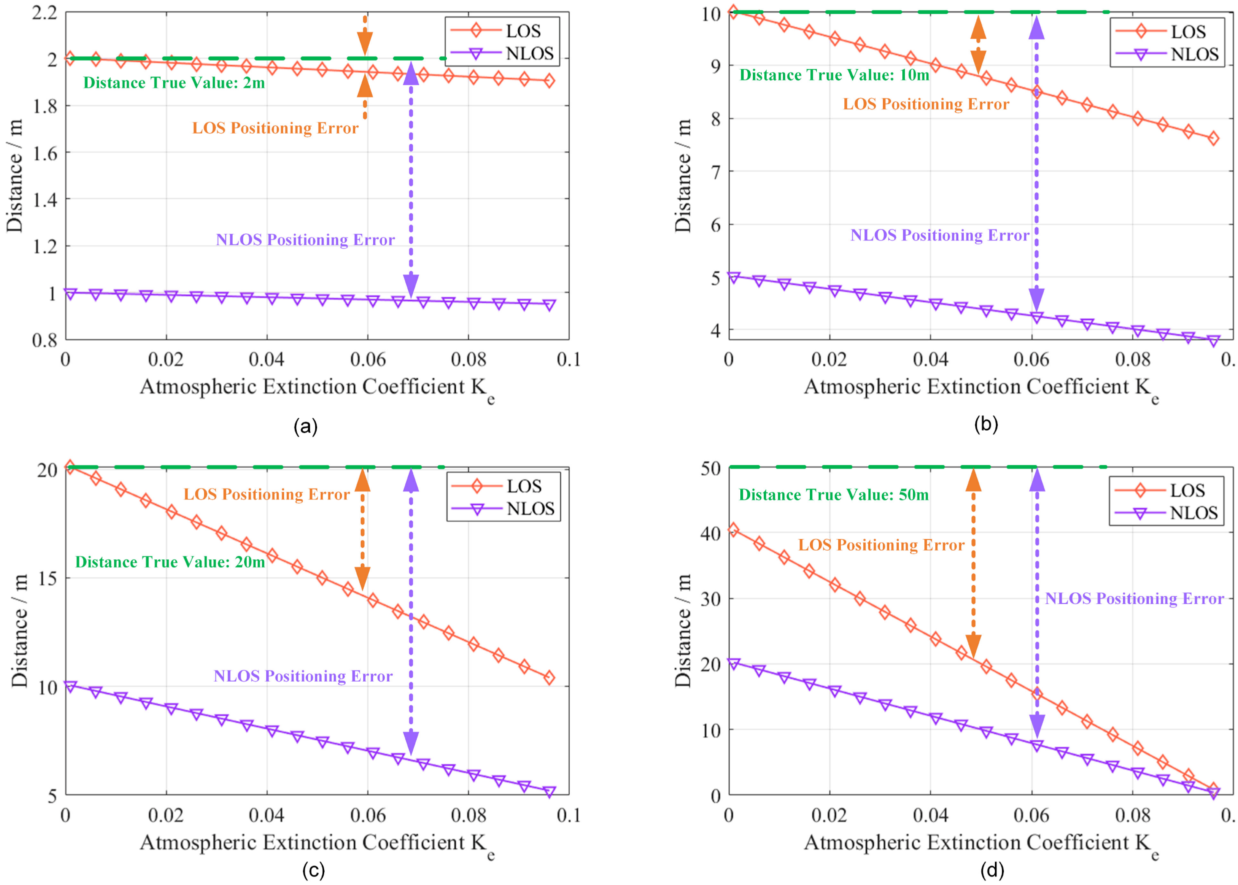

FIGURE 6. The curves of positioning results varying with the extinction coefficient Ke. (a) r = 2m. (b) r = 10m. (c) r = 20m. (d) r = 50m.

By manipulating this equation, the distance from the transmitter to the receiver in NLOS conditions is:

$$r = \frac{lamberw\left(\frac{P_t A_r K_s K_e P_s \phi_1^2 \phi_2 (sin\theta_1 + sin\theta_2)}{P_{r,NLOS} 32\pi^3 sin\theta_1 \left(1 - cos\frac{\phi_1}{2}\right)}\right)}{\frac{K_e(sin\theta_1 + sin\theta_2)}{sin(\theta_1+\theta_2)}}. \quad (8)$$

In the above four formulas, P_t represents the transmitted power, A_r is the aperture area of the receiver, P_s is the scattering phase function, K_s is the atmospheric scattering coefficient, and K_e is the atmospheric extinction coefficient. ϕ_1 is the FOV at the transmitting end, ϕ_2 is the FOV at the receiving end, θ_1 is the elevation angle at the transmitting end, and θ_2 is the elevation angle at the receiving end. $P_{r,NLOS}$ is the received optical power. Based on Eq. (6) and Eq. (8), plot the UV LOS and NLOS positioning results at different communication distances as the extinction coefficient varies.

Set $P_t = 200mW$, $A_r = 0.001m2$, $\phi_1 = 10°$, $\phi_2 = 20°$,$\theta_1 = 30°$,$\theta_2 = 30°$. K_e varies between 0.001 and 0.1, and the standard distances are 2m, 10m, 20m, and 50m, respectively, to obtain the positioning distance versus extinction coefficient curves shown in Fig. 6.

From Fig. 6, it can be observed that at shorter communication distances, the LOS positioning error and NLOS positioning error differ significantly, with their curves approximating parallel, indicating a clear advantage in precision for LOS positioning. As the communication distance increases to 10m, 20m, and 50m, both the LOS and NLOS positioning errors gradually increase and become more similar. This is because with the increase in communication distance, both the LOS and NLOS links experience significant signal attenuation, no longer meeting the centimeter-level positioning accuracy. At very long distances, even meter-level or even tens of meters of accuracy are difficult to achieve. However, since the transmitted power in the above simulation is set at 200mW, increasing the power would expand the range of accurate positioning. Based on the above analysis, it is evident that the advantage of UV positioning is limited to NLOS positioning within a certain range, and LOS positioning is not its primary characteristic. Therefore, researching UV NLOS positioning technology within a certain range is reasonable and necessary. Reference [73] has, for the first time, realized a pulsed UV laser positioning system based on 4H-SiC 4-QD. The system demonstrates high uniformity in performance across all four quadrants, including low dark current and high UV responsivity. By utilizing Charge Storage Amplifiers (CSAs) as an effective method for linear amplification of photocurrents, the system exhibits excellent linearity and high positioning accuracy. Furthermore, a prototype laser beam deflection angle self-calibration system has been developed, achieving low-error angle calibration. Reference [74] introduces a NLOS ranging method based on UV-C band communication, which does not require prior knowledge of the directions of the transmitter and receiver. Detailed sensitivity analysis is performed through Monte Carlo simulations, considering key parameters such as background noise, shot noise, photon sampling time, spacing between spatial samples, and steering angle errors. Based on this analysis, the article proposes a method for range estimation using UV-C links in complex GPS-denied NLOS scenarios. Reference [75] derived the geometric and physical constraints for NLOS UV positioning using linearly-arrayed receivers. Subsequently, the article derived the analytical relationship between the location parameters and pointing parameters of an unknown transmitter and proposed a NLOS UV positioning method with acceptable computational complexity. Simulation results indicate that the NLOS UV positioning method using photon-counting receivers can achieve a distance error less than 2 meters when the transmitting elevation angle is greater than 30 degrees and the separation distance is greater than 2 meters. Reference [76] proposed an UV NLOS positioning method based on a simplified single-scattering channel model, which can simultaneously obtain the positioning and pointing direction of the transmitter. Numerical results demonstrate that, under typical transceiver geometries within a 100-meter range, using two photon-counting receivers can achieve a positioning error less than 2 meters and an azimuth error less than 2 degrees. Additionally, the article found that the positioning performance can be improved by increasing the gap between the two receiving elevation angles. Reference [77] proposed a method of NLOS link incidence angle estimation based on the energy received by the detector array, similar to the RSS method in the LOS link localization technique, which requires that the transmitter is pointing at the receiver in a certain dimension. However, the transmitter in a real UV communication system can point in any direction, so there are major limitations in realizing localization using this method. Reference [78] designed a UAV swarm UV communication landing assistance system and studied the optical power distribution of UV LED arrays, the article based on the Lambert irradiance characteristics of UV LEDs. As the number of LEDs in the array at the transmitter end increases, the power distribution tends to be uniform. As the inclination angle of the receiver increases, the received optical power becomes smaller, and when the receiver angle is fixed, there exists a Lambertian order that maximizes the received optical power. The design is essentially a positioning technique similar to the MISO structure. Reference [79] then studied the UAV UV communication and positioning system with different structures, and investigated the SNR and the effect of the receiver and transmitter elevation angles of the SIMO system, the MISO system, and the MIMO system on the above mentioned indexes of the BER. The results show that increasing the number of transceiver devices can effectively improve the quality of UAV swarm UV communication, which in turn improves the accuracy of ranging, localization and swarm control.

In addition to the methods that use LOS links or NLOS links alone to achieve localization, some researchers have also considered both LOS and NLOS scenarios to solve for the coordinates of the point to be localized. Based on the four-node localization method, [80] arranged the UV LEDs into a spherical structure and placed the omnidirectional receiver at the top of the spherical structure. The method can achieve more than 80% localization accuracy in a space with a length, width and height of 200m with an average error of less than 10m.

Distinguishing from the above localization algorithms, UV image localization is also an important localization method. Whether it is coarse localization by using the position change of UV light points in the image or precise localization by using the four-quadrant offset of the UV beam, these approaches have important applications on mobile platforms such as UAVs. Reference [81], [82], [83] proposed a fast localization method for indoor and outdoor UAVs with the help of UV LEDs and named the system UVDAR. The researcher proved through experiments that the system can guarantee the accuracy of relative positioning between UAVs, and the positioning error is less than 0.02 rad in a distance of more than 3m. Then, [84] proposed a wireless communication system based on UV camera based on the above UVDAR system, which decodes the original position information by processing the image captured by the UV camera. At the same time, the transmitter's position is tracked using Kalman filtering, and the transmitted signals from multiple UAVs are processed simultaneously using 4D Hough transform. UVDAR technology further enhances the effectiveness of UV positioning. Compared to traditional UV positioning technologies, UVDAR does not require complex communication networks and possesses strong environmental adaptability, maintaining stability and accuracy in various environments. Additionally, UVDAR is particularly suitable for formation control of multi-rotor UAVs, capable of guiding follower UAVs to maintain given three-dimensional positions and orientations relative to the lead UAV. Successful validations under stringent outdoor conditions have paved the way for the application of UVDAR in actual multi-UAV formations. The innovative significance of UVDAR technology in UV communication positioning lies mainly in its provision of a new method for relative positioning between UAVs without the need for complex communication infrastructure. By utilizing UV light for real-time control, it offers new possibilities for UAV formations to operate within small teams. Overcoming the limitations of traditional positioning technologies in complex environments, UVDAR technology provides greater flexibility and reliability for UAV applications in various settings through the use of the UV spectrum for relative position and yaw measurements.

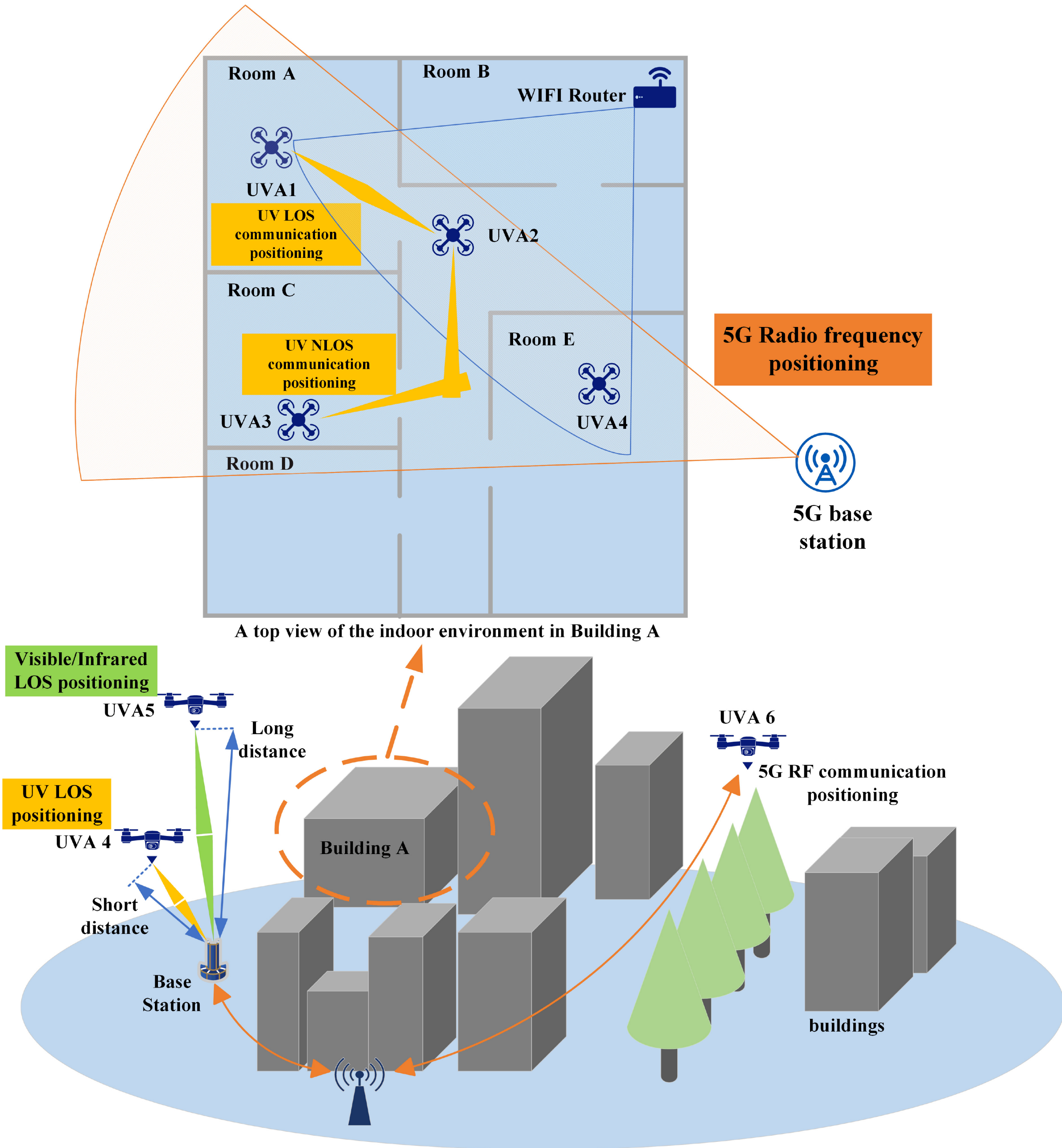

FIGURE 7. Battlefield Search and Rescue.

To more specifically demonstrate the advantages of UV communication, we have chosen the case of battlefield search and rescue, where there are two types of positioning needs: outdoor wide-area positioning and indoor small-area positioning. The positioning methods for drones are set as UV LOS positioning, UV NLOS positioning, VLC positioning, WIFI communication, and 5G radio frequency communication positioning, respectively. The optimal communication method needs to be selected under different conditions. As shown in Fig. 7, UAV1-UAV4 are conducting search and rescue operations indoors, while UAV5-UAV7 are conducting search and rescue operations outdoors.

- If the enemy is not conducting RF signal interference at this time, then UAV1-UAV7 can all choose 5G RF communication for positioning, with a positioning accuracy of 2m-3m. However, for indoor positioning, if higher accuracy is required, it is necessary to further select WIFI positioning technology. But when the walls of the building are thick, it is difficult to establish a stable connection with WIFI positioning (as shown in Fig. 7, the signal generated by the WIFI router is difficult to continue propagating to UAV3 after passing through the walls). In this case, the NLOS positioning technology of UV communication can be used as a supplementary means. At the same time, due to factors such as the ease of WIFI signal leakage and difficulty in implementation, the feasibility of using WIFI positioning is not high. Therefore, UV positioning technology becomes the best choice for indoor NLOS situations (as shown in Fig. 7, the mutual positioning between UAV2 and UAV3).

- If the enemy is conducting RF signal interference at this time, then UV communication, VLC, or infrared communication can be chosen for outdoor operations. If it is necessary to avoid the light source being monitored (for example, visible light should be avoided at night), UV positioning technology can be selected. The positioning accuracy can reach the centimeter level, but it is limited to small-scale communication and positioning (i.e., the positioning technology used by UAV4 in Fig. 7). When a larger communication range is required, infrared positioning technology with lower path loss can be chosen, achieving centimeter-level accuracy (i.e., the positioning technology used by UAV5 in Fig. 7). However, the drawback of infrared positioning is that it cannot achieve NLOS positioning. In large-scale NLOS positioning scenarios, UV positioning technology is still needed. If avoiding the monitoring of the light source is not necessary, in large-scale LOS communication scenarios, visible light positioning technology with even lower path loss can be chosen.

The aforementioned scenarios demonstrate the advantages of UV communication technology in indoor and outdoor positioning, which can be summarized as the capability to achieve NLOS positioning and high confidentiality. To make the comparison clearer, we summarize the characteristics of UV communication and conventional communication, as shown in Table 3.

As shown in Table 3, various positioning methods have their own characteristics. RSS positioning is simple but limited by channel conditions; TDOA and PDOA have high accuracy but are complex to implement; AOA relies on known channel information and has low expandability. Visual positioning equipment is simple but has limited accuracy; UV communication positioning includes LOS, NLOS, and combined positioning, with strong adaptability but requires LOS conditions; UV image positioning is efficient but cannot adapt to NLOS situations. 5G RF and WiFi positioning technologies are mature but have limited accuracy; LIDAR positioning is accurate but costly. Generally, each method has its unique advantages and limitations, and the choice of the appropriate positioning technology should be based on the specific application scenario, environmental conditions, and accuracy requirements. However, another approach is to promote the integrated development of various technologies. For the topic of this article, two types of integrations can be considered: RF communication positioning + UV communication positioning, and WiFi communication positioning + UV communication positioning. Table 4 shows the effects that can be achieved with these two integrated technologies.

This section presents the methods and characteristics of UV communication positioning, and compares its advantages over traditional positioning methods such as VLC and RF communication. This is achieved through the use of NLOS signals that do not rely on reflective surfaces for positioning. This advantage is both a feature of UV communication and its positioning technology. However, this does not mean that UV communication positioning technology is superior to traditional positioning technology in all cases, as both have their own application scenarios and advantages. The former is suitable for NLOS scenarios such as indoor search and rescue, small-scale communication on the battlefield, etc., while the latter is more suitable for conventional communication scenarios. Therefore, in future research, the NLOS advantages of UV communication should be fully utilized to optimize existing LOS and NLOS positioning technologies. At the same time, UV communication, as a supplement to traditional communication methods, combines with traditional positioning technologies (such as GPS, WiFi, RF, etc.), which is another important research direction. This is because the fusion of multi-source information can significantly improve the accuracy and reliability of positioning. In addition to the above two aspects, with the development and maturation of UV detection devices, the miniaturization, noise resistance, resolution, and sensitivity of large-scale UV detector arrays are gradually improving, which provides the possibility for the practical application of UV image positioning technology.

V. BEAMFORMING

Although UV communication has the advantage of high confidentiality due to its high path loss, in UAV UV communication scenarios, there is still the risk of eavesdropping due to the random movement of the transceiver. In MIMO and network communication scenarios, interference between links is a more difficult problem than the eavesdropping risk. Therefore, we hope that the transmitter can generate directional beams with specific parameters so that the SNR near the receiver is high and in the area outside the receiver is low, thus minimizing the risk of eavesdropping. At the same time, we also want to minimize inter-link interference in MIMO and network communication scenarios. In order to achieve the above goals, beamforming technology is one of the solutions that can be used [93].

In the field of adaptive antenna, the beamforming technique weights and synthesizes the vector signals generated by multiple antenna array elements to suppress the non-target direction signals and form the target direction signals. And in the field of intensity modulation and direct detection of FSO communication, its channel is a Gaussian scalar channel, not a vector channel, so beamforming is generally realized by controlling the optical power [94]. Unlike conventional beamforming, the tuned signal driving the LED must satisfy certain current amplitude constraints to avoid distortion during the switching process. So current amplitude constraints rather than power constraints are usually imposed when assigning shape to the LED beam [95], [96]. The design of the

TABLE 3. Characteristics of different positioning methods.

Name	Principle	Accuracy	Advantages	Disadvantages	Application Scenarios	References
VLC RSS	Distance is estimated by measuring the power of the received wireless signal, which is inversely proportional to the distance. The receiver collects RSSI values and converts them into distance estimates after comparing with reference values.	Error is less than 5cm within a range of 60cm×60cm.	Simple and easy to implement in hardware.	High requirements for channel conditions; accuracy is low when there are floating particles or obstacles in the channel.	Indoor short-range positioning, such as smart homes and indoor navigation.	[85]
VLC TDOA	Distance is estimated by the time difference of arrival of signals emitted from a light source at the receiving end.	Error is less than 5.3cm within a space of 50cm×50cm.	Does not require the use of atomic clocks for high-precision synchronization, reducing reliance on high-performance devices.	Difficult to implement.	Indoor positioning requiring higher precision, such as high-precision positioning systems in unmanned factories.	[86]
VLC PDOA	The direction of signal arrival is determined by using the phase difference of the same signal received by multiple receivers, and the signal's direction of origin is calculated based on the relationship between phase difference and angle.	Average 2D tracking error is 4.3 cm, and average tracking error in 3D tracking scenarios is 9.3 cm.	High precision.	Depends on a high-precision synchronization system and analog-to-digital conversion devices, high cost, and high computational complexity of the algorithm.	Situations requiring high-precision positioning, such as precision instrument control.	[87]
VLC AOA	Uses trigonometry to locate by determining the angles between the user device and multiple positioning anchors.	Angular resolution is less than 1 degree when the distance between the detector and the light source is greater than 3cm.	High precision.	Relies on known channel information, low expandability.	Situations requiring determination of the direction of signal origin, such as indoor positioning and navigation.	[88]
VLC Visual positioning	Uses a camera or image sensor to receive VLC signals, thereby obtaining the ID and position information of the LED.	The minimum error can reach 6.5cm.	Simple equipment, low cost.	Limited precision, and each target object's position is encoded to create a graphic code.	Situations requiring high-precision positioning, such as precision instrument control and robot navigation.	[89]

(Continued)

TABLE 3. Characteristics of different positioning methods (Continued).

Name	Principle	Accuracy	Advantages	Disadvantages	Application Scenarios	References
UV NLOS Link Positioning	Utilizes the characteristics of UV NLOS channels to calculate the distances between multiple light sources and detectors, and then determines the detector's position based on spatial geometric relationships.	Error less than 3 degrees in static scenes, and less than 7 degrees in dynamic scenes.	Can achieve non-line-of-sight positioning that does not rely on reflective surfaces.	Requires the transmitter to point in one dimension towards the receiver, limiting the use of scenarios.	Outdoor positioning in complex environments such as cities and forests.	[77]
UV LOS and NLOS Link Combined Positioning	Estimates the position of the receiver by combining LOS and NLOS channel information.	Error below 10m within a range of 200m.	Wide application range, strong anti-interference capability.	Depends on accurate channel models.	Suitable for indoor and outdoor positioning requiring high precision and strong adaptability.	[80]
UV Image Positioning	Processes the images captured by the UV camera to decode the original position information. Simultaneously, uses Kalman filtering to track the pose of the transmitter and uses 4D Hough transform to process the transmission signals from multiple drones simultaneously.	Achieves stable communication connections in a 320-degree horizontal field of view and a 110-degree vertical field of view.	Can process multiple positional information in parallel, high efficiency.	Unable to adapt to non-line-of-sight situations.	High-precision positioning scenarios such as drone navigation, robot positioning, etc.	[84]
5G RF-based Localization	Estimates the position of the receiver using RSS, TOA, TDOA, and AOA, etc.	Typically between a few meters to tens of meters.	Mature technology, relatively low cost, easy to deploy.	Affected by multipath effects, signal attenuation, and occlusion, with limited precision.	Suitable for high-speed transmission and high-precision positioning scenarios such as autonomous driving, smart transportation, etc.	[90]
WiFi Communication Positioning	Determines the position by measuring the received wireless signal strength (RSSI) or signal propagation time.	Several meters in indoor environments, and has poor accuracy in outdoor environments.	Simple deployment, low cost, wide signal coverage.	Affected by signal interference, with unstable positioning accuracy, and high power consumption.	Suitable for indoor short-range positioning, such as smart homes, indoor navigation, etc.	[91]
Laser LIDAR Positioning	Measures the distance between the target and the sensor through laser scanning, combined with camera or radar images to determine the position.	Up to centimeter level, especially in short distances.	High precision, not affected by radio interference, suitable for complex environments.	High cost, sensitive to environmental light	autonomous driving, robot navigation, etc.	[92]

TABLE 4. UV communication integrated positioning method.

Positioning Methods	Characteristics
RF Communication Positioning	• Advantages: Mature technology, widely used, with a broad coverage area. Relatively low cost, easy to deploy. • Disadvantages: Limited positioning accuracy due to multipath effects and signal attenuation. Highly susceptible to environmental interference and obstructions.
UV Communication Positioning	• Advantages: High precision positioning over short distances. Strong anti-interference capability, less affected by radio signal interference. • Disadvantages: Relatively low technology maturity, higher cost. Limited coverage area, mainly used for specific regions.
WIFI Communication Positioning	• Advantages: Wide signal coverage, simple deployment. Supports high-speed data transmission, suitable for applications with large data volumes. • Disadvantages: Positioning accuracy is greatly affected by the environment, easily interfered with. High power consumption, not suitable for continuous operation over long periods.
RF Communication and UV Communication Fusion Positioning	Combines the broad coverage of RF communication with the high precision positioning advantage of UV communication. Improves the robustness and adaptability of the positioning system, especially in complex and changing environments. Increases in cost and technical challenges, requiring more complex data fusion algorithms.
WIFI Communication Positioning and UV Communication Fusion Positioning	Combines the wide coverage and high-speed data transmission capabilities of WIFI communication, along with the high precision positioning advantage of UV communication. Suitable for indoor and outdoor positioning, especially in scenarios requiring high-speed data communication. Higher system complexity, greater cost and technical challenges.

beamforming system is mainly based on this principle in VLC, which is dominated by the LOS channel, and in UV communication, which is dominated by the NLOS channel.

In the field of UV beamforming, the researchers proposed an indoor UV dynamic beamforming system based on positioning technology, which utilizes the user's position information in the current phase to realize beamforming in the next phase. However, the study was conducted based on the UV LOS channel, and beamforming in the UV NLOS channel has not been considered [97]. In the same year, Sudhanshu Arya et al. considered the LOS link and NLOS link in MIMO channel, and modeled the downlink beamforming problem as a second-order cone planning problem to maximize the SNR at the receiving end [98]. In addition to this, little research has been reported on UV beamforming, in contrast, beamforming research in the field of VLC is more abundant. Based on the similarity between UV communication and VLC in terms of hardware model, LOS channel and information processing, we can get some inspirations from beamforming technology in VLC field [99].

The first is the use of beamforming to enhance the confidentiality of the signal transmission process. Wyner has shown in 1975 that when the channel capacity between the target receiver and the transmitter is larger than the capacity of the eavesdropping channel, the confidential transmission of the signal can be realized [100]. But the exact expression of the secrecy capacity is complicated. In 2015, AymanMostafa et al. studied the secrecy and LED beamforming problem of SISO system and MISO system. The article pointed out that it is difficult to get the analytical expression of the secrecy capacity even in the simplest SISO case. Therefore, in a certain fixed-form communication scenario, it is generally assumed that the eavesdropper exists in a specific region and that the transmitter does not have access to the full channel information of the eavesdropper. The problem is ultimately modeled as maximizing a lower bound on the confidentiality performance of the communication link in each legitimate channel [94]. In the same year, the team investigated the beamforming problem for LED arrays, where the amplitude and polarity of the signal are used to shape the overall radiation pattern of the LED array, pointing the main lobe towards the intended receiver while minimizing the signal level in other regions. The problem was modeled as a linear optimization problem with moderate complexity, and the worst-case secrecy rate [101] was given. Next, the team investigated the design of beamformers in MISO eavesdropping channels, and the problem was reduced to maximizing the secrecy rate under an amplitude constraint. However, the original problem is nonconvex, so the article transformed it into a quasi-convex optimization problem and solved the beamforming weight vector that maximizes the secrecy rate [102]. Compared with the power constraint, the amplitude constraint describes the LED more accurately, which makes the above work also an important reference value for the study of the confidentiality of UV communication.

In addition to the modulation of the carrier, the distribution characteristics of the signal itself have an effect on the performance of beamforming. The related team investigated the secrecy rate of the input signal under amplitude constraints for different input distributions [103], [104]. Zaid et al. improved on the above research work by analyzing the secrecy of the system at truncated Gaussian input distribution and found that the effect is better than the secrecy when it consists of uniform inputs. The article also estimated the eavesdropper's channel using location information and used maximizing the secrecy rate lower bound as a strategy for beamforming [103]. Arfaoui et al. investigated the achievable secrecy rate of various input signal distributions including truncated generalized normal, Gaussian, and uniform distributions in a beamforming scheme considering artificial noise. The truncated generalized normal distribution has a significant effect on the secrecy rate improvement compared to the other two distributions [104].

In addition, the beamformer, which is centered on network precoding, is also an important factor in the design process. Pham et al. investigated the design of forced-zero precoding for a multiuser MISO broadcast channel. In the research, convex optimization modeling of the optimal beamformer is carried out based on upper and lower bounds on the capacity of the amplitude-constrained Gaussian channel. Using the precoding design, the bounds on the maximum-minimum fairness and maximum sum rate are derived. The results show that the generalized inverse design has better performance than the pseudo-inverse design [105]. Pham et al. continued to study the precoding design in the case of multiuser active and passive eavesdropping, and designed the artificial noise-assisted precoding and forced-zero precoding schemes to improve the confidentiality of the system [106]. Arfaoui et al. proposed a new linear precoding scheme and its iterative algorithm respectively, which outperforms the traditional forced-zero precoding scheme in terms of confidentiality performance. However, the time complexity of the algorithm proposed in the article has increased, which is a detail that can be improved in future beamforming precoding work [107].

In UAV communication scenarios, the position between the target channel and the eavesdropping channel often varies, and the positional distribution of eavesdroppers is also a factor affecting the secrecy of the beamforming system. Reference [108] analyzed the secrecy outage probability (SOP) when eavesdroppers are randomly distributed using stochastic geometric methods. The paper improved the security performance of the system by minimizing the average SNR of the eavesdropper (ED) and maximizing the SNR of the target user. Reference [109] applied a Poisson distribution model to model the random location of eavesdroppers. The article considered several configurations of transmitters and receivers with different numbers and distributions, and derived a closed form for the probability of secrecy disruption in each case. In the research, the secrecy performance of the downlink is improved based on the LED selection scheme of the legitimate user's location. In addition, in [110], the researchers analyzed the secrecy performance in the presence of random colluding eavesdroppers.

Above is a brief introduction about the use of beamforming technology to enhance the system confidential. The beamforming design in the field of UAV UV communication is still in its infancy. The channel of UV communication is dominated by NLOS, and the FOV, pointing angle and link distance of the transceiver will affect the distribution characteristics of the LEDs and the channel gain [111]. In the design of the UV beamforming system, we need to consider the influence of the above system parameters, instead of using the Lamb distribution characteristics as the main basis for the channel gain in the above research work. In addition, the analytical representation of the UV NLOS channel model is difficult to obtain, and the existing work is based on the Monte Carlo integral model, which generates a high time complexity. Therefore, in the design of UV beamforming with convex optimization modeling as the main means, one of the key issues is to obtain a concise expression of the channel gain, and then the beamforming problem is expressed or approximated as a convex optimization problem, so as to obtain a computationally efficient beamforming algorithm [112]. At present, practical UV communication band is concentrated in the UVC band, which has a narrower linewidth and a higher requirement for the use of frequency division multiplexing to reduce inter-link interference. In the above study, a precoding scheme is considered to improve the confidentiality and inter-link interference, which is undoubtedly an important reference value for the link interference and confidentiality of UV MIMO systems and network communications.

VI. POWER OPTIMIZATION

On the one hand, the path loss of UV signals is serious, and the energy at the receiver decreases significantly with the increase of communication distance, so it is necessary to enhance the transmit power of the signal to ensure the quality of communication. On the other hand, the external environment has limited resistance to UV radiation, and it is necessary to control the UV power below a certain threshold value. Therefore, the power control strategy that reasonably weighs the transmit power and the communication performance index is an important link in UV communication [16], [18].

Currently, research work on LED emitted power control is concentrated in the field of VLC, which can be categorized into hardware dimming (HD) [113], [114], [115], [116], [117], [118], software dimming (SD) [119], [120], [121], [122], [123] and hybrid dimming [124], [125], [126], [127], [128].

HD relies on the actual physical variables in the communication system for power control, and realizes the regulation of optical and electrical power by controlling variables such as LED on-current, number of conductors, LED optical axis pointing, and divergence angle [124]. HD subsystems are often nearly independent of data transmission subsystems and are a simple and efficient solution [115]. According to the different application scenarios, HD can be divided into HD for SISO systems, HD for MIMO systems, and HD for broadcasting systems, and most of them are modeled as convex optimization problems that can be solved quickly [116]. In the modeling process, in addition to the aforementioned transmitter parameters, the receiver pointing angle can also be used as a control variable. Although the difficulty of hardware implementation has increased, the power control accuracy has been improved [113]. There are also optimization designs that aim to maximize the received energy, such as the optimization problem of an integrated communication and energy supply system, in which a suitable objective function needs to be designed to balance communication quality and energy transmission [117]. As for the HD of broadcasting systems, the power allocation scheme is a major concern, and related studies have demonstrated that the optimal symbol modulation power allocation scheme possesses lower energy consumption than the equal power allocation scheme [114].

SD controls the duty cycle and modulation depth of the modulating signal to achieve the optimization of optical or electrical power with no change in hardware parameters. For specific implementation, Variable Pulse Position Modulation (VPPM), Variable On/Off Keying Modulation (VOOK), Variable Multi-Pulse Position Modulation (VMPPM) and Variable Quadrature Amplitude Modulation (VMQAM) can be used as the specific solutions for SD [120], [123]. For low-order modulation methods such as VPPM and VOOK, when controlling the transmit power by adjusting the signal duty cycle, the carrier frequency needs to be higher than a certain value, otherwise the BER performance of the dimming system is not significantly improved compared to the original system. In contrast, the use of modulation depth to control the transmit power offers superior flexibility [122]. For higher-order modulation methods such as VMPPM and MQAM, the adjustment of the signal duty cycle is the main part of power control, but the demodulation of higher-order modulated signals requires a high degree of smoothness in the signal energy. So in addition to balancing the signal quality and the transmit power, the trade-off between the resolution of the power control and the accuracy of the signal demodulation is a much more important issue [119], [121]. The advantages of SD are real-time and low cost, and the disadvantages are limited dimming effect, which needs to be combined with HD to achieve the desired effect in airborne dynamic communication scenarios.

Hybrid dimming integrates the characteristics of HD and SD to adjust the electrical parameters of the LED array, the optical structure and the parameters of the modulation signal under the limitations of optical power, band utilization, BER and other indicators. In addition to the adjustment of the structure of the transmitter, the change of the angle of the receiver and the appropriate demodulation algorithm can further mitigate the negative impacts of environmental noise, multipath dispersion and frequency distortion, so as to obtain higher spectral efficiency, lower detection error and more uniform power change curve [126], [128]. Hybrid dimming can further expand the power dynamic range of HD and SD, and enhance the robustness of the system in complex scenarios. It is an excellent dimming method.

The previous research relies on the known LOS channel gain, but the channel characteristics of UV communication, in which NLOS is the main application scenario, are difficult to be expressed in closed form. So its optimization method cannot be directly applied to UV communication. Therefore, it is valuable to study power control schemes applicable to UV communication systems [129]. In the current work, [112] proposed an alternative iterative Newton method (AINM) to optimize the repeater position and transmission power for full-duplex relay-assisted multihop UV communications with respect to UV NLOS characteristics. However, the study failed to point out the convexity of the established model, so the optimization algorithm used is the computationally inefficient alternating descent method. Therefore, establishing the power control problems in different kinds of UV communication systems into clearer models, using the information of the models themselves such as derivatives to provide the execution basis for the optimization algorithms, and trying to improve the accuracy of the optimization models and the execution efficiency of the optimization algorithms is a direction for future development in this field.

VII. DIVERSITY

Atmospheric scattering effect is the most important transmission mechanism of UV communication system, however, there is not only path loss, but also slow fading and fast fading in the signal transmission process. Among them, fast fading comes from the strong scattering of UV light in the atmosphere, and slow fading is generated by the undulation of light intensity caused by atmospheric turbulence [130]. Within a distance of a few tens of meters, the effect of atmospheric attenuation on the system performance can be ignored, and the system performance is mainly affected by the environmental noise. However, when the channel distance is hundreds of meters or more or when there are more suspended objects, the joint effect of the two needs to be considered. The use of diversity techniques can effectively improve this situation [131].

Diversity technology, which is the use of multiple receivers in a communication system, can mitigate the effects of atmospheric attenuation and environmental noise on the system, and is widely used in FSO [132], [133]. At present, the mainstream diversity techniques mainly include space diversity, frequency diversity and time diversity. In UV communication system, the cost of time diversity is too high, and the realization of frequency diversity is difficult, so the most widely used is spatial diversity technology [134]. In practical spatial diversity systems, the spatial correlation between UV beams can significantly degrade the performance of the system, so effective aperture separation is the key to achieving maximum diversity gain [135]. However, the relative concentration of different links will increase the inter-link interference, which is contradictory to the enhancement of diversity performance. So it is necessary to design suitable algorithms to take both into account, and realize the effective merging of signals from different links [136]. The physical structure design scheme of space diversity technology is limited, and the merging algorithm of signals has become an important direction in the study of space diversity technology in UV communication.

Signal merging techniques appropriately merge multiple statistically independent fading signals received, thereby reducing the effects of fading and improving system performance [137]. Currently commonly used merging algorithms include maximum ratio combining (MRC), equal gain combining (EGC), selective combining (SC), and maximum likelihood combining (ML) [138]. Reference [139] analyzed EGC diversity reception technique and validates it with experimental results. Unlike EGC, MRC compensates for channel differences between each photomultiplier tube (PMT) receiver. Based on the original MRC algorithm, [140] proposed a MRC algorithm that can compensate the channel difference between each PMT for UV communication systems. Relative to the EGC algorithm, this method can produce a larger output power, which effectively reduces the BER of the system. Subsequently, [141] investigated the effects of transmission distance and transmitter FOV angle on the EGC merging technique in UV single-input-multiple-output (SIMO) systems, and the results showed that the EGC algorithm can produce better diversity gain under small transmitter FOV and short link conditions. However, when the FOV angle at the transmitter is too large or the distance is too far, the EGC provides little improvement in BER. Reference [142] proposed a selective maximum ratio combining algorithm (SMRC), and conducted experiments at distances ranging from 5 to 35 meters. The results show that the SMRC algorithm reduces the BER by 32% and 46% compared to the MRC and EGC algorithms, respectively, at a link distance of 30 m.

Diversity system can improve the performance of the system, but it does not mean that the more number of receivers is better. For the number of receivers, [143] investigated the BER of UV NLOS communication systems under different number of receivers and elevation angles of the transceiver. The results show that the BER performance of the four-receiver system is significantly better than that of the two-receiver system under the same distance and receiver-transmitter elevation angle conditions. Reference [144] demonstrated that in UV systems, when the number of receivers reaches a certain value, the effect on the system performance is negligible. The link structure, on the other hand, has a large impact on the diversity performance, and we would like the receivers to be far enough apart from each other to obtain a better reception performance. However, in UV communication systems, the distance between receivers is often limited and the system may also operate in NLOS conditions. For the UV NLOS link structure, [145] derived the ML diversity detection scheme for spatially correlated UV NLOS links based on [132]. Simulation results show that ML merging outperforms SC and EGC when the SNR are the same in weak turbulence environments, and SC and EGC outperform ML in strong turbulence environments. However, SC and EGC merging methods are able to include some or all of the state information of the channel, which is not available in ML merging [146]. Similarly, two reception techniques, SC and ML, have been studied for UV communication systems. Reference [147] studied the BER performance of SC and ML in weak turbulence environment. The results show that ML and SC schemes can significantly improve the BER performance of the system, and the performance of ML is due to SC in weak turbulence environments. Reference [148] proposed an M-PSK based NLOS switching-dwell receiver diversity technique for the UV NLOS link, and analyzed the relationship between the BER and the modulation depth. The article points out that the average bit error rate (ABER) of the system decreases as the modulation parameter M increases. Reference [149] investigated the secrecy of NLOS systems, and by comparing the secrecy of a single-link system with that of a system to which the EGC and MRC diversity techniques are applied. It was found that the diversity technique improves the secrecy performance of the system with a small off-axis error.

Regarding diversity in UV MIMO systems, [150] investigated different diversity reception schemes for diversity in 2×2 MIMO systems under dispersive and non-dispersive channel conditions, respectively. The results show that the use of multibeam approach can significantly improve the throughput of the system. In addition to that, proper MIMO coding can achieve higher diversity gain. Space-time coding (STC) is a typical representative of MIMO coding technique, which uses a two-dimensional time interval and spatial coding method to encode the original sequence into a redundant sequence, which is then transmitted in parallel using multiple transmit antennas [151]. Reference [152] improved one of the simplest Alamouti codes in STC and applied it to the MIMO system of NLOS, and the results showed that the scheme can effectively reduce the system BER. However, the Alamouti code used in this study requires real-time channel state information (CSI) of the UV channel, so its practical application is greatly restricted [153]. In order to compensate for this shortcoming, [154] studied the application of differential space-time block codes (DSTBC) in 2×2 MIMO UV communication systems, and the results showed that DSTBC coding does not need to obtain real-time CSI in time-varying fading UV channels, which is a great advantage of DSTBC over Alamouti codes. Next, [155] applied the symmetric optical pulse position-orthogonal space-time block code (SOPP-OSTBC) to a 2×2 MIMO system with a ML merging scheme at the receiver. The results showed that the design outperforms its combination with the 2PPM modulation method when combined with the OOK modulation method. Reference [156] compared the performance of three merging methods, SC, EGC and MRC, under BPSK modulation, and the results showed that the use of MRC merging enables the system to obtain the maximum communication distance.

The above studies show that for a fixed diversity merging method, there should be an optimal modulation method, and similarly, for a deterministic modulation or coding method, there is an optimal diversity merging method. Of course, the trade-off between different methods needs to be based on a deterministic system structure. The current research on diversity techniques in MIMO systems focuses on two major categories, SIMO and 2×2 MIMO. So extending the existing research to MIMO systems above the second-order is a key research direction in the future.

Overall, in UV communication systems, diversity techniques widely adopted include spatial, frequency, and time diversity, with spatial diversity being most commonly utilized due to its relative simplicity and cost-effectiveness. An analysis of existing technologies and research allows us to forecast potential trends and directions for future research in diversity technologies for UV communication systems:

- Enhanced Design of Diversity Receivers: Research into more effective diversity reception technologies is needed to improve the stability of signal reception and reduce BER. This includes optimizing the layout of receivers and designing more efficient reception algorithms to better cope with atmospheric scattering and turbulence.
- Integration of Multi-beam and MIMO Technologies: Combining multi-beam with MIMO technologies can significantly enhance the throughput and signal stability of UV communication systems. Future research should explore innovative applications in this area, especially under NLOS communication conditions.
- Optimization of Coding and Modulation Techniques: Current research has demonstrated the impact of various coding and modulation techniques on diversity performance. Future studies might further investigate how to optimize these techniques to suit different environments and communication distances, particularly selecting the most appropriate coding and modulation technologies for UV communication systems.
- Accurate Acquisition of CSI: Certain diversity techniques, such as the Alamouti code, require real-time CSI, which can limit their application under some conditions. Future research could explore methods and algorithms for efficient signal merging and coding without relying on real-time CSI.
- Optimization of Link Structure and Receiver Configuration: Research indicates that the relative positioning of link structure and receivers significantly impacts diversity performance. Future studies might explore how to optimize these parameters to improve the overall system performance and reliability.

Exploration and research in these directions can enable diversity technologies in UV communication systems to better adapt to complex and variable communication environments, thereby enhancing system stability and efficiency and leading to breakthroughs in future communication technologies.

VIII. NETWORKING

The high path loss of the UV channel makes the communication distance of the UV SISO system limited, and the networking technology can effectively improve this situation. As shown in Fig. 8, in complex environments with obstacles, UV networking communication can effectively expand the coverage of the original communication link. In addition, in the field of FSO communications such as VLC and laser communications, FSO networking technology is seen as a measure to solve the last kilometer of the communication network [157]. Regarding the general concepts and principles of UVC networking, [158] proposed requirements such as NLOS, not easily eavesdropped, and not requiring strict direction alignment, as well as the concept of an unattended ground transmission network. Reference [159] analyzed enemy and friendly aircraft links in three different scenarios, and proposed the concept of maximum standoff distance (i.e., the maximum distance that can simultaneously ensure that a friendly aircraft can be detected and an enemy aircraft cannot be detected). The authors pointed out that the channel gain, detection probability and maximum standoff distance all decrease as the communication distance increases. Apart from that, most of the related studies have been conducted on access control protocols and the structure of UV networks.

In UV communication networking, Multiplexed Access Control (MAC) plays a key role in defining how the network shares data during transmission, and efficient MAC protocols are essential for improving network performance [160], [161]. As shown in Fig. 9, there are three main types of current MAC protocols [162]. The first type is the competitive MAC protocol based on random access, which has lower requirements for the coordination mechanism and can adapt well to changes in the network configuration. In competitive MAC protocols, data streams share a common channel. When there is a conflict between UAV A and UAV B, the protocol enters a competitive phase, and the winner of the competition has the right to send information first. However, as the amount of node information increases, conflicts during transmission will increase, making the network performance significantly degraded [163], [164]. The second category is the non-competitive MAC protocol, which allocates a dedicated channel to each node and eliminates the competition for channel resources. In non-competitive MAC protocols, data sent by different UAV nodes have dedicated channels, which can be specific frequencies, specific times, or specific code words. Compared to the random access mechanism, non-random MAC protocols provide better channel utilization and reliability in high network traffic states [165]. The third category is the hybrid MAC protocol, which combines the advantages of both competing and non-competitive MAC protocols. Hybrid MAC protocols can improve the utilization of channel resources when the traffic load is low like competitive protocols, avoid conflicts when the network traffic increases like non-competitive type protocols, and solve the problem of synchronous allocation of network resources [166]. Reference [167] proposed a one-way ant colony routing algorithm based on the traditional two-way ant colony routing algorithm, which selects the path with the optimal performance in terms of delay and bandwidth, and the overall connectivity and survivability of the network is greatly improved. Reference [168] took

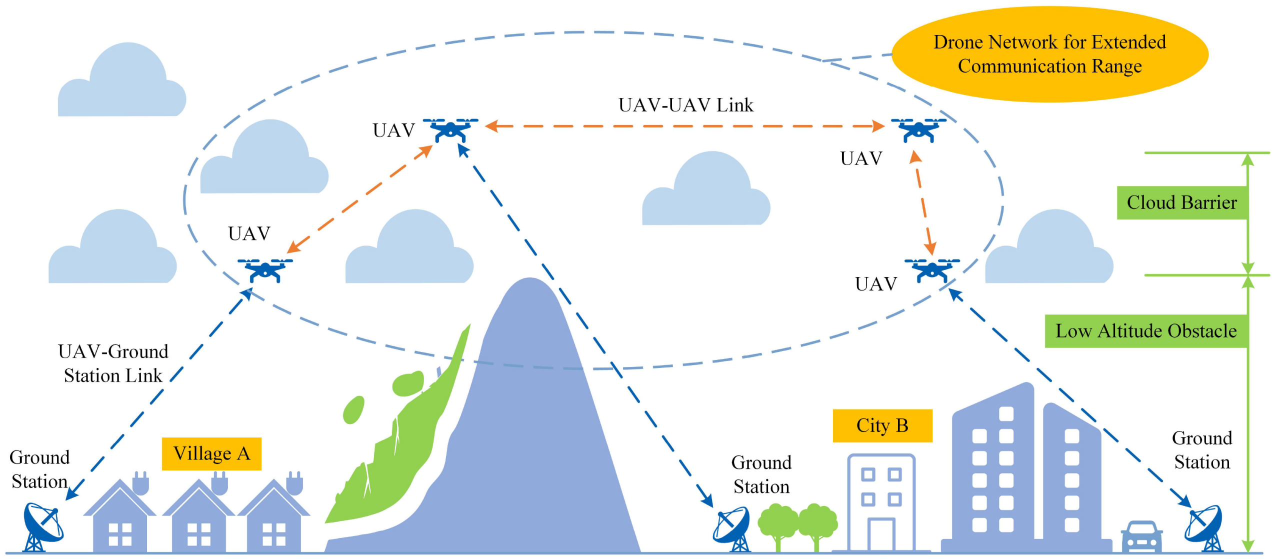

FIGURE 8. Expansion of Communication Range through Multi-Point Networking Technology for UVC in UAV.

obstacle avoidance between nodes and improvement of coverage and connectivity as the optimization objectives, and proposed a path selection algorithm for UV communication networking in three-dimensional space. Compared with the random-type MAC protocol, the coverage of the network and the average convergence time of the algorithm are both improved. Reference [169] designed a multipoint topology access protocol for star-shaped UV networks, which has a large improvement in the normalized throughput compared to the CSMA/Ca-like protocol, and is suitable for the combination of telecommunication networks and UV communication sub-networks. Reference [170] proposed an adaptive node assignment and power allocation method subject to capacity and node connectivity constraints for hierarchical UV scattering networks. This method can improve the communication rate of the worst node by more than 10%.

Compared with the research on MAC protocols for UV communication networks, the research on network structure configuration is more extensive. Reference [171] proposed a hierarchical area coverage optimization algorithm based on genetic algorithm, which improves the coverage of the network compared with the existing coverage algorithms, but the method is only applicable to the deployment in coplanar area. Reference [172], on the other hand, proposed a mesh non-coplanar MIMO structure based on linear geometry, which has lower reuse cost. The article also improved the original spherical decoding algorithm, and the improved algorithm reduced the complexity while ensuring the same computational accuracy. Reference [173] proposed a diamond-shaped structure based on the single-scattering model of UV NLOS links. Compared with the square-structured network, the diamond-shaped network sacrificed the effective coverage area to improve the connectivity, and the performance index of the network was yet to be further improved. These studies are dominated by node configuration, but the node configuration method is only one aspect of the network structure configuration. Reference [174] also studied the coverage radius and communication performance of NLOS UV communication networks in arbitrary polygonal regions. The results showed that, compared to the node model in quadrilateral regions, the node model of the network uniformly distributed in a circular region requires more stringent communication parameters. And the smaller the elevation angle of the transceiver is, the better the connectivity performance of the network is. On the other hand, [175] investigated the effects of changes in node density, transmit power, and data rate on the connectivity of UV communication networks for UAVs. The article pointed out that the connectivity of the network increases with the increase of node density and transmit power, and decreases with the increase of data transfer rate. The number of network nodes required for uniform distribution is lowest for the same connectivity.

Connectivity and coverage area are important parameters describing the performance of the network structure, and inter-link interference is an important criterion for evaluating the stability of its performance. The analysis and suppression of inter-link interference is of great significance for UV communication networking [176]. Reference [177] deduced the nature of the distribution of interference and its upper and lower bounds based on the Poisson clustering process of network nodes. The article also considered the probability of successful transmission of a signal in an interference-limited channel in the context of the Rayleigh fading model. Reference [178] proposed a topology control algorithm for the channel interference problem in three-dimensional k-connected UV communication networks. The algorithm first generates an initial k-connected network, then streamlines the network structure, removes redundant parts, and finally uses a particle swarm optimization (PSO) algorithm to obtain an approximate optimal power allocation scheme. The improved

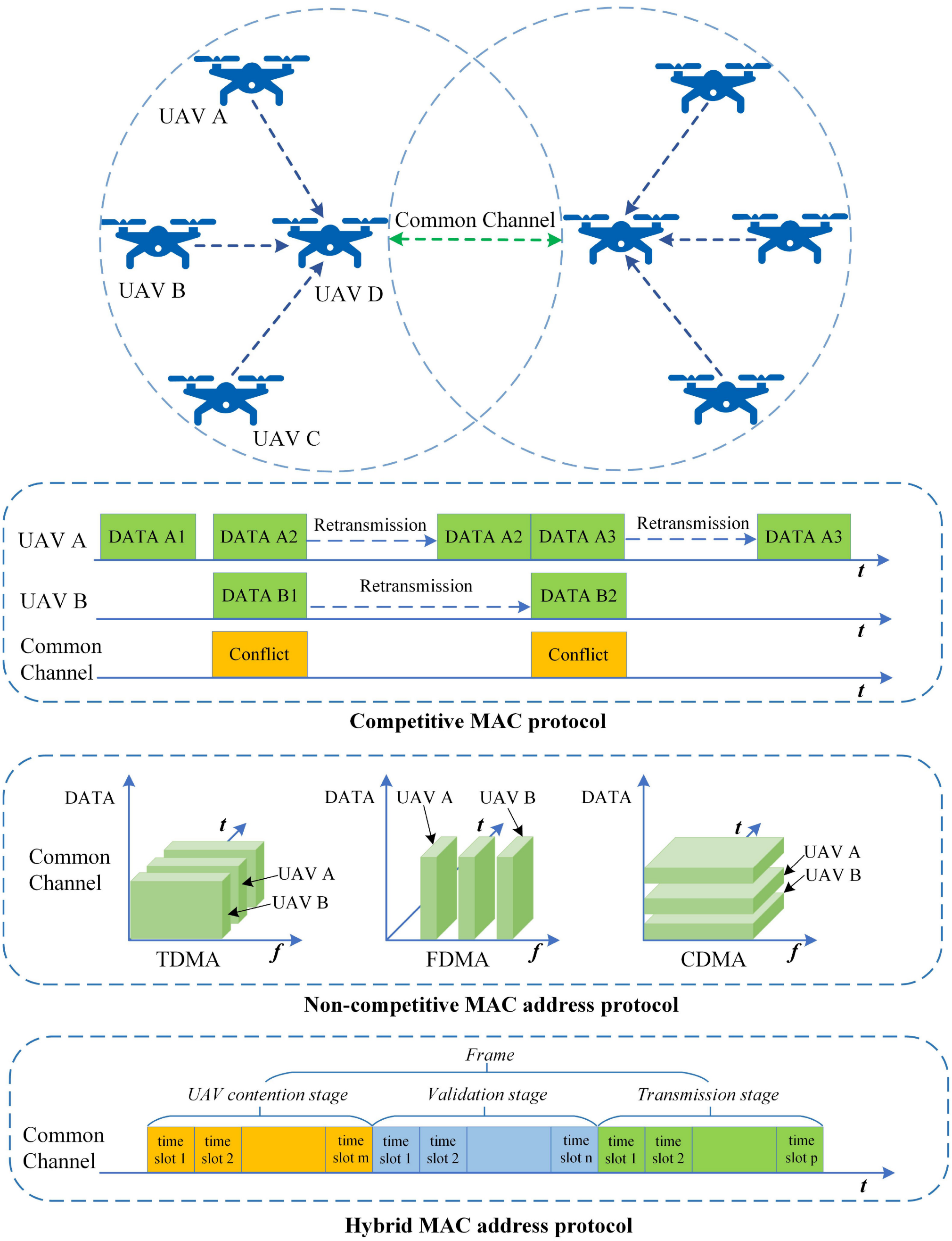

FIGURE 9. Three types of MAC protocols.

algorithm not only generates a fault-tolerant topology, but also significantly reduces the inter-channel interference, which is suitable for networks with high stability requirements. Reference [179] proposed a new topology control algorithm, the main purpose of the algorithm is to construct a k-connected topology graph, which allows the network to remain connected when k-1 nodes fail. The network structure generated by this algorithm is able to control the node interference value to a stable value that does not increase with the number of nodes. Reference [178] proposed a low-interference fault-tolerant networking algorithm based on the 3D k-YG algorithm and the PSO algorithm [180], which can effectively reduce the interference in the UV communication network and improve the stability of the topological network. Reference [181] improved the link weight function for the residual energy and channel loss of communication nodes, and proposed a three-dimensional spatial communication network generation algorithm based on the optimal rigid graph. The network structure generated by this method can reduce the energy loss of the system and has good connectivity.

The related team has also explored the transceiver parameters and the number of nodes in the network that make up the UVC network. Reference [182] investigated the effects of the number of nodes, transmit power and data rate on the performance of the k-node network under different transceiver elevation angles. The results show that the smaller the transceiver elevation angle is, the larger the node communication range is. Reference [183] designed a geometric model for UAV ground-to-air UV communication networking. In this geometry, multiple transmitters are evenly distributed on the ground and the UAV receives signals in the air. The number of transmitters required by the system is inversely proportional to the horizontal distance between the receiving and transmitter, and the maximum coverage of the network can be obtained while meeting the BER metrics. Reference [184] investigated the BER and minimum irradiance after interference compensation on the basis of [183]. The article pointed out that the BER gradually increases with the number of network interference sources and the receiver field of view angle.

Besides, UV UAV self-organizing network technology is also an important direction. Mobile self-organization technology is based on some unique UV network characteristics, such as constantly changing topology and nodes within the network being both routing and destination nodes [185]. Most of these characteristics are constraints on the network nodes, and for a particular node in the network, a neighbor discovery algorithm is the basis for achieving its interconnection with surrounding nodes [186]. In the field of traditional communication, there have been related studies on neighbor discovery algorithms with known information about surrounding nodes [187], [188] and neighbor discovery algorithms with unknown a priori information [189], [190], [191]. However, none of these studies can be directly used in UV communication due to the differences in channel characteristics.

In recent years, there has been extensive attention on the access mechanisms for UV self-organizing networks. Research in this area primarily falls into two categories: random access protocols based on Time Division Multiple Access (TDMA) and random access protocols based on contention.

For TDMA protocols, time is divided into periodic frames, each frame further subdivided into several time slots, with fixed slots assigned according to certain allocation principles. However, since nodes in a self-organizing network are constantly changing, dynamic TDMA should be used, where time slots are dynamically competed based on node priorities. In 2016, researchers proposed a new dynamic TDMA protocol that improves performance by reallocating node priorities to reduce collisions among nodes with the same priority [192]. In 2023, a new TDMA-based random access cooperative network protocol was proposed, combining the advantages of synchronous and asynchronous media access control protocols. This protocol achieved higher throughput with lower latency and packet loss rates through a dynamic slot allocation mechanism [193]. Additionally, a 2023 study proposed a dynamic distributed TDMA protocol based on theoretical analysis and network simulation verification, using a fully connected matrix of nodes for distributed scheduling [194]. In 2024, to accommodate large-scale UV networks, researchers proposed a UV MAC protocol combining clustering algorithms with TDMA, featuring clustering mechanisms and dynamic slot allocation characteristics [164].

In networks with a large number of nodes, clustering algorithms are undoubtedly an effective method to enhance performance. In 2016, Yu et al. proposed a novel mobile prediction clustering algorithm for dynamic self-organizing networks to address the adaptability issues of traditional clustering algorithms in high-dynamic large-scale networks [195]. In 2017, Zeng and Zhang introduced a Low Energy Adaptive Clustering Hierarchy (LEACH) algorithm [196]. That same year, Wu et al. proposed an optimized clustering algorithm based on LEACH, which effectively reduced network energy consumption and extended network lifespan by considering the remaining energy of nodes in wireless sensor networks [197]. Reference [162] proposed a UVOC-MAC protocol specifically designed for outdoor UV communication networks. The article first introduced the impact of signal propagation and the physical layer on medium access through experiments, and established a non-coplanar path loss model to describe signal attenuation. Then, it described in detail the working process of the UVOC-MAC protocol, including idle state, sending and receiving of RTS and CTS messages, data transmission, etc. Specifically, the core steps of the UVOC-MAC protocol include:

- Initialization: The node initializes and maintains relevant tables, such as connection tables and occupancy tables.
- Data transmission: When the node has data to send, it first checks the connection table and occupancy table to select the best direction and pointing angle.
- Request to Send: The node sends an RTS message containing pointing angle information, thereby implicitly conveying the selected data rate.
- Clear to Send: After receiving the RTS, the receiving node checks whether it can receive data and sends a CTS message, which contains the highest possible data rate.
- Data transmission: The sending node sends data based on the data rate in the CTS. If possible, it uses full-duplex mode.
- Update tables: The node updates relevant tables after sending or receiving data.

These steps ensure that the UVOC-MAC protocol can efficiently utilize spatial dimensions, reduce collisions, and adapt to changing network environments. Subsequently, the article analyzed the effectiveness of the UVOC-MAC protocol in providing high throughput and reducing collisions through simulations. In addition, the article compared the UVOC-MAC with traditional MAC protocols used in radio frequency communications, emphasizing its uniqueness and applicability in outdoor UV communication environments.

In self-organizing networks, the dynamic nature of node positions leads to continuous changes in network topology, making neighbor discovery algorithms crucial as they are a prerequisite for random access protocols. Reference [198] considered the stability characteristics of UV communication network nodes, and utilized multi-feature fusion and GRF-MAP methods to sense the distributed dynamic network topology, and realized a dynamic adaptive routing protocol. In 2011, Wang et al. proposed a UV neighbor discovery algorithm based on the leader's dominant capability. During neighbor discovery, only the leader can send signals, continually optimizing to ensure all nodes in the network can equally become leaders [199]. In 2015, Yang et al. introduced a new TDMA-based UV communication directional neighbor discovery algorithm. This algorithm uses a backoff delay mechanism based on directional transmission and reception to quickly adapt to topology changes and resolve node collision issues [200]. In 2016, Zhang et al. developed a multi-channel UV communication directional channel access protocol based on spatial division multiplexing, establishing a UV communication network model for aircraft and addressing the "deafness" problem in UV directional communication in flight formations [201]. Reference [202], on the other hand, used an evaluation mechanism to rank the possible transmission directions of nodes, and then proposed a neighbor discovery protocol for UV self-organizing networks that can improve the search performance based on the information of node transmission directions. Assuming that the distribution of self-organizing network nodes obeys a Poisson process, [170] investigated the connectivity probability of the network and the minimum power for the network to remain connected under different antenna parameters. In addition, the article considered a two-tier network using directional antenna arrays and designed node assignment and power control algorithms. Reference [186] proposed a neighbor discovery algorithm based on probabilistic separation, which uses scheduling reference techniques to recommend nodes and avoids direct references to nodes in clusters, achieving a balance between neighbor discovery efficiency and energy efficiency.

Considering the dynamic nature of nodes in self-organizing networks, node mobility can impact network performance, necessitating the study of network connectivity during node movements. In 2018, Zhao et al. explored UV communication technology suitable for UAV networks, discussing network connectivity under random waypoint (RWP) and circular motion models [175]. In 2019, a study on UAV UV communication under circular uniform distribution conducted simulation experiments on the effects of elevation angles, node density, transmission power, and data rates on network connectivity (k=1,2) [182]. A 2020 study analyzed the impact of elevation angles of receiving and transmitting ends on network connectivity in UV communication network models when nodes move according to the RWP motion model, finding that irregular polygonal area models fit reality better than prototype models, reflecting the dynamic movement characteristics of network nodes [203].

In other research details, [204] improved the formation coordination algorithm for UV communication UAV swarms. The results show that the stability of the UAV swarm tends to stabilize with the increase of flight time. Reference [205] proposed an obstacle avoidance algorithm for UV communication of UAV swarm on the basis of the augmented vector field histogram algorithm, which can effectively prevent collision between UAV swarms. Reference [206] proposed a double ascent algorithm to determine the optimal position of the relay node for UV communication in the case of obstacle obstruction, which is superior to the traditional Bellman-Ford algorithm.

In the context of UV communication networking, it is essential to focus on both the reliability and rate of individual links, as well as the overall performance of the network. Directional antenna arrays enhance signal strength and quality through concentrated transmission and reception, effectively mitigating signal attenuation caused by scattering. By employing beamforming techniques, directional antenna arrays can optimize the propagation direction of signals, thereby reducing interference and multipath effects, which ultimately improves transmission efficiency. These characteristics enable them to provide more stable and efficient signal transmission in UV communication.

As previously discussed, constructing directional antenna arrays and designing node allocation algorithms for UV communication networks necessitates the selection of high-gain antennas suitable for the UV spectrum, as well as the adoption of linear, planar, or three-dimensional array configurations to optimize signal transmission direction and minimize interference. Additionally, beamforming techniques should be utilized to adjust the amplitude of UV signal transmission antennas to enhance the quality of signals directed towards target users, while adaptive algorithms must be designed to respond to environmental changes. Moreover, the rational design of network topology and node density is crucial for network performance. The optimization of the aforementioned parameters helps to enhance the network's connectivity and throughput, ensuring the efficient operation of the ultraviolet communication network.

On the other hand, node allocation algorithms aim to optimize the layout and power distribution of nodes based on the characteristics of UV communication networks. A well-designed layout and allocation mechanism can effectively reduce interference between signals, thereby enhancing transmission efficiency and increasing the overall data throughput of the network. The design of node allocation algorithms should be grounded in network modeling and utilize optimization algorithms, including swarm intelligence algorithms such as genetic algorithms and particle swarm optimization, as well as convex optimization techniques, to determine the optimal positions and power allocations of nodes, ensuring network coverage and connectivity while maintaining dynamic adaptability. Proper node allocation can significantly enhance network connectivity and throughput, ensuring efficient and reliable UV communication in complex environments.

In summary, in UV communication networking, the network must dynamically adapt to the continuously changing topology and node roles through various methods. Adaptive routing algorithms (such as AODV, OLSR, etc.) adjust data transmission paths in real-time to accommodate the addition or removal of nodes. Topology discovery and maintenance use topology control protocols to regularly update network topology information, ensuring that all nodes are aware of the latest network structure. Load balancing mechanisms optimize resource usage and improve network performance by dynamically adjusting task and data flow distribution, especially during changes in node roles. Node role assignment implements flexible role allocation mechanisms (such as master and slave nodes, coordinators and worker nodes), dynamically assigning tasks and responsibilities based on node capabilities and network needs. Additionally, fault tolerance and recovery mechanisms establish robust fault-tolerant strategies and rapid recovery plans to address node failures or anomalies, ensuring network stability and reliability.

IX. MODULATION

The modulation method of a communication system should be adapted to the characteristics of the signal itself (wavelength, intensity, etc.) and the transmission environment (path loss, occlusions). Although there are often multiple modulation methods for a signal, in practice the choice of the best modulation method for the current transmission environment is limited [207].

As shown in Fig. 10, the SNR of UV communication, VLC, and infrared communication are simulated in a conventional atmospheric environment. The theoretical basis for this simulation is the photon scattering theory based on Mie scattering and Rayleigh scattering. Mie scattering refers to the scattering phenomenon that occurs when light waves encounter particles comparable in size to their wavelength, applicable to larger particles, with scattering intensity related to the size, shape, and refractive index of the particles. Rayleigh scattering, on the other hand, describes the scattering phenomenon when light waves interact with particles much smaller than their wavelength, primarily affecting short-wavelength light (such as blue light). The relationship between scattering intensity and wavelength for Mie scattering is more complex, while the intensity of Rayleigh scattering is inversely proportional to the fourth power of the wavelength, and both phenomena jointly affect the propagation of light.

The wavelength of UV light is shorter than that of visible light, and the wavelength of visible light is shorter than that of infrared light. Except for the fact that the wavelength of UV light is comparable to the diameter of particles in the air, the carrier wavelengths of the other two traditional communication methods are much larger than the diameters

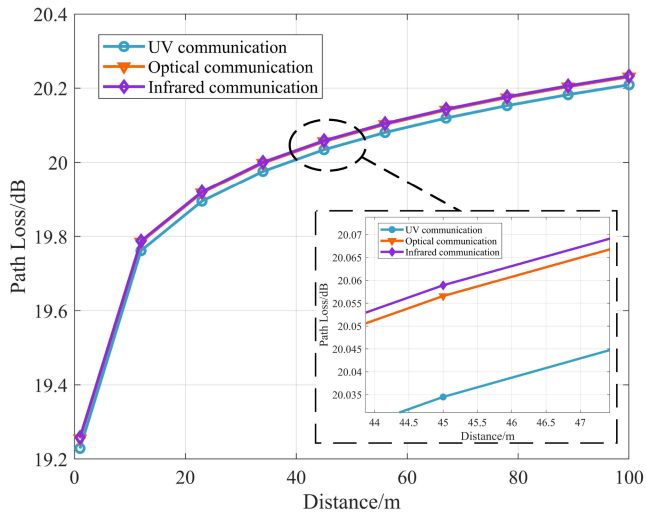

FIGURE 10. Comparison of the three communication methods.

of air particles. In other words, the Mie scattering effect for UV particles is more pronounced, while the Mie scattering effects for the other two types of particles are relatively weak. Therefore, under the same modulation scheme, we set the Mie scattering coefficient for VLC to be one-tenth of that for UV communication, and the Mie scattering coefficient for infrared communication to be one-hundredth of that for UV communication. We then performed simulations on the system's SNR, resulting in the outcomes shown in Fig. 10 [56]. In the simulation, the transmission power is set to $Pt = 30 \times 10^{-3}$; the atmospheric model parameters are $k_{sr} = 0.24 \times 10^{-3}$, $k_{sm} = 0.25 \times 10^{-3}$, and $k_a = 0.9 \times 10^{-3}$. The area of the receiving window is $A_r = 1.77 \times 10^{-4}$. The model parameters are $\gamma = 0.017$, $g = 0.72$, and $f = 0.5$. The transmission end elevation angle $\theta_T = 60$, the receiving end elevation angle $\theta_R = 60$, the transmission end FOV angle $\phi_T = 60$, and the receiving end FOV angle $\phi_R = 60$. The results indicate that in short-range scattering communication scenarios, specifically NLOS communication scenarios, UV communication has a higher SNR compared to traditional communication methods, leading to a lower BER and a higher achievable transmission rate.

The wavelength of most UV communication systems is concentrated in the C-band between 200nm and 280nm. Compared to RF communication, infrared optical communication and VLC communication, UV has shorter wavelengths and stronger energies, which require higher modulation devices [13]. Traditional modulation mechanisms include electro-absorption modulation, electro-optical modulation and photoacoustic modulation. Electro-absorption modulation utilizes the absorption and emission of electrons and holes in the semiconductor to achieve modulation of the optical signal. Electro-optical modulation uses an electric field to control the refractive index of the material to achieve modulation of the optical signal [208]. Optoacoustic modulation utilizes the photoacoustic effect, in which the propagation of a light wave in a medium causes acoustic waves in the medium, to achieve modulation of the optical signal [209]. Unlike common radio frequency communication and fiber optic communication, the wavelength of UV light is shorter, and the particle nature is more pronounced (commonly described by Mie scattering and Rayleigh scattering) when the weak UV signal interacts with particles in free space [210]. In communication scenarios where UV LEDs are used as light sources, the constraints of the particle nature of the signal (i.e., wavelength limitations) on the one hand, and the process limitations of the analog modulation device on the other, are imposed. This makes it difficult for UV communication system to realize the precise modulation of the phase and frequency of the waveform as in the traditional RF communication, but rather the intensity modulation is realized in a number of code element cycles. Commonly used digital modulation techniques in UV communications include on-off keying (OOK), digital pulse interval modulation (DPIM), pulse position modulation (PPM), and a series of derivative versions of PPM modulation (this paper takes Digital Pulse Position Modulation as an example) [211], [212]. Methods such as m-pulse position modulation (MPPM) and quadrature amplitude modulation (QAM) modulation are also used in some high-speed communication scenarios.

For UV communication systems using intensity modulation, the intensity of the ambient light has a strong influence on the channel model. When the effect of ambient light is weak, the received signal is usually modeled using a Poisson process [213]. When the effect of ambient light on the signal is strong, the received signal is modeled as Additive White Gaussian Noise (AWGN) plus a DC offset [214]. In general, there are many measures of the performance of a digital communication system, the two most important of which are transmission efficiency and reliability [215]. Assume that the communication method is LOS communication, the channel model is Gaussian noise model, the number of source bits of the UV communication system is M, and the number of data bits transmitted in the channel is $L_B = 2^M$. When the bit rate R_{bit} and the total transmit power P_{total} are certain, the average transmit power, bandwidth, transmission capacity, and anti-code interference performance of the above five modulation methods are shown in Table 5 [216], [217], [218], [219].

Let the total power P_{total} be 20mW, then the relationship between the average transmit power and the number of data bits is shown in Fig. 11(d). It can be found that the OOK modulation method has the maximum average transmit power and the PPM modulation method has the minimum average transmit power within M gaps when the number of bits of the transmitted signal is the same. Setting the bit rate R_{bit} to 6400bit/s, the curve of bandwidth versus the number of data bits is shown in Fig. 11(a). When the number of data bits increases, the bandwidth required for UV communication also increases, and when the amount of data is greater than 6 bits, the bandwidth required by the PPM modulation method is the largest and the bandwidth required by the OOK modulation method is the smallest. The transmission

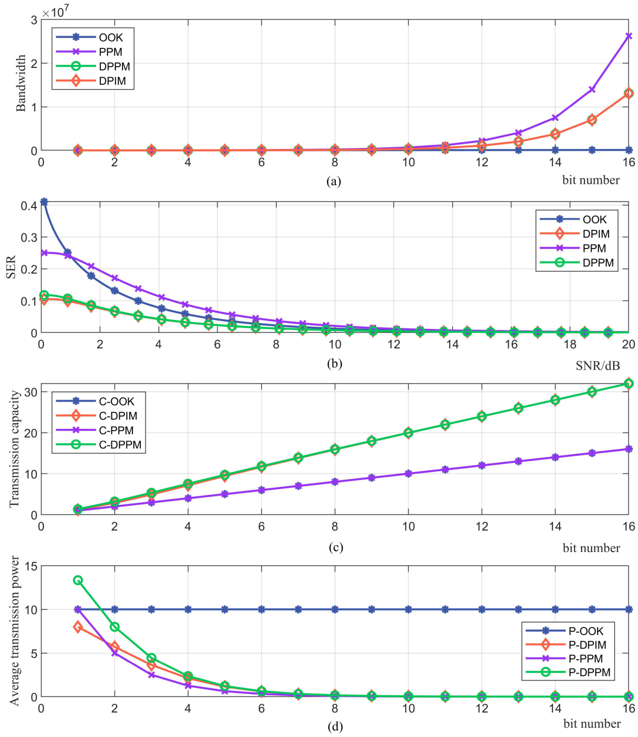

FIGURE 11. **Performance of different valence modulation techniques. (a) Relationship curve between average transmit power and number of data bits. (b) Relationship curve between bandwidth and number of data bits. (c) Relationship curve between transmission capacity and number of data bits. (d) Relationship curve between error time slot rate and signal-to-noise ratio.**

capacity versus number of bits curve is shown in Fig. 11(c), from which it can be seen that the two have a linear or quasi-linear relationship, and the transmission capacity of DPPM modulation is the largest, and the transmission capacity of PPM modulation is the smallest.

Assuming that the mean of the noise is 0 and the variance is σ_n^2, the formula for calculating the error time slot rate shown in Table 6 can be obtained when the optimal threshold values are obtained for the above four modulations [220]. where $SNR = S_t/2\sigma_n^2$. Setting $M = 4$, i.e., the number of symbol bits is $L_B = 2^M$, the relationship curve between the error time slot rate and the SNR is obtained, as shown in Fig. 11(b). From Fig. 11(d), it can be seen that the error time slot rate of all the four modulation modes decreases with the increase of the SNR, and when the SNR are the same, the error time slot rate of the PPM and OOK is larger than that of the DPPM and OOK modulation. In UV communication systems, the choice of modulation scheme significantly affects system performance. Under the same SNR conditions, DPPM and OOK modulation schemes have lower error time slot rates compared to PPM and OOK modulation schemes, which means that DPPM and OOK modulation schemes can provide more stable communication performance under the same SNR conditions. Additionally, in UV communication systems, increasing the SNR can effectively reduce the error time slot rate, thereby improving the performance of the communication system. Therefore, in practical applications, without changing

TABLE 5. Performance of four modulation methods.

Modulation Method	OOK	DPIM	PPM	DPPM
Average Transmit Power	$P_{OOK}=\frac{P_{\text{total}}}{2}$	$P_{DPIM}=\frac{2P_{\text{total}}}{2^M+3}$	$P_{PPM}=\frac{P_{\text{total}}}{2^M}$	$P_{DPPM}=\frac{2P_{\text{total}}}{2^M+1}$
Bandwidth	$B_{OOK}=R_{\text{bit}}$	$B_{DPIM}=\frac{(L_B+3)R_{\text{bit}}}{2\log_2 L_B}=\frac{(2^M+3)R_{\text{bit}}}{2M}$	$B_{PPM}=\frac{L_B R_{\text{bit}}}{\log_2 L_B}=\frac{2^M R_{\text{bit}}}{M}$	$B_{DPPM}=\frac{(L_B+1)R_{\text{bit}}}{2\log_2 L_B}=\frac{(2^M+1)R_{\text{bit}}}{2M}$
Transmission Capacity	$C_{OOK}=M$	$C_{DPIM}=\frac{2M(2^M+1)}{2^M+3}$	$C_{PPM}=M$	$C_{DPPM}=2M2^M(2^M+1)$
Anti-Interference Ability	stronger	relatively weak	relatively weak	relatively strong

TABLE 6. Performance indicators (error time slot rate) of four modulation methods.

Modulation Method	Missed Time Slot Rate
OOK	$\frac{1}{2}erfc\left[\frac{\sqrt{SNR}}{2}\right]$
DPIM	$\frac{1+erfc\left[\frac{1}{2\sqrt{SNR}}ln\left(2^M+\frac{1}{2}\right)-\frac{1}{2}\sqrt{SNR}\right]+\frac{2^M+1}{2}\left[1-erfc\left(\frac{1}{2\sqrt{SNR}}ln\left(2^M+\frac{1}{2}+\frac{1}{2}\sqrt{SNR}\right)\right)\right]}{2^M+3}$
PPM	$\frac{1+erfc\left[\frac{1}{2\sqrt{SNR}}ln\left(2^M-1\right)-\frac{1}{2}\sqrt{SNR}\right]+(2^M-1)\left[1-erfc\left(\frac{1}{2\sqrt{SNR}}ln\left(2^M-1\right)+\frac{1}{2}\sqrt{SNR}\right)\right]}{2^M-1}$
DPPM	$\frac{1+erfc\left[\frac{(M-1)ln2}{2\sqrt{SNR}}-\frac{1}{2}\sqrt{SNR}\right]+\frac{2^M-1}{2}\left[1-erfc\left(\frac{(M-1)ln2}{2\sqrt{SNR}}+\frac{1}{2}\sqrt{SNR}\right)\right]}{2^M+1}$

TABLE 7. Performance indicators of recently reported LOS UVC modulation technology.

Time	Modulation Method	Transmit Power	Link Length	Data Rate	Bit Error Rate	References
2019	OOK	196uW	0.3m	800Mbps	3.8×10^{-3}	[226]
2019	OFDM	196uW	0.3m	1.1Gbps	3.8×10^{-3}	[226]
2020	QAM	6mW	5m	2.4Gbps	—	[227]
2021	16-QAM-OFDM	0.854mW	0.5m	2Gbps	3.8×10^{-3}	[228]
2021	16-QAM-OFDM	0.854mW	5m	0.82Gbps	3.8×10^{-3}	[228]
2021	OFDM	2mW	5m	4Gbps	3.8×10^{-3}	[229]
2022	QAM	0.4mW	17m	4Gbps	3.8×10^{-3}	[230]
2022	QAM	0.567mW	0.5m	2.6Gbps	3.8×10^{-3}	[231]
2022	OOK	3mW	2m	1.27Gbps	2.0×10^{-2}	[232]
2022	QAM	0.4mW	10m	6.94Gbps	3.8×10^{-3}	[233]
2022	QAM	0.4mW	116m	1.19Gbps	3.8×10^{-3}	[233]

hardware conditions, the SNR can be improved by increasing transmission power, adopting more effective channel coding techniques, or modulation and demodulation techniques, to achieve better communication performance.

Table 7 shows the recently reported performance specifications of UV modulation techniques for UAV-oriented communication. In addition to the above modulation methods, QAM modulation is also a more widely used higher-order modulation scheme that can support Gbps communication rates. Compared with RF communication, UV communication has limited options for signal detection in medium and long range scenarios, most of which are directly detected, and suitable modulation and demodulation can improve the BER performance of the system to a certain extent [221].

Taking PPM modulation as an example, in the presence of strong interference such as log-normal atmospheric turbulence, the unconditional BER for binary PPM modulation in an UV communication system is approximately:

$$P_e=\frac{1}{\sqrt{\pi}}\sum_{i=1}^{n}w_iQ\left(\frac{exp\left(2\left(\sqrt{2}\sigma_k x_i+m_k\right)\right)}{Fexp\left(\sqrt{2}\sigma_k x_i+m_k\right)+K_n}\right), \quad (9)$$

where Q is the electronic charge, F is the noise figure of the detector, and m_k is the mean of $ln(K_s)$. $K_n=\frac{2\sigma_{Th}^2}{Gq}+2FK_{Bg}$, and $\sigma_k^2=ln(\sigma_N^2+1)$. $[w_i]_{i=1}^n$ and $[x_i]_{i=1}^n$ are the weights and zeros of the nth-order Hermite polynomials, respectively. $K_{Bg}=\eta\lambda\frac{T_s}{hc}$ represents the average number of photons produced by background radiation power P_{Bg} within a PPM time slot. $\sigma_{Th}^2=(2\kappa T_e T_{s_{ppm}}\frac{q}{R_b})$ is the equivalent thermal noise within the PPM time slot. The fluctuation of K_s is caused by atmospheric turbulence, and its ensemble average is given by [222]:

$$E[K_s]=exp\left(\frac{\sigma_k^2}{2}+m_k\right). \quad (10)$$

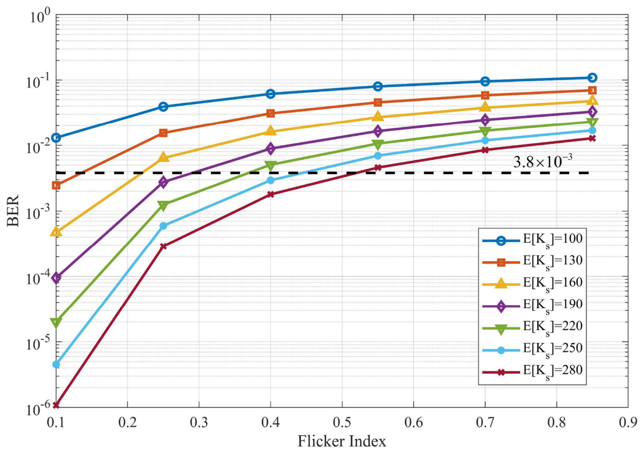

FIGURE 12. Trend of BER with flicker index in UV LOS communication systems.

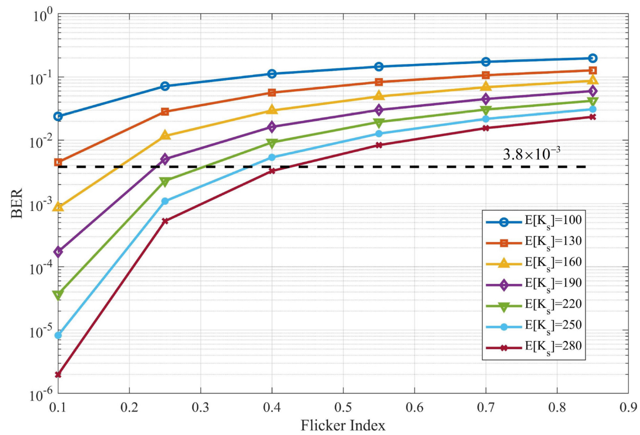

FIGURE 13. Trend of BER with flicker index in UV NLOS communication systems.

For an M-PPM system, the upper bound of the BER, P_e^M, is given by:

$$P_e^M = \frac{M}{2\sqrt{\pi}} \sum_{i=1}^{n} w_i Q\left(\frac{exp\left(2\left(\sqrt{2}\sigma_k x_i + m_k\right)\right)}{Fexp\left(\sqrt{2}\sigma_k x_i + m_k\right) + K_n}\right). \quad (11)$$

According to Eq.11, the trend of the BER of UV LOS communication systems with varying scintillation indices at different turbulence levels is illustrated in Fig. 12. Considering the UV NLOS link as a superposition of LOS links, the trend of the BER for UV NLOS communication systems with varying scintillation indices is shown in Fig. 13. In the simulation, the bit rate R_b is set to 155×10^{-6}, the load resistance R_L is 50, the temperature is 300K, the electronic charge Q is 1.602×10^{-19}, and the Boltzmann constant k is 1.38×10^{-23}.

Fig. 12 and Fig. 13 illustrate that, under the same scintillation index, as the turbulence average intensity increases, the system's BER significantly rises. Under the same average intensity, an increase in the turbulence scintillation index leads to a higher BER. Additionally, turbulence has a greater impact on the performance of UV LOS communication systems compared to UV NLOS communication systems.

In practical applications, it is necessary to select a modulation scheme that is suitable for specific environmental conditions. For long-distance UV communication systems, the impact of weak turbulence on BER performance must be considered when designing the modulation scheme. For systems operating in strong turbulence environments, PPM is a better choice due to its superior BER performance under the same environmental conditions, which will be explained in the following content. Additionally, the design of UV communication systems also needs to take into account the influence of link type (LOS or NLOS) on system performance. LOS links are significantly affected by turbulence, hence require special attention during design. In contrast, NLOS links are less sensitive to turbulence, allowing other performance indicators to be focused on during design.

As can be inferred from the previous analysis, for modulation schemes with higher information rates such as OOK and QAM, their BER performance is worse than that of M-PPM under the same environmental conditions. The following section conducts a simulation analysis of the BER performance of UV communication systems in LOS and NLOS links under different turbulence intensities and scintillation indices, and examines their impact on various modulation schemes.

In weak turbulence channels, the intensity distribution follows a log-normal distribution, and the BER of the UV communication system in the LOS link can be represented as:

$$P_{LOS} = \int_0^\infty f(I)P(I)\, dI, \quad (12)$$

where $f(I)$ is the probability density function of the normal distribution, given by:

$$f(I) = \frac{1}{\sqrt{2\pi}\sigma_s X} e^{-\frac{lnX + \frac{\sigma_s^2}{2}}{2\sigma_s^2}}. \quad (13)$$

Here, σ_s^2 is the log-amplitude variance, and X is the normalized average scintillation coefficient. $P(I)$ represents the BER of the UV communication system under the condition of no turbulence, and when the modulation scheme is OOK, PPM, PAM, and QAM, the expressions for $P(I)$ are respectively:

$$\begin{cases} P_{OOK} = Q\left(\frac{\sqrt{SNR_{LOS}}}{2}\right), \\ P_{PPM} = \frac{L_B}{2} Q\left(\frac{\sqrt{L_B log_2 L_B SNR_{LOS}}}{8}\right), \\ P_{PAM} = \frac{2(L_B-1)}{L_B log_2 L_B} Q\left(\frac{\sqrt{log_2 L_B SNR_{LOS}}}{2(L_B-1)}\right), \\ P_{QAM} = \frac{2(L_B-1)}{L_B log_2 L_B} Q\left(\frac{\sqrt{log_2 L_B SNR_{LOS}}}{8(L_B-1)}\right) \end{cases} \quad (14)$$

where SNR is the SNR for UV LOS communication, and L_B is the number of bits in the modulated signal. The system's BER is then:

$$\begin{cases} P_{OOK,LOS} = \int_0^\infty f(I)Q\left(\frac{\sqrt{SNR_{LOS}I}}{2}\right)dI, \\ P_{PPM,LOS} = \int_0^\infty f(I)\frac{L_B}{2}Q\left(\frac{\sqrt{L_B log_2 L_B SNR_{LOS}I}}{8}\right)dI, \\ P_{PAM,LOS} = \int_0^\infty f(I)\frac{2(L_B-1)}{L_B log_2 L_B}Q\left(\frac{\sqrt{log_2 L_B SNR_{LOS}I}}{2(L_B-1)}\right)dI, \\ P_{QAM,LOS} = \int_0^\infty f(I)\frac{2(L_B-1)}{L_B log_2 L_B}Q\left(\frac{\sqrt{log_2 L_B SNR_{LOS}I}}{8(L_B-1)}\right)dI \end{cases} \tag{15}$$

Similarly, treating the UV NLOS communication link as a combination of two LOS links, its probability density function is obtained from the conditional probability formula based on Eq. (14), eventually taking a form similar to Eq. (15). Set the communication distance of the system to 200m, the data transmission rate R to 0.5Mbps, the transmitter FOV angle to 20°, the receiver FOV angle to 30°, the elevation angle of the transmitter and receiver to 30°, and the transmission power to 50mW to simulate the performance of the system. The BER trends of UV LOS and UV NLOS communications under different turbulence scintillation indices with varying SNR are illustrated in Fig. 14.

From Fig. 14, it can be observed that as the scintillation index increases, the performance of the system's BER gradually deteriorates. Under the same turbulent conditions, the BER performance of the LOS link is superior to that of the NLOS link. Under the same turbulent conditions and link structure, the BER performance of PPM modulation is better than that of OOK modulation, OOK modulation is better than that of PAM modulation, and QAM modulation has the worst performance. This indicates that for specific conditions, the optimal modulation scheme can be found, which satisfies both the rate and the BER. Therefore, in strong interference or long distance communication scenarios, other approaches such as adaptive modulation techniques are required to obtain better BER or higher communication rates. Specifically, selecting an appropriate modulation scheme requires consideration of the system's power efficiency and channel coding scheme. In some cases, adopting more complex modulation techniques may result in higher communication rates, but it will also increase system complexity and power consumption. Therefore, when designing a modulation scheme, it is necessary to combine methods such as swarm intelligence, deep learning, and convex optimization to achieve an effective trade-off between communication rate, BER performance, power efficiency, and system complexity.

For fading caused by atmospheric turbulence, the transmitter can change the transmission parameters such as power, modulation size, and code rate according to the channel conditions, i.e., adaptive coding and modulation (ACM). There are three common types of adaptive modulation: variable rate variable power systems, variable rate constant power systems and constant rate variable power systems [223]. Based on these classifications, it can be found that adaptive modulation technique is not a standalone technique, it is often combined with beamforming, power control and other techniques for integrated design, as related to the relevant sections in the previous section. For the modulation technique itself, [224] utilized the constant envelope property of S-PSK to adjust the modulation order of SPSK according to the turbulence-induced transient state and BER requirements, resulting in an effective increase in the capacity of the FSO channel. In order to improve the spectral efficiency, [225] changed the modulation order of the MPSK scheme according to the instantaneous channel state and BER limits to improve the spectral efficiency. Reference [137] by adopting N-ary coding adaptive spatial modulation (SM) in FSO communication and combining it with M-ary PPM, and using diversity methods with MIMO and MISO configurations, significantly alleviated the signal attenuation caused by atmospheric turbulence, thereby reducing the system's BER. Simulation results show that this approach enhances the stability and integrity of the signal, laying a foundation for high-capacity, robust optical wireless communication, and can effectively address the challenges posed by atmospheric turbulence. In addition to this, adaptive modulation techniques are mostly used as a comparison strategy in the design of HD systems and beamforming systems, and there are still fewer related researches specialized in adaptive modulation techniques for UV communication.

X. CODING

The UAV transmits a wide range of data types during its mission, including data information such as images and videos and control information such as position, attitude, altitude and speed. The structure of the transmission system includes air-to-air transmission and air-to-ground transmission. Similar to adaptive modulation techniques, adaptive coding techniques aim to trade-off rate and BER in different scenarios [234], [235]. Related studies have pointed out that when the transmission rate of the system is less than the channel capacity given by Shannon's theorem, an arbitrarily small BER can be obtained at a given SNR by appropriate coding error correction techniques [236]. For practical UV communication systems, under specific turbulence intensity and link distance conditions, the selection of appropriate coding techniques can significantly reduce the BER of the system or achieve the minimum transmit power at a given BER condition. The latter is important for reducing ambient radiation versus improving the energy utilization of UV communication systems for UAVs [237], [238].

In recent years, the more widely used channel coding techniques are Reed-Solomon (RS) codes, Low Density Parity Check (LDPC) codes, Polar codes and Turbo codes. The latter three error-correcting codes have attracted wide attention in RF communication due to their excellent error-correction performance and ability to approach the Shannon limit [239], [240], [241], and the performance advantages and disadvantages of the above error-correcting codes in

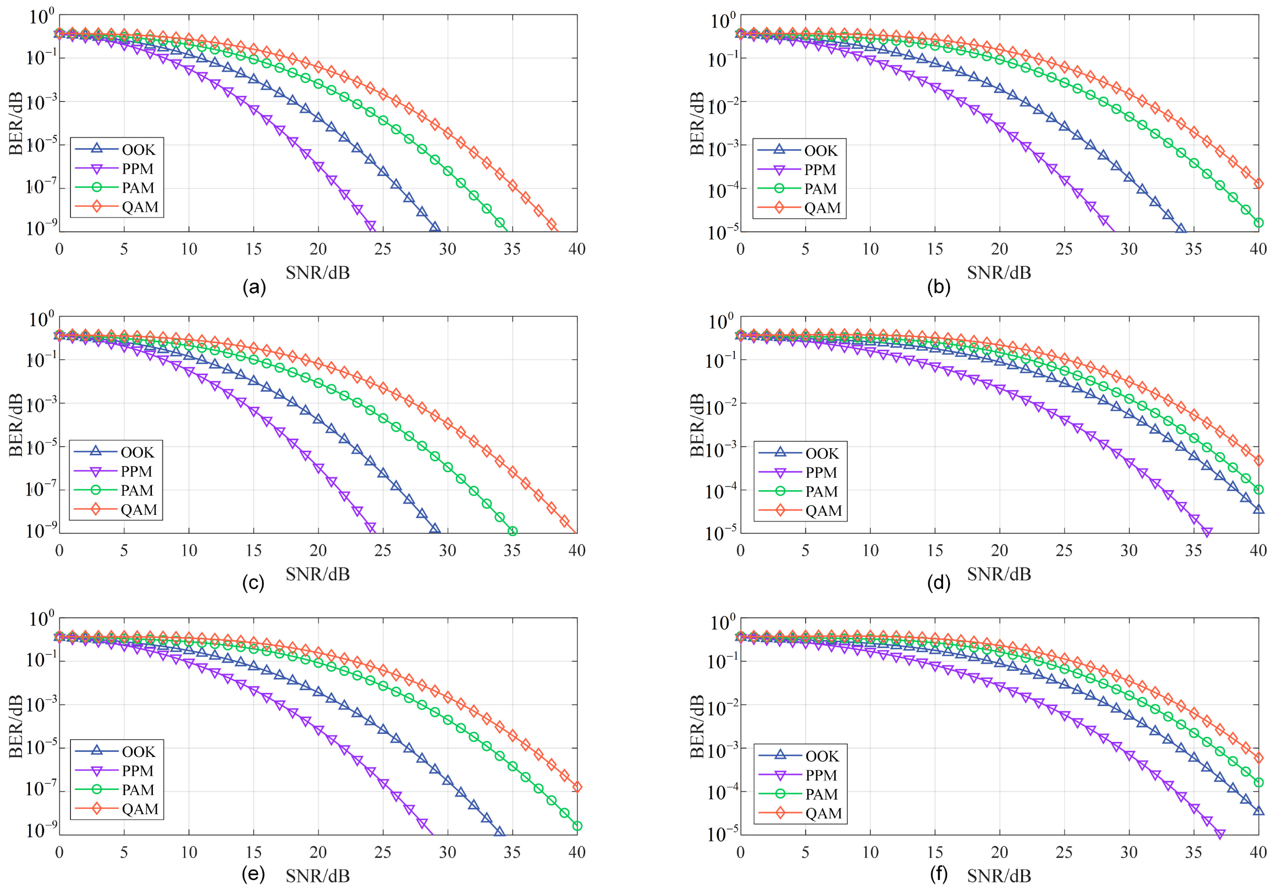

FIGURE 14. **The relationship between BER and SNR in UV communication system under turbulent conditions: (a) LOS link, $\sigma_s = 0.1$; (b) NLOS link, $\sigma_s = 0.1$; (c) LOS link, $\sigma_s = 0.3$; (d) NLOS link, $\sigma_s = 0.3$; (e) LOS link, $\sigma_s = 0.5$; (f) NLOS link, $\sigma_s = 0.5$.**

different types of communication systems have become one of the focuses of attention. Reference [242] investigated the farthest communication link for UV communication supported by RS code and LDPC code under a given power and BER. The experimental results show that the communication distance supported by LDPC codes is more than twice that of RS codes, i.e., LDPC has better communication performance. Reference [243] compared the performance difference between LDPC codes and Turbo codes in UV communication systems and concluded that LDPC codes have better BER performance and complexity than Turbo codes. References [241] and [244] compared the BER and secrecy performance of Polar and LDPC codes, respectively. The authors point out that Polar codes have better BER performance and secrecy than LDPC codes. Polar codes, as a later born channel code, the improvement of its codeword construction and decoding method is an important research direction, while there are still fewer cases about the application of Turbo in UV communication. Therefore, the current research status of LDPC codes and Polar codes in UV communication systems in recent years will be described next.

In terms of the algorithmic application of LDPC, [245] applied LDPC codes to UV communication systems and simulated the BER performance at different distances. It is found that the LDPC code helps a lot to improve the performance of the system, but this improvement is limited by the distance, and the BER shows a waterfall jump trend with the increase of distance. When the transmission distance varies around a certain threshold, the BER changes drastically. When the transmission distance is much larger than this threshold, the improvement of BER by LDPC code is not obvious, and when the transmission distance is smaller than this threshold, the improvement of BER by LDPC code is better. Reference [246] combined the LDPC coding scheme with spread spectrum technology to propose an effective system scheme. The results of analyzing the system model show that the scheme can effectively suppress multipath interference and improve the BER performance of UV communication. Reference [156], on the other hand, applied the LDPC algorithm to the coplanar MIMO system as a preamble channel coding algorithm for different merging algorithms in the diversity technique, and achieved reliable analytical results. Regarding the physical structure configuration of the LDPC system, taking the [247] as an example, the authors proposed a scheme of UV communication system that employs LDPC coding, and this study investigated the BER performance of the system by taking into account the macroscopic physical parameters of the device, the microscopic mechanism, and the system structural parameters. The study reveals the advantages of adaptive coding.

In terms of performance enhancement and analysis of LDPC compiled code algorithms, [248] proposed a heuristic checksum matrix construction algorithm for LDPC codes to approximate the upper bound of the data transmission rate based on the received response characteristics of the UV scattering channel. The algorithm achieves a better BER on short-link UV communication systems compared to conventional LDPC coding methods. References [246] and [249] investigated the performance of LDPC coding in UV communication systems at different code lengths and BER algorithms. The results show that the belief propagation (BP) algorithm with log-likelihood-ratio confidence propagation (LLR BP) has superior BER performance compared to the bit-flip (BF) decoding algorithm and the minimum-sum (MS) decoding algorithm. Beyond that, long codes should be used in UV communication systems. Reference [250] expanded the previous results of LDPC coding research under the single scattering assumption to multiple scattering channels, established a Monte Carlo simulation model, and analyzed the impact of different decoding algorithms on the performance of UV communication systems. The results show that the BP decoding algorithm has the best performance compared to BF and MS algorithms. From these studies, it can be found that the integration of LDPC codes with practical UV communication systems has been widely used, especially for SISO and LOS types of systems. So the extension of the application to 3D high-order MIMO systems is a feasible research direction, while the performance advantages of Turbo codes have not been fully released, the research focus will still be on the decoding algorithm.

Unlike LDPC codes and Turbo codes, Polar codes can be theoretically proved to reach the capacity of arbitrary binary input discrete memoryless channels. But due to its late start, its code word construction and decoding algorithms are not as mature as those of LDPC codes and Turbo codes, and its application in UV communication systems is not as widespread as that of LDPC codes. At present, the performance enhancement of Polar codes under finite length is a key research direction in this field. Reference [251] optimized the successive cancellation decoding algorithm by using the path loss model of UV communication, and implemented the successive cancellation list decoding algorithm. The results show that the SCL algorithm can improve the effective communication distance of the UV communication system, and the performance of the SCL decoding algorithm increases with the increase of SC. In order to optimize the bottleneck of performance enhancement that occurs after the number of SC increases to a certain degree, the article introduced Cyclic Redundancy Check (CRC) so that the system obtains a lower BER. Reference [252] considered the computational complexity issue from the perspective of coding length, derived the upper limit of Bhattacharyya for general polar codes in UV communication systems, and then give the length of the minimum codeword. The coding scheme for Polar codes proposed in the article can obtain better performance with lower complexity. In addition to this, coding methods applied to UAV swarm UV communication have also been proposed by scholars, such as [253], which proposes unequal level coding Lu by Transform (ULC-LT) and stepwise unequal error protection Lu by Transform (SUEP-LT) based on the fountain code, and the results show that both coding methods have a better performance than LT coding.

In order to trade-off the reliability and throughput of UV communication, we expect the transmitter to be able to adjust the parameters, which has been proved to be effective in RF communication systems [254], [255]. In the existing research on VLC communication systems, various types of adaptive transmission systems have been proposed and their feasibility and advantages have been verified. Safi provided an adaptive coding and power control scheme and analyzes the effect of channel estimation error in practical FSO systems [256]. Reference [257], on the other hand, investigated the joint adaptation of modulation size and transmission power. The study proposed an adaptive non-coding transmission algorithm that enables the transmission power and modulation size of the system to vary with channel conditions. Reference [258] investigated the coding system with fixed code rate and MPPM under average power constraints, and proposed an adaptive coding scheme for Turbo codes, which enables the system to select the modulation size at the transmitter based on CSI. References [259] and [260] designed adaptive coding rate adjustment algorithms based on LDPC codes, which are capable of achieving optimal throughput based on the real-time characteristics of the channel.

To address the negative impact of channel conditions on the system, [261] investigated the joint adaption of symbol rate and power, and the article considered adaptive symbol rate with symbol duration varying with channel conditions as a way to reduce the effect of atmospheric scintillation in FSO links. In order to mitigate the performance degradation in the presence of strong turbulence, [262] investigated three LDPC coded modulation schemes, namely, variable-rate variable-power adaptive scheme, fixed-rate channel inversion scheme, and truncated channel inversion scheme. The article pointed out that the fixed-rate channel inversion scheme is suitable for weak turbulence conditions, and the variable rate variable power scheme or the truncated channel inversion scheme is suitable for strong turbulence situations.

This chapter presents a study of coding techniques in UV communications, beginning with an introduction to commonly used LDPC and Turbo codes and their decoding algorithms, followed by a consideration of adaptive problems in the coding domain. As with techniques such as beamforming, power optimization, and confidentiality optimization, such adaptive problems are often modeled as optimization problems dependent on the channel state. In the field of UAV UV communication, adaptive coding techniques are a more flexible direction than traditional research on coding algorithms [263], [264]. For example, incorporating both adaptive coding and adaptive modulation techniques in systems that aim to reduce inter-link interference. Or in a HD system, use a solution to adjust the encoding bit rate instead of changing the modulation depth.The prerequisite for these techniques lies in the utilization of real-time characteristics of the UV channel. Not only that, but as a basis for implementing adaptive algorithms with lower time complexity, we would like to model non-black-box forms of more concise but no less accurate optimization in these cross-directions.

XI. CONCLUSION AND FUTURE DIRECTIONS

This paper provides a comprehensive overview of research on UV communication technology for UAVs. We present eight aspects of the current state of research in UV communications for UAVs from a communications engineering perspective: channel modeling, localization techniques, beamforming, power control, networking, diversity and merging, modulation and demodulation, and coding. With the help of this survey, readers can learn about the current state of development of UV communication technology for UAVs, so that they can conduct further research on the technical details of interest.

In the preceding analysis, the article was structured according to various technical categories. In dynamic environments, changes in external environmental parameters necessitate that the UV communication system automatically adapts to the impact on system parameters. This adaptive mechanism must be capable of integrating with multiple technologies to comprehensively enhance system performance. The implementation of adaptive technologies in UV communication systems primarily encompasses three aspects: adaptive coding, adaptive modulation, and beamforming.

In the realm of adaptive coding, the system is capable of selecting appropriate coding schemes based on the real-time characteristics of the channel conditions. For instance, when the channel conditions are favorable, the system may opt for LDPC codes to increase data transmission rates. Conversely, when channel conditions deteriorate, the system may switch to Turbo codes to bolster interference resilience. Furthermore, the system can dynamically adjust the coding rate; for example, it may increase the coding rate (e.g., from 1/2 to 3/4) under high signal quality conditions, while reducing the coding rate (e.g., from 3/4 to 1/2) when signal quality declines, thereby ensuring communication reliability.

Regarding adaptive modulation, the system can select suitable modulation schemes based on the instantaneous state of the channel and the requirements for BER. For example, under good channel conditions, the system may employ 64-QAM (Quadrature Amplitude Modulation) to achieve higher data transmission rates, whereas it may resort to 16-QAM or Quadrature Phase Shift Keying (QPSK) under poorer channel conditions to enhance signal robustness against interference. Additionally, by jointly adjusting modulation size and transmission power, the system can optimize performance across varying channel conditions; for instance, it may increase transmission power to extend range when signal quality is high, while reducing transmission power to mitigate interference when signal quality is low.

Beamforming technology optimizes the propagation direction of signals by utilizing directional antenna arrays. In multi-user environments, the system can employ adaptive beamforming techniques to focus signals towards specific users, thereby enhancing the signal strength for those users while reducing interference to others. Simultaneously, the system can dynamically adjust the amplitude and direction of the beam based on real-time channel states and user positions, ensuring stability and efficiency in signal transmission.

The comprehensive application of these adaptive technologies can significantly enhance the communication efficiency and reliability of UV communication systems. In addition to this, based on the previous research work, we summarize the future development trend of UAV UV communication technology:

- Channel modeling: Firstly, to address the challenges of communication systems in special contexts, including the effects of UAV flight characteristics, airframe vibration, altitude change pairs, and special reflective surfaces and obstacles on communication, further refinement of channel models is needed to improve communication quality. Secondly, as the transmission distance increases, the difference in average path loss between high-order scattering and second-order scattering is approximately 15dB, highlighting the increased significance of multiple scattering effects. Trends indicated in Fig. 4 suggest that future research will focus on developing models capable of accurately considering multiple scattering to improve the precision of UV channels. Lastly, it is crucial to prioritize the computational efficiency of the model (reducing the time complexity from $O(n^4)$ or even higher to $O(n^2)$ or $O(n)$), enabling the system to obtain channel information for UAV-based UV communication in real-time and efficiently.
- Positioning techniques: Firstly, for three-dimensional spatial positioning techniques, existing research has proposed methods that achieve average positioning accuracy of 3.5cm and 6cm, respectively. Studies indicate that determining height based on two-dimensional localization can achieve higher precision in positioning. Secondly, since the transmitter in actual UV communication systems can point in any direction, researching positioning techniques based on NLOS links has become an important direction. Additionally, combining the advantages of LOS links and NLOS links, the focus of future research will be on multi-link fusion positioning techniques. Currently proposed methods can

achieve an accuracy rate of over 80% with an average error of less than 10m within a space of 200m in length, width, and height. Lastly, the application of UV image-based positioning techniques on mobile platforms is of significant importance. Current technology has achieved stable communication connections within a horizontal FOV of 320 degrees and a vertical FOV of 110 degrees. Therefore, the future focus of UV communication positioning technology research will be on three-dimensional spatial positioning techniques, NLOS link positioning techniques, multi-link fusion positioning techniques, UV image-based positioning techniques, and multidimensional data fusion positioning techniques. The development of these directions will promote the efficient, safe, and reliable application of UV communication in UAV groups.

- Beamforming Technology: The objective of UV communication beamforming technology is to minimize mutual interference in MIMO and network communication scenarios while enhancing the confidentiality of signal transmission. According to previous research, different input signal distributions have varying impacts on the secrecy rate, with truncated Gaussian distribution input signals showing better performance in terms of secrecy rate. Therefore, it is necessary to adjust the distribution characteristics of the signals to further enhance the system's confidentiality. Secondly, in multi-user MISO communication scenarios, the design of effective precoding schemes can further improve the system's secrecy and anti-interference capabilities. Current research has been able to significantly enhance the system's secrecy and fairness through precoding schemes designed based on optimization models of upper and lower bounds. Additionally, studies have shown that addressing the issue of target channel and eavesdropper channel position changes in UAV communication scenarios, by analyzing the random distribution of eavesdroppers, can effectively improve system security. By minimizing the average SNR of the eavesdropper and maximizing the SNR of the target user, the system's security can be significantly improved. Therefore, the future focus of research on UV communication beamforming technology will be on enhancing the confidentiality of the signal transmission process, designing effective precoding schemes, and analyzing the issue of target channel and eavesdropper channel position changes in UAV communication scenarios, with actual data supporting these research directions.
- Power optimization: Compared to UV communication systems without power optimization technology, those that employ power optimization techniques can effectively reduce environmental radiation. For UV-specific power optimization systems, they can significantly decrease the system's transmission power while maintaining the BER, providing a solid foundation for outdoor applications of UAV-based UV communication. The development direction of power optimization technology for UAV-based UV communication mainly includes three aspects. Firstly, by integrating the characteristics of UV channels, establishing a power control model suitable for UV communication systems to enhance communication quality and energy efficiency. Secondly, researching hybrid dimming schemes that utilize the advantages of both HD and SD to expand the dynamic range of power and enhance system robustness. Lastly, improving the execution efficiency of optimization algorithms, using the information from the model itself to provide a basis for execution, in order to enhance the accuracy of the optimization model and the efficiency of the algorithm.
- Diversity techniques: First, further optimization of diversity reception schemes, such as the use of multi-beam methods to improve system throughput, the combination of appropriate MIMO coding to achieve higher diversity gain, and the improvement of coding schemes such as STC, DSTBC, and so on, in order to reduce the system BER. The second is to explore the performance of different combining methods under different modulation conditions, such as comparing the performance of SC, EGC and MRC combining methods under BPSK modulation, as well as exploring the combination of new modulation methods and combining schemes, such as the combination of SOPP-OSTBC and 2PPM modulation. Future research focus will be extended to MIMO systems above second order to further refine the application of diversity techniques in UV communications.
- Networking technology: The development direction of UV networking technology mainly focuses on dynamic TDMA protocols, contention-based random access protocols, and optimized network topology and node density. As shown in Fig. 7, dynamic TDMA protocols improve network performance through dynamic time slot allocation mechanisms, while contention-based random access protocols allow nodes to compete for channel access during idle time slots. The former achieves higher throughput, lower latency, and lower packet loss rates through dynamic time slot allocation mechanisms, while the latter can effectively reduce interference between signals, thereby improving transmission efficiency and the overall data throughput of the network. In addition, optimizing network topology and node density is crucial for improving network connectivity and throughput. Through improvements in these three areas, UV networking technology can better adapt to changes in network topology and node roles, enhancing network flexibility and reliability. At the same time, for special application scenarios shown in Fig. 6, research on aspects such as UAV

swarm collaboration, obstacle avoidance, and relay node optimization should be strengthened to further improve the performance and communication range of UV communication networks.

- Modulation technology: Based on the results shown in Fig. 9, higher-order modulation schemes can increase channel capacity and transmission rates, but they also reduce the system's anti-interference capability and BER performance under complex conditions. In Fig. 12, with relatively deteriorated channel conditions, when the turbulence intensity and scintillation index are the same, QAM modulation has the highest BER, while PPM modulation has the lowest BER. As the SNR decreases, the BER magnitude between the two increases gradually from about 10^{-6} dB to close to 1 dB. Therefore, the following aspects can be considered for the improvement of modulation schemes. First, integrating techniques such as beamforming and power control to achieve a comprehensive design and improve system adaptability and performance. Second, utilizing modulation schemes with constant envelope characteristics, such as S-PSK, and adjusting them according to channel conditions and BER requirements to increase communication capacity. Third, adopting more flexible modulation schemes, such as MPSK, based on instantaneous channel conditions and BER constraints to improve spectral efficiency. The development of these technologies will enable UAV UV communication systems to better adapt to different environments and communication requirements, enhancing the reliability and efficiency of communication.
- Coding technology: The introduction of this paper on UV communication coding technology points out that LDPC codes have received considerable attention due to their excellent error correction performance and ability to approach the Shannon limit, while the application of Turbo codes in UV communication is not yet widespread. Therefore, related research will continue to explore how to improve system performance by adjusting coding techniques, especially in the optimization and application under specific transmission distances and environmental conditions. Secondly, as an emerging coding technology, the performance enhancement of Polar codes at finite lengths is the focus of current research, and the optimization and application of their decoding algorithms will be the main research direction in the future. Finally, with the development of artificial intelligence and machine learning, adaptive coding technology for UAV UV communication may introduce more intelligent adaptive algorithms, improving the flexibility and adaptability of the system, thus further enhancing communication efficiency and performance. These development trends will make the coding technology of UAV UV communication play a more important role in the future and provide higher-quality communication services for various application scenarios.

Unlike the well-known RF, IR and VLC communications, UV communication technology is relatively less well known. UAV-based UV communication has been less researched, and the challenges it faces (availability, stability, effectiveness) are more severe. However, the various properties of UV communication have shown its potential to be applied to UAV communication (For example, as indicated in Fig. 8, UV communication has the advantage of low path loss in short-distance NLOS scenarios.), and more research work will be conducted in the future centering on the above challenges.

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