Access Frameworks and Application Scenarios for Hybrid VLC and RF Systems: State of the Art, Challenges, and Trends

Fubin Wang, Fang Yang, Jian Song, and Zhu Han

Abstract

The further demand for data traffic growth makes the conventional radio frequency (RF) wireless network face ever increasing challenges such as spectrum shortage and access congestion. Visible light communication (VLC) is envisioned as a promising candidate for wireless communication in the future, but it also has limitations like limited coverage and inconvenient uplinks. Naturally, it is a rational strategy to combine VLC and RF systems to form hybrid systems, which can take full advantage of high data rate in VLC and wide coverage in RF. In this article, the current research on hybrid VLC and RF systems is reviewed. First, the structures of hybrid access frameworks are introduced as complementary single-hop networks and heterogeneous multihop networks, while common frameworks in the current literature are summarized. Moreover, the technical characteristics and specific advantages of hybrid VLC and RF systems are discussed in different application scenarios for high data rate, high energy efficiency, and high reliability. Finally, the future trends of hybrid VLC and RF systems are looked forward to in some typical enabling technologies.

Introduction

Wireless access is becoming the main way for wide area networks in future communication systems. Wireless data traffic and network services have been swelling exponentially, while the popularization of massive machine type communication (mMTC) in the Internet of Things (IoT) has spawned a tremendous number of intelligent devices. With the prospect of the sixth generation (6G) era, higher frequency spectra and diversified access methods will be explored, where visible light communication (VLC) is regarded as a considerable complementary technology of conventional radio frequency (RF) communications [1].

VLC uses light emitting diodes (LEDs) and photodiodes to transmit and receive wireless signals, which makes full use of the visible light spectrum with abundant bandwidth [2]. Extensive lighting infrastructures can be adopted as the natural basis for VLC deployment, achieving illumination and communication simultaneously. However, the coverage of a single VLC access point (AP) is limited, which is easily affected by occlusion, while it is inconvenient for the mobile terminals (MTs) to realize uplinks based on VLC.

Therefore, a hybrid VLC and RF system is worth investigating as a potential candidate for future wireless access. On one hand, the VLC spectrum has huge unlicensed bandwidth, which alleviates overcrowding and interference problems of the sub-6 Gb/s RF spectrum [3]. On the other hand, RF communication can provide large coverage and superior reliability with strong resistance to the deficiency of line-of-sight (LoS) links [4]. Moreover, it is much easier for RF communications to realize uplink transmission than VLC.

There are still many challenges in research on hybrid VLC and RF systems. First, the communication resources in practical systems are limited generally, and need to be allocated in different types of devices. The allocation schemes of communication resources should not only ensure the fairness of users and the stability of networks, but also have adaptive ability for the randomness of systems and channels [5]. In addition, the access frameworks should be constructed according to diverse application scenarios, and the design of handover schemes is also necessary to avoid outage and reduce delay, including both the horizontal handover between VLC links and the vertical handover between VLC and RF [6]. Moreover, the hybrid systems will be highly heterogeneous since various network services and MTs have different requirements, while the corresponding methods should be selected reasonably [5].

Compared to [6], our discussion is based on access frameworks and application scenarios, while different problems are discussed in combination with practical communication characteristics. Moreover, the comprehensive requirements of humans and devices are considered, and the possible directions of future technology development are discussed at multiple levels of the whole communication system.

The contributions of this article are summarized as follows. First, the existing common frameworks are categorized, and the structures of hybrid access frameworks are investigated innovatively as complementary single-hop networks and heterogeneous multihop networks. Then the complementary advantages of VLC and RF in multifarious application scenarios are discussed based

The authors envision visible light communication (VLC) as a promising candidate for wireless communication in the future, but it also has limitations like limited coverage and inconvenient uplinks. Naturally, it is a rational strategy to combine VLC and radio frequency (RF) systems to form hybrid systems, which can take full advantage of high data rate in VLC and wide coverage in RF.

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In heterogeneous multihop networks, the inter-communication among multiple users may be cooperative or antagonistic. Moreover, there are more options for compensation or eavesdropping due to the existence of more links.

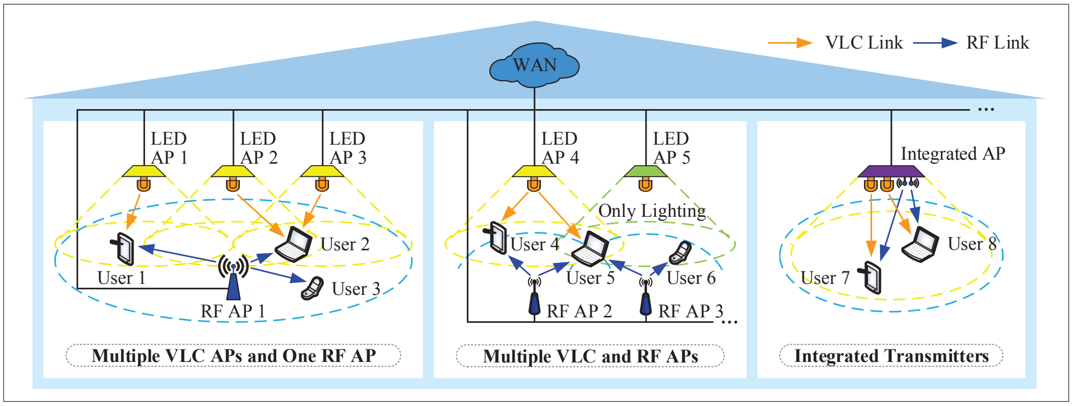

FIGURE 1. Complementary single-hop networks of VLC and RF with various numbers of APs for diverse services.

on diverse communication characteristics, and the joint allocation of multi-dimensional resources is considered. Finally, several challenges and feasible trends of hybrid VLC and RF systems are discussed with respect to different modules of the whole communication system and comprehensive requirements of humans and devices.

Hybrid Access Frameworks

There has been research that divides the access modes of hybrid VLC and RF systems into autonomous and centralized, while the deployment topology of hybrid APs is discussed [6]. Furthermore, based on different cooperation modes of hybrid links, hybrid access frameworks are summarized into two categories in this article: complementary single-hop networks and heterogeneous multihop networks.

In complementary single-hop networks, it must be taken into consideration that the APs and users are connected with LoS VLC or RF links. Once the coverage of single-hop networks is not ideal, relays are needed for forwarding or inter-communication among multiple users, which are referred to as multihop networks collectively. The common frameworks in the current literature are integrated in this structure, and the differentiation is also investigated in more detail.

It should be noted that it is challenging for VLC networks to realize uplinks, since the uplink VLC transmission will cause visual interference for users. In current research, the uplink data stream is mainly provided by RF links [7], so the downlink network is mainly of concern here.

Complementary Single-Hop Networks

According to the various functions of multiple APs and the combination strategies of VLC and RF, complementary single-hop networks can be further divided into three typical scenarios, which are illustrated in Fig. 1.

Multiple VLC APs and One RF AP: A common design of hybrid VLC and RF systems is to deploy multiple VLC APs and a single RF AP in the network, which is the trade-off between effectiveness and reliability. VLC APs are distributed in the coverage area [6], while the single RF AP can be placed in the center or at the edge [5]. VLC plays a dominant role in this scenario, providing high data rates within the coverage of each VLC AP. The single RF AP fills the whole coverage area, which ensures the reliability of communication. If the LoS links of VLC are blocked, or the receiver has exceeded the coverage of VLC APs, the user can switch to RF channels. This situation is suitable for MTs with higher mobility, but the design of handover schemes between VLC and RF APs makes it challenging to maintain the stability of communication.

Multiple VLC and RF APs: Apart from playing different roles in the above-mentioned framework, VLC and RF both can be used for high-data-rate communication in hybrid systems [1]. In this situation, multiple RF APs are deployed just like VLC APs, and each receiver in the coverage area of the hybrid system can receive multiple VLC or RF signals synchronously. The transmit powers of RF are constant generally, while VLC transmitters may be in the status of turning off or only lighting without communication. There is no intuitive tendency for the selection of VLC and RF links in such systems, and more APs are needed to compensate for the lack of LoS links. This framework is suitable for RF APs with higher frequency, while the technologies of improving the system capacity need further research, taking advantage of the large bandwidth of both VLC and RF.

Integrated Transmitters: In addition to deploying VLC and RF transmitters simultaneously, VLC and RF chains can also be aggregated together to form integrated transmitters [4]. These kinds of integrated systems can be regarded as multiple-input multiple-output (MIMO) systems, while the channel gain and parameter limitation for different links still need to be modeled separately [8]. The link integration and handover strategy of VLC and RF requires sophisticated design and future exploration. The integrated transmitter can realize multi-dimensional resource allocation and hybrid signal processing in the physical layer directly instead of the data link layer, so it can provide higher scheduling efficiency and more pervasive access, which is conducive to the integration and standardization of hybrid VLC and RF systems.

Heterogeneous Multihop Networks

In heterogeneous multihop networks, the inter-communication among multiple users may be cooperative or antagonistic. Moreover, there are more options for compensation or eavesdropping due to the existence of more links. Several scenarios of hybrid cascaded links, cooperative communication, and eavesdropping are illustrated in Fig. 2.

Hybrid Cascaded Links: A common design of heterogeneous multihop networks is that the two

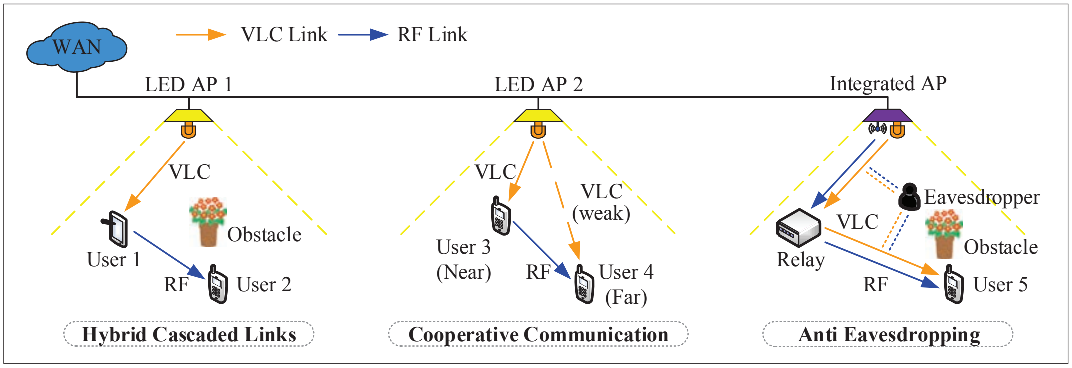

FIGURE 2. Heterogeneous multihop networks of VLC and RF for hybrid cascaded links, cooperative communication, and eavesdropping.

hops occupy VLC and RF channels individually, which enjoys the advantage of reducing the impact of LoS link occlusion [2]. Such a scheme is mostly adopted for coverage expansion of VLC APs, and RF links are more suitable for the communication among users, because the mobility of users is stronger and the possibility of occlusion is higher. The VLC and RF channels of the two hops are cascaded channels rather than independent channels. As a result, new challenges should be considered in the hybrid systems, such as the capacity matching of heterogeneous cascaded hops, the selection strategy of adjacent relays, or the power allocation among multiple APs and users.

Cooperative Communication: The cooperative communication among multiple users can also improve the communication performance of faraway users. Generally speaking, the VLC AP is adopted to achieve simultaneous coverage, while the RF channel is used for communication between users, so a faraway user can select or combine the receiving signals from the VLC LoS link and the RF link from the near user. The hybrid system can not only be a broadcasting system that transmits identical signals, but also take advantage of other technologies such as non-orthogonal multiple access to realize cooperation among multiple users and improvement of spectrum efficiency [9]. More issues need to be considered, including the selection strategy of hybrid links and the demodulation complexity of superimposed transmission.

Anti Eavesdropping: Apart from increasing the number of APs and benefiting from the large coverage of RF, hybrid relays are also conducive to dealing with the blockage of VLC links. Especially when a multihop framework is threatened by eavesdropping, the diversity of hybrid channels will improve confidentiality further, where the APs, relays, and users are equipped with both VLC and RF devices. Moreover, based on beamforming (BF) techniques, the transmit power of necessary signals can be concentrated in the user direction, while the jamming signals can also be transmitted to eavesdroppers [3]. The difficulty is to design the optimization algorithm of jamming signals for the maximization of the impact on eavesdroppers and the minimization of that on users.

Application Scenarios

Facing omnifarious requirements from various users and network applications, different communication characteristics of hybrid VLC and RF systems need attention. The application scenarios can be classified broadly into high-data-rate, high-energy-efficiency, and high-reliability scenarios, as listed in Table 1, and the emphases of multifarious requirements in each scenario are illustrated in Fig. 3.

Scenarios	Characteristics	Examples
High data rate	**VLC:** high transmission rate **RF:** load balancing **Hybrid:** low SINR	Video application Network conference AR/MR/VR
High energy efficiency	**VLC:** power constraint **RF:** high spectrum efficiency **Hybrid:** time slot allocation	mMTC in IoT Wireless sensors Environmental mapping
High reliability	**VLC:** link handover **RF:** low outage probability **Hybrid:** bandwidth allocation	Autonomous logistics Industrial control Blockchain

TABLE 1. Application scenarios of hybrid VLC and RF systems.

High-data-rate scenarios such as video applications are regarded as the most extensive ones, where the transmission rate and spectrum efficiency are the most important characteristics. The transmission delay should also be paid attention for some real-time applications like network conferences [10]. In high-energy-efficiency scenarios such as mMTC in IoT, the limited communication resources need to be fully utilized in order to improve spectral efficiency (SE) and reduce power consumption under identical communication requirements [5]. Outage probability should also be considered to avoid energy waste from communication failure. High-reliability scenarios pursue low outage probability and transmission delay, realizing ultra-reliable and low-latency communication [11]. In cases like industrial control, the requirements for data rates may not be high, while the success rate and real-time performance of communication need to be improved.

The different channel characteristics of VLC and RF, as well as the multifarious frameworks of hybrid systems, will lead to diverse impact on the communication performance and resource allocation. The limited communication resources, including power, bandwidth, and time slots, make the design of resource allocation particularly important, while different aspects need attention in various scenarios. Moreover, it is also necessary to explore the joint optimization of multi-dimensional resources in hybrid VLC and RF systems, as shown in Fig. 4, to further improve the system performance.

High-Data-Rate Scenarios

The most significant advantage of hybrid VLC and RF systems is that they integrate different spectra,

In order to improve the data rate, load balancing is required in the overlapping coverage of VLC and RF to reduce the delay time [6]. The signal-to-noise ratio of VLC and RF may vary greatly in hybrid networks, while the different distribution of user locations may lead to more energy waste for unnecessary coverage.

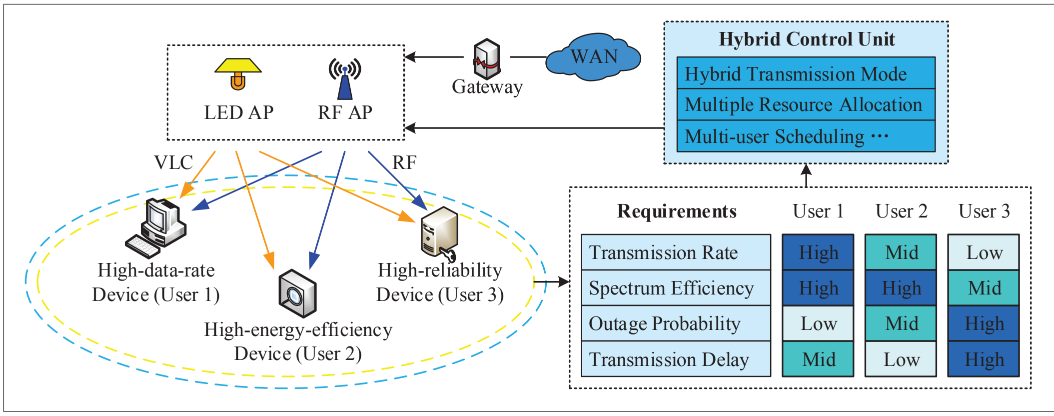

FIGURE 3. Different application scenarios for high data rate, high energy efficiency, and high reliability.

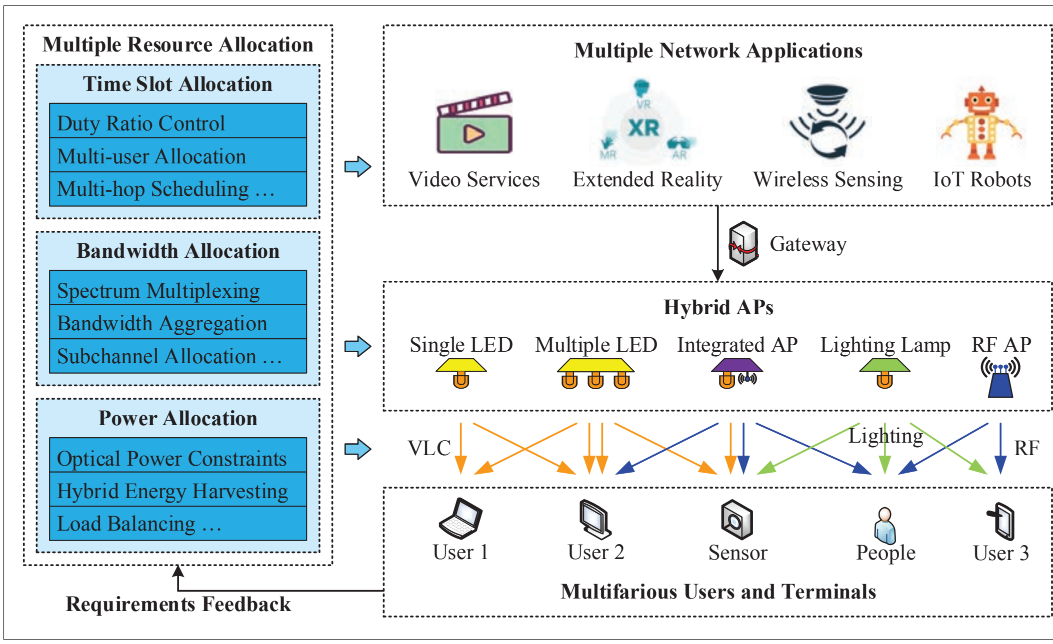

FIGURE 4. Multi-dimensional resource allocation of power, bandwidth, and time slots in hybrid VLC and RF systems.

which is the most effective way to improve the data rate [2], so the design of bandwidth allocation for various APs and users is important. The VLC spectrum can be fully multiplexed based on the limited coverage of single VLC APs, giving full play to the abundant VLC bandwidth. The problem of link blocking in VLC can be alleviated by RF coverage or relay forwarding, which improves the throughput of the whole system.

Compared to single systems, the signal-to-interference-plus-noise ratio (SINR) can be improved thanks to the combination of VLC and RF [6]. Meanwhile, there is a positive correlation between high data rate and high SE, so the reduction of co-channel interference is a reliable way to improve the data rate. The switching of VLC and RF subsystems has the potential to improve SE, which can be realized by bandwidth and power allocation.

In order to improve the data rate, load balancing is required in the overlapping coverage of VLC and RF to reduce the delay time [6]. The signal-to-noise ratio of VLC and RF may vary greatly in hybrid networks, while the different distribution of user locations may lead to more energy waste for unnecessary coverage. With the help of dynamic scheduling on data traffic, the load balancing between VLC and RF subsystems can be achieved, and the access of new users or the disconnection of old users will be dealt with adaptively.

High-Energy-Efficiency Scenarios

Based on sufficient research and analyses in [12], the power consumption of VLC systems has been proved to be determined by the bandwidth, modulation modes, data rates, and illumination requirements as well [1]. Thus, the hybrid VLC and RF systems can realize complementary advantages to improve energy efficiency (EE) further in different communication and illumication scenarios. Generally speaking, the optimization schemes of EE are under the constraints of illumination demands [1] and minimum requirements of data rates [1], realizing the trade-off between SE and EE.

Moreover, it is also necessary to analyze the different power consumption in VLC and RF. The total power of RF APs is limited generally, while the requirements for both illumination and communication place restrictions on the peak optical power and average optical power of VLC APs [4], which also needs to design the allocation between direct-current power and alternating-current power [2]. Thus, the optimization of EE ought to

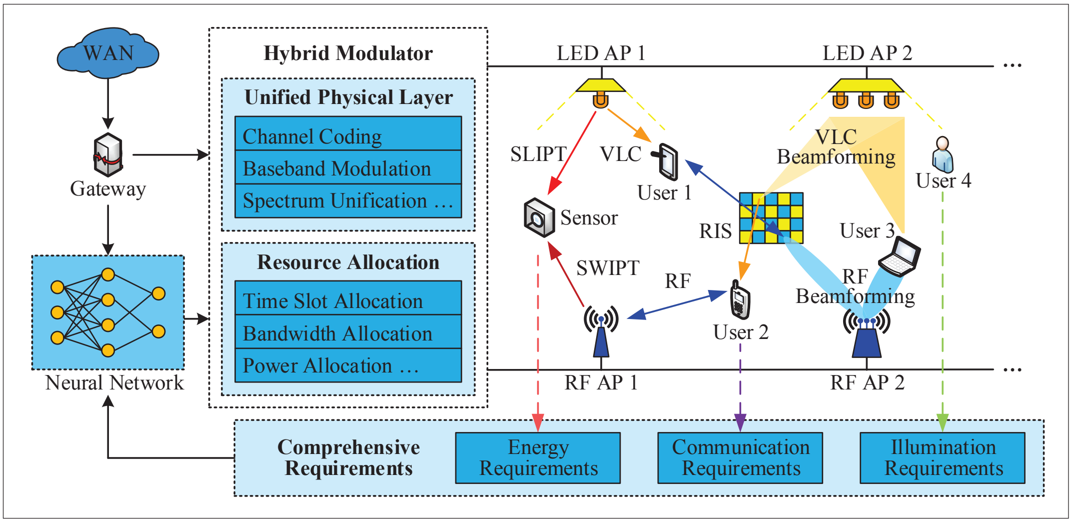

FIGURE 5. Future applications and emerging technologies of hybrid VLC and RF systems.

In order to simplify the handover between VLC and RF subsystems, the technology of bandwidth aggregation can be adopted, and the hybrid resource scheduling is processed based on identical protocols. The data stream of each user can be allocated to multiple heterogeneous links, and then combined at the receiver.

be improved, such as by adding some other cost items for illumination to the definition of EE [4, 5].

In addition, the allocation of time slots is significant in high-energy-efficiency scenarios, which is mainly related to the frame design for VLC and RF signals. On one hand, it is necessary to reduce power consumption of idle APs. On the other hand, the communication duty ratio is relatively low for the applications with limited data transmission like wireless sensor networks. In long periods without communication, VLC APs are responsible for illumination, and the optical energy can be collected for RF uplinks of sensor terminals [11].

High-Reliability Scenarios

The handover between VLC and RF links is of the most importance for reliability, which can be classified into AP-centered and user-centered methods. In AP-centered networks, it is necessary to model and analyze the behavior of users and blocking probability of VLC links [6]. The user-centered network relies on the automatic perception of nearby APs via RF links, which requires smarter devices [10].

In order to simplify the handover between VLC and RF subsystems, the technology of bandwidth aggregation can be adopted, and the hybrid resource scheduling is processed based on identical protocols. The data stream of each user can be allocated to multiple heterogeneous links and then combined at the receiver. For hybrid VLC and RF systems, it is necessary to implement dynamic handover according to the quality of different links; they also rely on RF links for data retransmission to deal with the outage of VLC links.

Furthermore, the integration of different spectra can be realized by subcarrier allocation, and the bandwidth of VLC and RF is combined at the modulation level, such as hybrid RF/VLC orthogonal frequency-division multiplexing (OFDM) [8]. The subcarrier indexes of VLC and RF can be adjusted dynamically according to different receiving conditions, and such kind of techniques make the handover between VLC and RF more convenient, improving the reliability and reducing the delay further.

Future Trends

There are still some possible directions worthy of further discussions for hybrid VLC and RF systems, as shown in Fig. 5 [10, 13]. Neural network (NN) technology will be adopted for multi-dimensional resource allocation and the processing of the physical layer, while dealing with comprehensive requirements fed back from various users. The comprehensive requirements include energy, communication, and illumination requirements, which pay close attention to hybrid energy harvesting (EH), hybrid BF and reconfigurable intelligent surface (RIS), and the technologies of integrated communication and illumination, respectively.

NN-Aided Hybrid Resource Allocation

The NN is a popular technology for artificial intelligence, which has been made use of gradually in wireless communications for channel modeling, coding, modulation, and so on [5, 13]. The advantage of NN is that it can approximate functional relationships that are difficult to express explicitly, which is suitable for dealing with the heterogeneity of hybrid VLC and RF systems. NN can be taken advantage of to discover the implicit interaction of VLC and RF subsystems, while achieving joint optimization for multiple objectives with multiple parameters, as well as the decision making of hybrid links in the network layer. There are many challenges in hybrid systems that can be solved by NN technologies, including scheduling strategies of load balancing based on mobility sensing [6], nonlinearity in high-speed VLC systems [13], and so on.

Unified Physical-Layer Integration

In order to simplify the handover between VLC and RF, unified physical-layer integration can be one of the optional technologies [14]. The transmitters of VLC links realize intermediate frequency (IF) modulation rather than baseband modulation, while the receivers of RF links convert RF signals into IF signals, whose band is the same as that in VLC. In this way, based on the identical IF, the transceivers can adopt the same methods and equipment of digital signal processing to deal with heterogeneous links. The structure of a unified physical layer will make VLC and RF links share the same backhaul, which achieves the simplification of resource allocation and network optimization [6]. Furthermore, the

In the design and optimization of hybrid VLC and RF systems, different optimization objectives should be selected for various communication requirements, and communication resources including power, bandwidth, and time slot need to be allocated reasonably based on diverse system or physical constraints.

unified physical-layer integration reduces the cost of horizontal handover within the same subsystem as well as the vertical handover between heterogeneous subsystems, ensuring the reliability of hybrid VLC and RF systems further.

Hybrid EH

Faced with the explosive growth of network devices, the problem of power supply ought to be solved urgently, so EH is a very attractive strategy, which retains the energy of electromagnetic waves while carrying out wireless communication [2]. It is called the simultaneous lightwave information and power transfer (SLIPT) and simultaneous wireless information and power transfer (SWIPT) for VLC and RF, respectively [15]. EH is especially suitable for IoT, as the duty ratio of IoT devices is relatively low and the burden of signal processing is not heavy [11]. The hybrid VLC and RF system provides abundant opportunities for EH, where the signal transmission and EH can be undertaken by VLC and RF, respectively, while the resource allocation of communication and illumination is adjusted dynamically.

Hybrid BF and RIS

Hybrid BF and RIS are technologies for expanding coverage and multi-user scenarios. Based on MIMO systems, BF controls amplitudes and phases of multiple transmit links to achieve signal amplification in specified directions [3], and RIS changes the direction, amplitude, and phase of the incident signal by passive reflection without power supply or signal processing [10]. Since there is no interference between VLC and RF channels [4], the hybrid BF and RIS technologies need to be implemented in two subsystems. With the integration of VLC and RF, the complementary subsystems are helpful for obtaining channel state information (CSI). For instance, the superior directivity of VLC applies to positioning, which provides prior CSI for the design of precoding matrices for RF communication. Moreover, the subsystems can play different roles and switch flexibly, such as VLC downlink transmission and RF uplink feedback.

Integrated Communication and Illumination

The QoS is adopted to measure the communication performance generally, while it is also necessary to consider the intuitive effect of human feelings with the quality of physical experience [10]. Visible light stimulates human feelings directly, which can be defined as the quality of illumination (QoI), so the trade-off between communication and illumination is realized in the design of hybrid systems. Limited by the QoI requirements, the optimization of hybrid systems needs further exploration, for physical characteristics may have recessive nonlinear relationships with human feelings, such as color temperature and light intensity [6]. The illumination requirements may also improve communication performance. For example, the lighting environment with better uniformity is more suitable for wireless communication scenarios with strong mobility of MTs.

Conclusion

The hybrid VLC and RF system realizes the complementary advantages of VLC and RF, and consequently improves the performance of wireless communications further. For the construction of hybrid access frameworks, the channel characteristics of VLC and RF need to be considered comprehensively to achieve efficient integration of heterogeneous networks according to multifarious application scenarios. In the design and optimization of hybrid VLC and RF systems, different optimization objectives should be selected for various communication requirements, and communication resources including power, bandwidth, and time slots need to be allocated reasonably based on diverse system or physical constraints. In the future, the hybrid VLC and RF system can integrate novel VLC and RF technologies, which has broad development prospects and will be adopted more popularly.

References

[1] A. Khreishah *et al.*, "A Hybrid RF-VLC System for Energy Efficient Wireless Access," *IEEE Trans. Green Commun. Net.*, vol. 2, no. 4, Dec. 2018, pp. 932–44.

[2] T. Rakia *et al.*, "Optimal Design of Dual-Hop VLC/RF Communication System with Energy Harvesting," *IEEE Commun. Lett.*, vol. 20, no. 10, Oct. 2016, pp. 1979–82.

[3] J. Al-Khori *et al.*, "Joint Beamforming Design and Power Minimization for Friendly Jamming Relaying Hybrid RF/VLC Systems," *IEEE Photonics J.*, vol. 11, no. 2, Apr. 2019, pp. 1–18.

[4] S. Ma *et al.*, "Aggregated VLC-RF Systems: Achievable Rates, Optimal Power Allocation, and Energy Efficiency," *IEEE Trans. Wireless Commun.*, vol. 19, no. 11, Nov. 2020., pp. 7265–78.

[5] H. Yang *et al.*, "Learning-based Energy-Efficient Resource Management by Heterogeneous RF/VLC for Ultra-Reliable Low-Latency Industrial IoT Networks," *IEEE Trans. Ind. Inform.*, vol. 16, no. 8, Aug. 2020, pp. 5565–56.

[6] X. Wu *et al.*, "Hybrid LiFi and WiFi Networks: A Survey," *IEEE Commun. Surveys & Tutorials*, vol. 23, no. 2, Feb. 2021, pp. 1398–1420.

[7] S. I. Mushfique *et al.*, "A Software-Defined Multi-Element VLC Architecture," *IEEE Commun. Mag.*, vol. 56, no. 2, Feb. 2018, pp. 196–203.

[8] F. Wu, L. Chen, and W. Wang, "HRO-OFDM Scheme Design and Optimization for A Hybrid RF/VLC Baseband System," *IEEE Photonics J.*, vol. 9, no. 5, Oct. 2017, pp. 1–13.

[9] M. Obeed *et al.*, "User Pairing, Link Selection, and Power Allocation for Cooperative NOMA Hybrid VLC/RF Systems," *IEEE Trans. Wireless Commun.*, vol. 20, no. 3, Nov. 2020, pp. 1785–800.

[10] W. Saad, M. Bennis, and M. Chen, "A Vision of 6G Wireless Systems: Applications, Trends, Technologies, and Open Research Problems," *IEEE Network*, vol. 34, no. 3, Oct. 2020, pp. 134–42.

[11] G. Pan *et al.*, "3-D Hybrid VLC-RF Indoor IoT Systems with Light Energy Harvesting," *IEEE Trans. Green Commun. Networks*, vol. 3, no. 3, Sept. 2019, pp. 853–85.

[12] L. Kong *et al.*, "Power Consumption Evaluation in High Speed Visible Light Communication Systems," *IEEE GLOBECOM*, Abu Dhabi, Dec. 2018.

[13] N. Chi *et al.*, "Visible Light Communication in 6G: Advances, Challenges, and Prospects," *IEEE Vehic. Tech. Mag.*, vol. 15, no. 4, Sept. 2020, pp. 93–102.

[14] F. Wang *et al.*, "Radio-Optics Hybrid Single Frequency Network for DTTB: Principle, Technology, and Practice," *IEEE Trans. Broadcast.*, vol. 66, no. 4, Dec. 2020, pp. 857–66.

[15] H. Tran *et al.*, "Ultra-Small Cell Networks with Collaborative RF and Lightwave Power Transfer," *IEEE Trans. Commun.*, vol. 67, no. 9, Sept. 2019, pp. 6243–55.

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