Ultraviolet-Based UAV Swarm Communications: Potentials and Challenges

Guozhi Chen, Tianfeng Wu, Fang Yang, Tengjiao Wang, Jian Song, and Zhu Han

Abstract

Unmanned aerial vehicle (UAV) swarm communication has received increasing attention thanks to its intriguing advantages, such as low costs, high mobility, and deployment convenience. However, this technology is also facing certain new challenges, for example, RF spectrum scarcity, interference, and network connectivity. To this end, ultraviolet (UV) communication is introduced in this article to tackle these problems due to its distinctive benefits, such as license-free operation, immunity to electromagnetic interference, and the ability of non-line-of-sight transmission. First, a comparison between UV communication and other alternatives is presented. Then the structural designs of the high-capability UAV and the low-capability UAV, the system communication protocol and mutual interference, and the network topology of the UV-based UAV swarm are investigated. Further, the bit error rate performance, data rate, and communication range are analyzed. In the end, an artificial-intelligence-aided UV-based UAV swarm system is put forward to tackle users' complicated requirements. Simultaneously, the challenges are discussed to direct future research work.

Introduction

The unmanned aerial vehicle (UAV) has been widely employed in military, public, and civil applications due to its distinctive advantages, such as low acquisition costs, flexible deployment, and high-altitude maneuverability [1], which give it an important role in border surveillance, fire and flood monitoring, rescue missions in disaster-affected areas, and so on.

Compared to the single UAV and the conventional fixed sensors, the UAV swarm has the potential to carry out more complicated missions. For example, a UAV swarm can be deployed as a flying base station (BS) to provide emergency communication for disaster areas due to its large coverage. Moreover, the UAV swarm's capability of cooperative communication makes it more robust than the individual UAV, especially in complex environments such as mountains and forests.

However, with the rapid advances in UAV swarm communication technology, it also faces certain new challenges, for example, radio frequency (RF) spectrum scarcity, mutual interference, and network connectivity problems. Since the sub-6G spectrum has been massively utilized in terrestrial communication networks, the widespread use of UAVs can severely disrupt the terrestrial cellular networks and decrease their system capacity much more than that anticipated in system planning, thereby degrading the quality of communications for ground users [2]. Furthermore, the UAV swarm's connectivity will be blocked in certain complex environments (e.g., scenarios full of uneven buildings or mountainous areas where there is no ground BS available) when performing exigent missions.

To promote the development of UAV swarm communication technology, it is imperative to address the problems mentioned above. In allusion to the RF spectrum scarcity and the mutual interference it brings, one of the current solutions principally focuses on the efficient use of cellular spectrum. For instance, an iterative sub-channel allocation and speed optimization algorithm is proposed in [3], which can upload 10 percent more data than the existing greedy algorithm. Beyond that, two spectrum sharing mechanisms, underlay and overlay, are studied in detail in terms of coverage probability and the rate of two link types and their interactions to determine the optimal sharing scheme [4]. To a certain degree, these studies mitigate the issue of RF spectrum scarcity; however, they are not applicable to cases of massive UAV communications.

In this article, ultraviolet (UV) communication is exploited to address the problems of RF spectrum scarcity, interference, and network connectivity for UAV swarm communication. To highlight its superiority, the comparison among visible light, millimeter-wave (mmWave), RF, and UV is presented in the next section. Then designs of high-capability UAVs and low-capability UAVs, UV-based UAV swarm topology, system communication protocol, and mutual interference are investigated. Further, the bit error rate (BER) performance, data rate, communication range, and effective techniques that can be utilized to extend the UV non-line-of-sight (NLoS) distance are provided. Apart from that, an artificial intelligence (AI)-aided UV-based UAV swarm system is proposed to address users' complicated communication requirements; meanwhile the challenges that deserve to be researched

Guozhi Chen, Tianfeng Wu, Fang Yang (corresponding author), and Jian Song are with Tsinghua University and Beijing National Research Center for Information Science and Technology, P. R. China; Fang Yang and Jian Song are also with the Key Laboratory of Digital TV System of Guangdong Province and Shenzhen City, Research Institute of Tsinghua University in Shenzhen, P. R. China; Tengjiao Wang is with Huawei Technologies Co., P. R. China; Zhu Han is with the University of Houston, USA, and also with Kyung Hee University, South Korea. Guozhi Chen and Tianfeng Wu contributed equally to this work.

Digital Object Identifier:
10.1109/MWC.007.2100405

1536-1284/22/$25.00 © 2022 IEEE

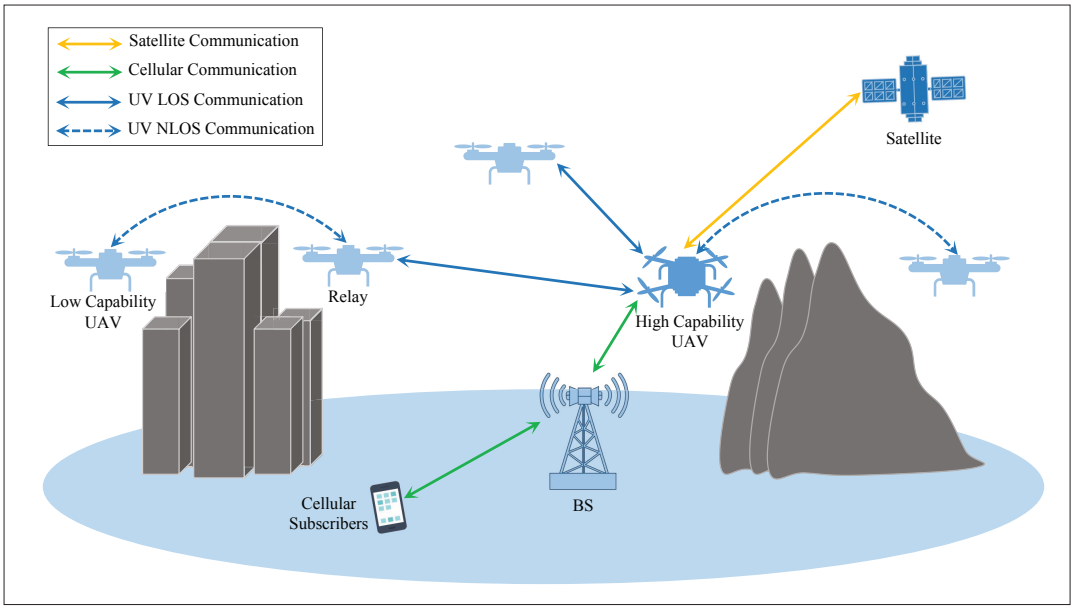


FIGURE 1. Illustration of the UV-based UAV swarm communication system — example scenario.

in future work are also discussed. Finally, our contributions are summarized in the final section.

The Potential of UV Communication

An understanding of the communication principle for the UV system begins with how UV signals interact with atmospheric constituents. Following [5], the dominant interactions between UV photons and atmospheric components can be characterized by scattering and absorption. For the former, mainly including Rayleigh (molecular) scattering and Mie (aerosol) scattering, it endows the UV system the ability to bypass obstacles (NLoS transmission) and relaxes information acquisition and tracking requirements. For the latter, it prevents crucial information from being eavesdropped (fine confidentiality) [6]. Further, the ozone in the upper atmosphere has a strong absorption impact on the deep UV range (200–280 nm) [7], which implies that the solar radiation reaching the ground in this band can be ignored (negligible background noise).

Motivated by the rapid advances in UV light-emitting diodes (LEDs), photodetectors including photomultiplier tube (PMT) and avalanche photodetector (APD), channel modeling, as well as performance improvement techniques [5], UV communication technology is once again in the spotlight, which can be utilized to make up for the deficiencies of the aerial access network and can be integrated into the ground-air-space communications. In this article, UV communication is combined with satellite and cellular communications to cope with the problems faced by the UAV swarm, as illustrated in Fig. 1. This combination can be applied to practical scenarios such as border surveillance and rescue in disaster-affected areas, among others. It is worth noting that during the mission of the UAV swarm, the UV power levels must be adjusted to comply with the safety regulations when approaching people. To be specific, in the deep UV range, the minimum exposure within 1 s duration occurs at 200 nm with a level of 100 mJ/cm^2, decreasing to 3 mJ/cm^2 at 270 nm and increasing to 3.4 mJ/cm^2 at 280 nm. More details regarding the relationship between UV exposure limits and wavelength can be found in [7].

Further, we compare UV technology with RF and other alternatives that may be applied to the UAV swarm to highlight its superiority. From the perspective of the spectrum, the available bandwidths of UV, mmWave, and visible light are much larger than RF, and thus can eliminate the interference caused by the repeated use of RF spectrum resources in the UAV swarm. In allusion to network connectivity, both UV and RF support LoS and NLoS communications [7, 8], while mmWave and visible light mainly support LoS communications [9, 10], which makes it challenging to maintain the dynamic connectivity of the UAV swarm. In addition, the noise for RF and mmWave primarily comes from terrestrial communications, while that for the visible light mainly originates from solar radiation. For the system complexity, RF and mmWave are inferior to the visible light and UV, especially for the mmWave communication that requires large-scale antennas for coordination and a certain-scale phased array for beamforming [9]. For the data rate, the mmWave communication performs best with a level of gigabits per second, followed by RF, visible light, and UV LoS communications with the order of megabits per second, and finally, UV NLoS communication with kilobits per second. Regarding the distance, RF can reach several kilometers, while mmWave, visible light, and UV can reach hundreds of meters. Note that the UV NLoS distance is mainly limited by the transmitted power due to the large path loss. For the sake of clarity, the comparison among the different spectra is summarized in Table 1.

Significantly, the introduction of UV technology in this article is not intended to completely replace the use of RF in the UAV swarm, but to mitigate communication bottlenecks caused by the scarcity of RF spectrum. Certainly, with the rapid advances in UV hardware technology, it is believed that UV will become an alternative to RF in certain scenarios in the future, such as short-range and low-bandwidth communications between unattended distributed sensors in a wireless network [8].

Characteristics		Sub-6G RF	mmWave	Visible light	UV-C
Signal	Wavelength	> 5 cm	1 mm ~ 1 cm	390 ~ 760 nm	200 ~ 280 nm
	Amplitude	Complex		Real-valued, non-negative	
	Noise	Terrestrial communications and thermal noise		Solar radiation	Negligible
Propagation	Distance	Several kilometers	Hundreds of meters	Hundreds of meters	
	Direction	Both LoS and NLoS	Mainly LoS	Mainly LoS	Both LoS and NLoS
	Data rate	~ Mb/s	~ Gb/s	~ Mb/s (Outdoor)	< 1 Mb/s (NLoS), ~ Mb/s (LoS)
	Confidentiality	Easy to intercept	Hard to intercept	Visible, easy to spot	Invisible, hard to intercept
Devices	Transmitter	Antennas		LEDs	
	Receiver	Antennas		Photoelectric detector	PMT, APD
Unique advantages		Easy to deploy	SDMA via beamforming	High power efficiency	Licence-free, NLoS transmission

TABLE 1. Comparison of UAV swarm communications among different spectra.

UV-Based UAV Swarm System

Swarm Topology

First, the topological structure of the UV-based UAV swarm is investigated. According to [11], the architecture of the UAV network topology for communication applications is an under-researched domain, and no clear recommendation for a specific strategy can be derived from the literature. For this reason, the applicability of two widely used existing UAV network topologies, star and mesh [11], is investigated in the following in combination with the inherent characteristics of UV technology.

In the case of star topology, each UAV needs to connect to the control center and execute single-hop communication between the node and the central point. Communications among all the UAVs would be implemented through the control center. Because of the high attenuation of the UV channel, the achievable distance cannot satisfy the communication demands between the UAV and the control center.

In the case of mesh topology, each UAV interconnects with several nodes, and a small proportion of UAVs are connected to the control center. One major advantage of this topology is that it allows data packets to convey from any data collection node to any destination through multiple intermediate nodes. This means that even if one of the intermediate nodes is out of action, it will not seriously affect the overall data transmission process. Furthermore, the mesh topology is highly adaptable to complex environments, for example, scenarios full of uneven buildings or mountains. Incorporating these crucial factors, we select the mesh topology as the prototype to research the UV-based UAV swarm communications, as illustrated in Fig. 1.

High-Capability UAV and Low-Capability UAV

The structural designs and associated functions of the two types of UAVs, high-capability UAV and low-capability UAV, involved in the UAV swarm are investigated.

To prevent misinterpretations, the definitions of the four typical UAV-to-UAV communication scenarios as shown in Fig. 2 are provided: in NLoS scenario I, the communication between the wide beam and the wide field of view (FoV); in NLoS scenario II, the communication between the wide beam and narrow FoV, or the narrow beam and wide FoV; in NLoS scenario III, the communication between the narrow beam and narrow FoV; and in the LoS scenario, the communication between the narrow beam and narrow FoV, where the transmitter and receiver are within each other's FoV.

High-Capability UAV: As illustrated in Fig. 2, it possesses two wide beams (or FoVs) and four narrow beams (or FoVs). The two wide FoVs can be applied to acquire the IDs, position information, communication requests, and the data packet sent at low speeds from the low-capability UAVs or relays. The two wide beams can be used to send information such as instructions or to transmit the information to other low-capability UAVs. Note that the communication scenarios mentioned above refer to NLoS scenarios I and II. The four narrow beams can be utilized to transmit some advanced requirements or data packets at a low speed via NLoS scenarios II and III or send data packets at a high speed via the LoS scenario. In regard to the four narrow FoVs, they perform the mission of high-speed data reception via the LoS scenario, and acquire the advanced demands or receive the data packet at low speeds via NLoS scenarios II and III. In addition to this, the high capability-UAV is also responsible for exchanging information with the satellites or ground BSs through RF communications.

Low-Capability UAV: As presented in Fig. 2, it is designed with a wide beam (or FoV) and two narrow beams (or FoVs). The wide beam's and wide FoV'sr functions are basically similar to that of the wide beam and wide FoV of the high-capability UAV, so we do not repeat them here. The two narrow beams can be applied to transmit information such as sensing and collecting data to the high-ca-

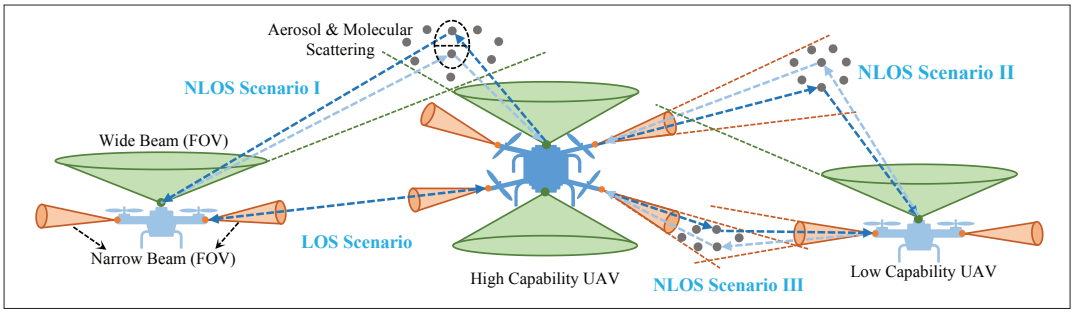


FIGURE 2. Illustration of the UV-based high-capability UAV and low-capability UAV as well as four typical UAV-to-UAV communication scenarios.

pability UAV at a high speed via the LoS scenario, or at a low speed via NLoS scenarios II and III. The two narrow FoVs can be utilized to receive the information such as the collected data from other low-capability UAVs through the LoS scenario, or a message such as advanced instructions from the high-capability UAV via NLoS scenarios II and III.

Mutual Interference

The UV mutual interference is investigated combined with the four typical communication scenarios.

For the LoS scenario, the interference mainly comes from photons' scattering of other UV signal transmission channels. Since the energy attenuation of the UV LoS channel is much less than that of the UV NLoS channel [7], this kind of interference can be neglected here.

For NLoS scenarios II and III, the transmitter beam axis and receiver FoV axis remain coplanar to the greatest degree during normal communications. The interference is composed of two parts: the scattering of photons from LoS channels and the scattering of photons from other NLoS channels. Actually, these two kinds of scattering can be classified into one case (i.e., the noncoplanar case), where the transceiver axes are not in the same plane. Following [5], it can easily be found that as the off-axis angle increases, the energy loss of the UV NLoS channel will increase significantly, which means that the interference can be mitigated dramatically by adjusting the UAV swarm layout.

For NLoS scenario I, where the transceiver axes usually point vertically to the sky, the interference is primarily caused by the vertical transmitters around the target receiver. Further, the transmissions of signal and interference both belong to the case of UV coplanar communication; hence, it is unfeasible to eliminate the interference through adjusting the deployment of the UAV swarm. Targeting this issue, three feasible solutions are provided here: wavelength-division multiple access (WDMA), employing different wavelength filter combinations in different links; time-division multiple access (TDMA), utilizing the same kind of light source to send the designated signals in different time slots; and code-division multiple access (CDMA), utilizing codes to activate or deactivate the transmitting and receiving mechanisms. Compared to TDMA and CDMA, WDMA will markedly increase the purchase and maintenance costs of high-capability UAVs and low-capability UAVs, as well as their hardware complexity, which is detrimental to the UAV swarm. Thus, TDMA and CDMA are more suitable for coping with this kind of interference.

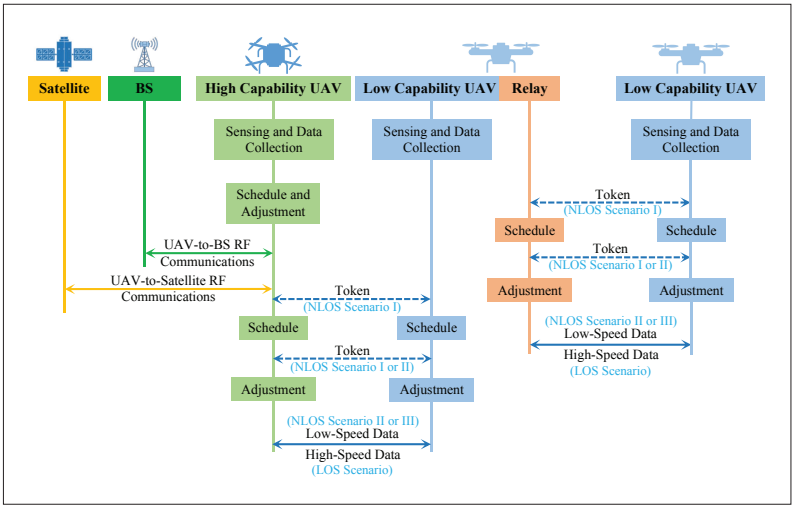


FIGURE 3. Illustration of the UV-based UAV swarm communication protocol.

Communication Protocol

Finally, the proposed protocol for the UV-based UAV swarm system is provided in Fig. 3, which can be summarized as the following five steps:

- Sensing and data collection. In this step, the UAV swarm performs data collection missions (e.g., border surveillance and missile detection). The collected data is saved in the caches and then transmitted in the next steps.
- Status report. Low-capability UAVs send the tokens to the high-capability UAVs or relays via NLoS scenario I, containing positions, speeds, communication requests, and so on.
- Schedule and adjustment. High-capability UAVs or relays will schedule their operation status and adjust associated parameter settings according to the received status report, and then return control signals to the low-capability UAVs via NLoS scenario I or II.
- Adjustment. When control signals are sent back to the low-capability UAVs, they will adjust their parameter settings to match the high-capability UAVs or relays.
- Data transmission. Once the pairing is accomplished, low-capability UAVs will send the collected data to the relays or high-capability UAVs via NLoS scenario II or III at a low speed or via the LoS scenario at a high speed.

When the data acquisition is complete, the high-capability UAVs will send the data packets to satellites or BSs through RF communications. Note that in the internal communications of the UAV swarm, the problem of beam steering needs to be addressed. Considering the joint localization of the

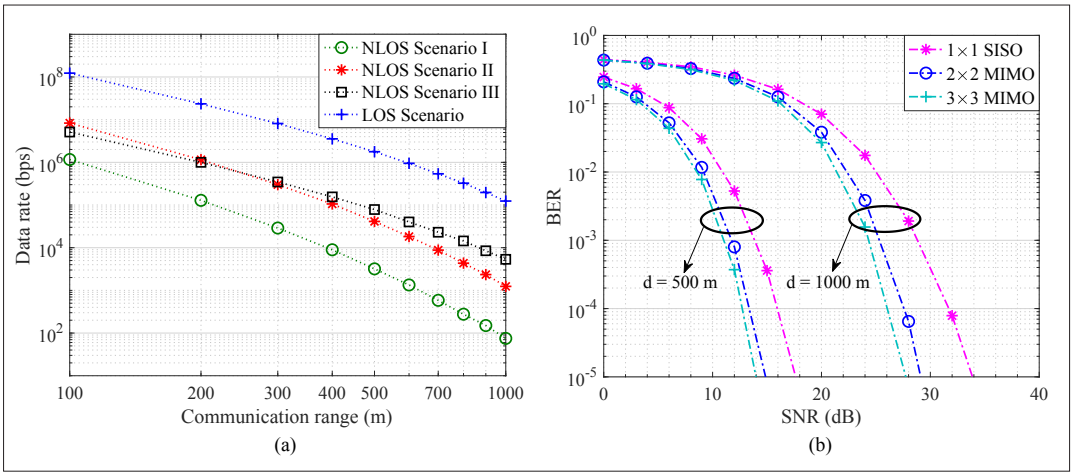


FIGURE 4. Performance analysis: a) data rate vs. communication range under four typical UAV-to-UAV scenarios; b) BER vs. SNR under different MIMO systems.

nodes, and multiple transmitters and receivers on each platform, TDMA and CDMA can be employed to tackle this problem. To be specific, TDMA is combined with time-hopping to minimize multiple access interference in an asynchronous system [7]. CDMA utilizes codes to activate or deactivate the pulse transmission, where these codes are made orthogonal or quasi-orthogonal to minimize the mutual interference among transceivers.

Simulation and Analysis

In this section, the relationship among the communication range, data rate, and four typical scenarios is first investigated, as shown in Fig. 4a. The associated parameter settings — beam angle, FoV angle, beam inclination angle, and FoV inclination angle — for NLoS scenarios I, II, and III, and the LoS scenario are (100°, 100°, 0°, 0°), (20°, 100°, 40°, 0°), (20°, 20°, 70°, 60°), and (20°, 20°, 75°, 90°), respectively. Note that the alignment error for the LoS scenario is incorporated here and set to 5° in the simulation because it is challenging to keep the transmitter and receiver within each other's FoV when the communication range is large. More details can be found in [12]. For tractable analysis, the on-off keying modulation scheme and the direct detection method are adopted here. Further, the expressions and noise measurements provided in [13] are utilized to make sure that the simulation results are credible. In addition, the transmitter can be composed of UV LED arrays with total power 1 W, and the BER is set to 10^{-3}. Simulation results indicate that the data rate performance of the LoS scenario is superior to that of the NLoS scenarios. To be specific, as the communication range is set to 500 m, the data rates for the LoS scenario, and NLoS scenarios I, II, and III are 1.69 Mb/s, 3.12 kb/s, 40.26 kb/s, and 76.56 kb/s, respectively.

The impacts of multiple-input multiple-output (MIMO) systems on UV communication are investigated, as provided in Fig. 4b. The BER expression and parameter settings are in accordance with [14]. Simulations show that MIMO systems can improve UV BER performance observably, especially for the circumstances of small BER requirements or long-range communications. For example, as the range is set to 500 m and the minimum BER requirement is 10^{-2}, the SNRs for single-input single-output (SISO), 2 × 2 MIMO, and 3 × 3 MIMO are 10.98 dB, 9.25 dB, and 8.63 dB, respectively, which implies that MIMO systems can be utilized to enlarge the UV NLoS communication range. In addition to this, the UV NLoS range can also be extended by adopting direct sequence spread spectrum, forward error correction codes such as Reed-Solomon, and low-density parity-check codes [5], or by increasing the transmitted power.

Further, the influence of mobility on the BER performance of the UV-based UAV swarm system is analyzed. According to [15], UAV mobility can degrade the connectivity of the UAV swarm, which is detrimental to BER. To mitigate this negative effect, increasing the UAV deployment density and transmitted power, or decreasing the data rate are both effective ways. Moreover, the mobility model of the UAV also needs to be investigated. Compared to the circle movement-based model (CMBM) and random waypoint (RWP) model, the uniform distribution model (UDM) is more suitable for the UAV swarm. Specifically, to monitor an area of 3.142 km^2, the number of UAVs required for RWP and CMBM are 80 and 270, respectively, while that for UDM is 50.

Challenges and Future Trends

Introducing UV technology can address the problems of RF spectrum scarcity, interference, and network connectivity for the UAV swarm communication system, and meanwhile brings opportunities for its further development. Figure 5 describes a potential future system that combines UV-based UAV communication with AI and other emerging technologies (i.e., integration of sensing and computing, edge computing, and cloud computing) to satisfy users' complicated requirements. During this process, there are certain challenges that deserve to be researched.

UV Devices

The research on the UV hardware system mainly focuses on UV solar-blind LEDs and detectors. According to [5], the power level of a single UV LED can reach 150 mW and fully meet the current communication requirements. For the issues of low external quantum efficiency and lifetime, [5] points out that the associated technological roadblocks have been overcome. Currently, two typical types of photodetectors exist, PMTs and APDs.

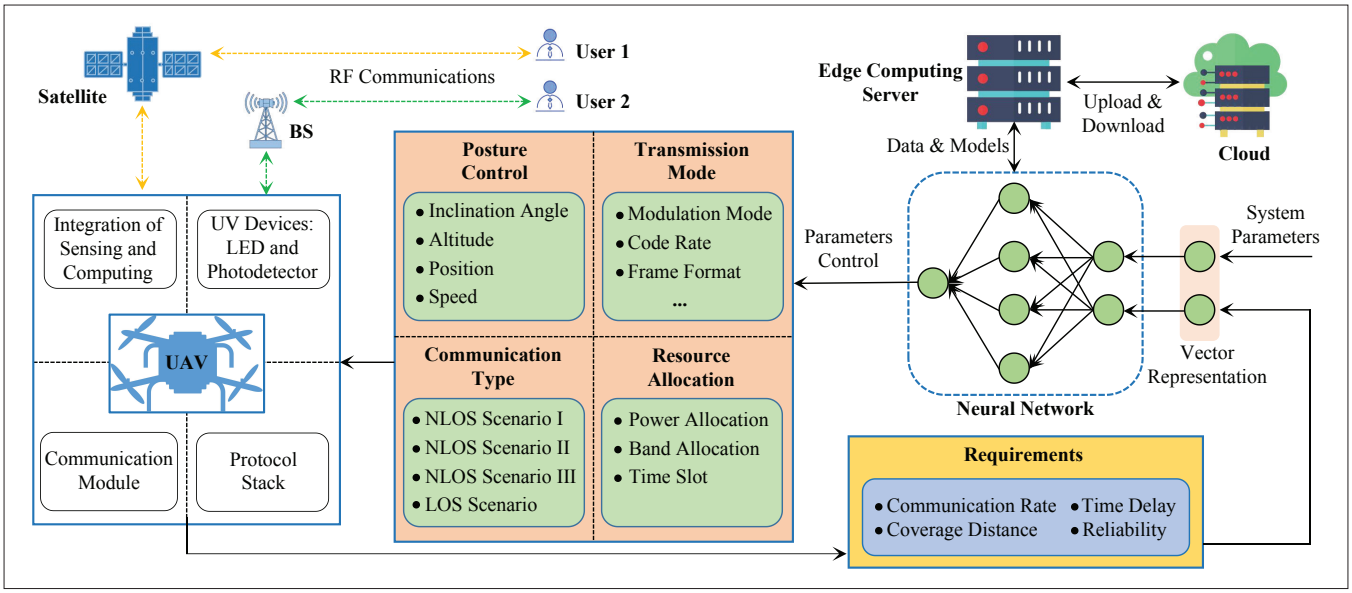


FIGURE 5. Future application of the UV-based UAV swarm system integrated with emerging technologies.

Since PMT is very energy-consuming, heavy, and fragile, the Defense Advanced Research Projects Agency initiated the Deep Ultraviolet Avalanche Photodetector program in 2007. Until now, certain achievements have been made. For example, $Al_xGa_{1-x}N$-based devices can provide adequate blocking of unwanted signals without using additional filters. Further, semiconductor photodetectors made of materials such as Si, SiC, and GaP have significant advantages of small size, high reliability, and low power consumption.

Channel Model

Influenced by the mobility of UAVs, the path loss and impulse response time of the UV NLoS channels will change over time. Accurately predicting these two crucial metrics is significantly important for the real-time evaluation of system performance. At present, the studies on UV NLoS channel models are primarily focusing on static scenarios [5, 12]. These efforts sufficiently investigate the impacts of transceiver elevation angles and FoV angles, communication range, transmitted power, atmospheric turbulence, and so on, on the channel characteristics via numerical calculations (e.g., single scattering models) and Monte Carlo simulation methods (e.g., Monte Carlo multiple scattering models). This provides a solid foundation for the subsequent research on UV dynamic NLoS channel modeling.

Physical Layer

The heterogeneous architecture of UV and RF should be adopted in the framework of Fig. 5, where RF communications are utilized to exchange information between high-capability UAVs and satellites (or BSs) to convey users' demands (e.g., border surveillance) or to transmit the collected data to users. UV communication is primarily utilized for the internal communications of the UAV swarm. Considering the UV NLoS channel with large path loss (atmospheric scattering, absorption, and turbulence) and long pulse spreading time (numerous multiple scattering paths) as well as the dynamic behaviors of a UAV swarm, efficient data modulation schemes, advanced channel coding, and beam shaping techniques with proper optical design are of great importance.

Network Layer

Considering the joint localization of the nodes and their mobility as well as the users' real-time requirements, it is intractable to find an immediate solution in a huge feasible space. For this reason, data-driven AI technology is employed in the proposed framework to improve system policy decisions. By integrating the uploaded parameters and useful historical information, the neural network can understand system status comprehensively and produce the specific instructions for the UAV posture control, transmission mode, communication type, and resource allocation. Moreover, the local neural network can also exchange information with the edge servers, which can provide crucial guidelines for the local network training. This is primarily because the cloud collects various information from different regions. The edge and cloud computing technologies play important roles during the whole process.

Conclusion

UV communication technology is exploited in this article to tackle the issues faced by the UAV swarm. To highlight its importance, the comparison of UV communication with alternatives is presented. Then the UAV swarm topology, designs of high- and low-capability UAVs, communication protocol, and mutual interference are investigated to promote the development of the UV-based UAV swarm system. Moreover, performance indicators such as BER, data rate, and communication range are provided to guide system deployment and parameter settings. Further, an AI-aided UV-based UAV swarm system is proposed to cope with users' complicated requirements, and the challenges that deserve to be researched are discussed simultaneously. We believe that in the future, the UV-based UAV swarm system will play an important role in integrated ground-air-space communications.

We believe that in the future, the UV-based UAV swarm system will play an important role in integrated ground-air-space communications.

Acknowledgments

This work was supported by the Beijing National Research Center for Information Science and Technology (BNR2022RC01017), and the National Natural Science Foundation of China (61871255), the Fok Ying Tung Education Foundation, and was partially funded by NSF CNS-2128368 and CNS-2107216, Toyota, and Amazon.

References

[1] S. Hayat, E. Yanmaz, and R. Muzaffar, "Survey on Unmanned Aerial Vehicle Networks for Civil Applications: A Communications Viewpoint," *IEEE Commun. Surveys & Tutorials*, vol. 18, no. 4, Apr. 2016, pp. 2624–61.
[2] M. J. Marcus, "Spectrum Policy Challenges of UAV/Drones," *IEEE Wireless Commun.*, vol. 21, no. 5, Oct. 2014, pp. 8–9.
[3] S. Zhang *et al.*, "Cellular UAV-to-X Communications: Design and Optimization for Multi-UAV Networks," *IEEE Trans. Wireless Commun.*, vol. 18, no. 2, Feb. 2019, pp. 1346–59.
[4] M. M. Azari *et al.*, "UAVto- UAV Communications in Cellular Networks," *IEEE Trans. Wireless Commun.*, vol. 19, no. 9, Sept. 2020, pp. 6130–44.
[5] A. Vavoulas *et al.*, "A Survey on Ultraviolet C-Band (UV-C) Communications," *IEEE Commun. Surveys & Tutorials*, vol. 21, no. 3, Feb. 2019, pp. 2111–33.
[6] M. J. Weisman *et al.*, "Analysis of the Low-Probability-of-Detection Characteristics of Ultraviolet Communications," *Opt. Express*, vol. 28, no. 16, Aug. 2020, pp. 23,640–51.
[7] Z. Xu and B. M. Sadler, "Ultraviolet Communications: Potential and State of the Art," *IEEE Commun. Mag.*, vol. 46, no. 5, May 2008, pp. 67–73.
[8] G. A. Shaw *et al.*, "NLoS UV Communication for Distributed Sensor Systems," *Proc. SPIE*, vol. 4126, San Diego, CA, July 2000, pp. 83–96.
[9] Z. Xiao, P. Xia, and X. G. Xia, "Enabling UAV Cellular with Millimeter-Wave Communication: Potentials and Approaches," *IEEE Commun. Mag.*, vol. 54, no. 5, May 2016, pp. 66–73.
[10] Y. Wang *et al.*, "Deep Learning for Optimal Deployment of UAVs with Visible Light Communications," *IEEE Trans. Wireless Commun.*, vol. 19, no. 11, Nov. 2020, pp. 7049–63.
[11] L. Gupta, R. Jain, and G. Vaszkun, "Survey of Important Issues in UAV Communication Networks," *IEEE Commun. Surveys & Tutorials*, vol. 18, no. 2, Nov. 2016, pp. 1123–52.
[12] R. J. Drost, T. J. Moore, and B. M. Sadler, "UV Communications Channel Modeling Incorporating Multiple Scattering Interactions," *J. Opt. Soc. Amer. A*, vol. 28, no. 4, Apr. 2011, pp. 686–95.
[13] Q. He, B. M. Sadler, and Z. Xu, "Modulation and Coding Tradeoffs for Non-Line-of-Sight Ultraviolet Communications," *Free-Space Laser Commun. IX*, vol. 7464, Aug. 2009, pp. 1–12.
[14] M. H. Ardakani, A. R. Heidarpour, and M. Uysal, "Performance Analysis of MIMO NLoS UV Communications over Atmospheric Turbulence Channels," *IEEE Wireless Commun. Networking Conf. Wksps.*, Doha, Qatar, Apr. 2016.
[15] T. Zhao *et al.*, "Connectivity Properties for UAVs Networks in Wireless Ultraviolet Communication," *Photon. Net. Commun.*, vol. 35, no. 3, Jan. 2018, pp. 316–24.

Biographies

Guozhi Chen (chen-gz19@mails.tsinghua.edu.cn) received his B.S. degree from the Department of Electronic Engineering, Tsinghua University, Beijing, China, in 2019. He is currently pursuing a Ph.D. degree with the DTV Technology Research and Development Center, Department of Electronic Engineering, Tsinghua University. His research interests lie in the fields of wireless communications, ultraviolet communications, and unmanned vehicle communication.

Tianfeng Wu (wtf22@mails.tsinghua.edu.cn) received his B.S. degree in instrumentation and electrical engineering from Jilin University, Changchun, China, in 2015, and a double Master's degree in precision instruments from Tsinghua University, Beijing, China, and automotive engineering from RWTH Aachen University, Germany, in 2019. He received a Deutscher Akademischer Austausch Dienst (DAAD) scholarship from 2015 to 2016. He is currently pursuing a Ph.D. degree with the Department of Electronic Engineering, Tsinghua University. His research interests include ultraviolet communications and wireless communications.

Fang Yang [M'11, SM'13] (fangyang@tsinghua.edu.cn) received his B.S.E. and Ph.D. degrees in electronic engineering from Tsinghua University in 2005 and 2009, respectively. Currently, he is an associate professor with the Department of Electronic Engineering, Tsinghua University. He has published over 180 peer-reviewed journal and conference papers. He holds over 50 Chinese patents and two PCT patents. His research interests are in the fields of power line communication, visible light communication, and digital television terrestrial broadcasting. He received the IEEE Scott Helt Memorial Award (best paper award in *IEEE Transactions on Broadcasting*) in 2015. He is a fellow of IET.

Tengjiao Wang [S'19, M'21] (wangtengjiao6@huawei.com) received his B.S. and Ph.D. degrees from the Department of Electronic Engineering, Tsinghua University in 2016 and 2021, respectively. He was a visiting scholar at the Massachusetts Institute of Technology, Cambridge, in 2019. Currently, he is a principal engineer with the Radio Access Network Research Department, Huawei Technologies Co., Ltd., Shanghai, China. His research interests include 5G-Advanced wireless communications, visible light communications, and machine learning.

Jian Song [M'06, SM'10, F'16] (jsong@tsinghua.edu.cn) received his B. Eng and Ph.D. degrees in electrical engineering from Tsinghua University in 1990 and 1995, respectively. Currently, he is the director of the Tsinghua DTV Technology R&D Center. He has been working in quite different areas of fiber optic, satellite, and wireless communications, as well as power line communications. His current research interest is in the area of digital TV broadcasting. He has published more than 300 peer-reviewed journal and conference papers. He holds two U.S. and more than 80 Chinese patents. He is a Fellow of IET.

Zhu Han [S'01, M'04, SM'09 F'14] (zhan2@uh.edu) received his B.S. degree in electronic engineering from Tsinghua University in 1997 and his M.S. and Ph.D. degrees in electrical and computer engineering from the University of Maryland, College Park in 1999 and 2003, respectively. From 2000 to 2002, he was an R&D engineer at JDSU, Germantown, Maryland. From 2003 to 2006, he was a research associate at the University of Maryland. From 2006 to 2008, he was an assistant professor at Boise State University, Idaho. Currently, he is a John and Rebecca Moores Professor in the Electrical and Computer Engineering Department as well as in the Computer Science Department at the University of Houston, Texas. His research interests include wireless resource allocation and management, wireless communications and networking, game theory, big data analysis, security, and smart grid. He received an NSF Career Award in 2010, the Fred W. Ellersick Prize of the IEEE Communication Society in 2011, the EURASIP Best Paper Award for the *Journal on Advances in Signal Processing* in 2015, the IEEE Leonard G. Abraham Prize in the field of Communications Systems (best paper award in the *IEEE Journal on Selected Areas in Communications*) in 2016, and several best paper awards in IEEE conferences. He was an IEEE Communications Society Distinguished Lecturer from 2015 to 2018, and has been an AAAS Fellow since 2019 and an ACM Distinguished Member since 2019. He is a 1 percent highly cited researcher since 2017 according to the Web of Science. He is also the winner of the 2021 IEEE Kiyo Tomiyasu Award, for outstanding early to mid-career contributions to technologies holding the promise of innovative applications, with the following citation: "for contributions to game theory and distributed management of autonomous communication networks."