Dimming Techniques of Visible Light Communications for Human-Centric Illumination Networks: State-of-the-Art, Challenges, and Trends

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

Abstract

Visible light communication (VLC), which utilizes the ubiquitous illumination network to implement high-speed communication, is rapidly emerging as one promising candidate to complement conventional radio frequency communication. In practical VLC systems, the illumination network is required to be human-centric to provide adjustable lighting for different user requirements, which limits the resource utilization of the communication aspect. Dimming control techniques, which provide compromise resource management solutions between illumination and communication, are critically essential in the implementation and commercialization of VLC. In this article, state-of-the-art dimming techniques for VLC are illustrated from a multi-dimensional perspective, including the intensity domain, the time domain, the frequency domain, and the spatial domain. We provide a comprehensive comparison of these techniques on their principles, key features, system performance, and so on. In addition, the challenges and the future research trends are presented to provide researchers with insights of future improvements and prospect of advancement in the field. Moreover, the concept of the software defined multi-dimensional dimming is also proposed for the human-centric illumination network by utilizing multi-dimensional resources according to the diversified system requirements.

Introduction

The explosive growth of mobile devices and increasing demand of wireless communication worldwide have posed challenging requirements for future 5G and beyond wireless communications. Visible light communication (VLC), which utilizes the ubiquitous light-emitting diodes (LEDs) illumination network to provide communication services, has been regarded as one promising candidate to supplement future radio frequency (RF) communication and enable novel mobile wireless use cases [1]. The strengths of VLC include high-speed transmission due to the wide unlicensed visible light spectrum, large capacity resulting from high degree of spatial reuse, and enhanced security because of the isolation property of the radiation-free visible light. In VLC, data information is conveyed based on the instantaneous intensity of the visible light, which is called intensity modulation and direct detection generally [1]. The characteristics of visible light as transmission medium limit the utilization of the resources. For instance, the transmitted time-domain signals need to be real and positive. Therefore, the modulation schemes in VLC are different from those in RF communications, including single-carrier modulation and multi-carrier modulation. On-off keying (OOK), pulse position modulation (PPM) and pulse width modulation (PWM) are the most popular single-carrier modulation schemes. Multi-carrier modulation schemes are mainly based on orthogonal frequency division multiplexing (OFDM). In order to obtain real-valued time-domain signals, many OFDM-based schemes in VLC require the frequency-domain signals to satisfy the Hermitian symmetry, which means the positive-frequency components and the negative-frequency components are the complex conjugates of each other [1]. These schemes include direct current biased optical OFDM (DCO-OFDM), asymmetrically clipped optical OFDM (ACO-OFDM), and so on [1].

In practical VLC systems, other than the photo-diode (PD), human eyes are also important receivers of the transmitted visible light [2]. Different from the receivers of electronic devices, human eyes do not decode the information conveyed by the visible light, but perceive the average intensity of the visible light during a period of time [3]. In practical VLC systems, the illumination is required to be human-centric to provide intelligent lighting. According to research in the human-computer interaction fields, lighting is an important aspect of the visual environment for humans, and the illumination levels have great influence on the work efficiency and visual comfortableness of humans [4]. Therefore, the light of the VLC systems should be adjusted intelligently to meet the requirements of human comfortableness and expectations [5]. For example, the illumination of 300 lux (lumen per square meter) is suggested for reading tasks; however, it is recommended to be 30 lux for com-

Digital Object Identifier:
10.1109/MWC.001.1900388

Tengjiao Wang, Fang Yang, and Jian Song are with Tsinghua University; Zhu Han is with the University of Houston, and also with Kyung Hee University.

1536-1284/20/$25.00 © 2020 IEEE

Authorized licensed use limited to: Tsinghua University. Downloaded on August 27,2020 at 08:25:45 UTC from IEEE Xplore. Restrictions apply.

puter tasks [4]. Mismatches in the illumination and human activities can cause visual fatigue and discomfort. Figure 1 shows several examples of human tasks requiring different illumination levels.

Recently, several dimming techniques are emerging as solutions to implement the resource management of the human-centric illumination networks, which have drawn a significant amount of academic and industrial attention [6–15]. This article focuses on these dimming techniques for VLC, which is essential to the implementation of VLC systems using the existing LED illumination network. We review the state-of-the-art dominant dimming techniques and classify them into two categories: the conventional single-dimensional techniques and the hybrid multi-dimensional techniques, as shown in Fig. 2. In the conventional single-dimensional category, the existing dimming techniques are sorted according to the domains of the resource management that are used to implement dimming control, consisting of the intensity domain [6, 7], the time domain [8, 9], the frequency domain [10], and the spatial domain [11]. In the hybrid multi-dimensional dimming category, joint management of the multi-dimensional resources is applied to further improve the communication and illumination performance [12–15]. We investigate the principles, the key features, the advantages, and the disadvantages of these single-dimensional and multi-dimensional dimming techniques and provide a comprehensive comparison. On top of this, the remaining challenges and future research trends are also provided to inspire further research. Moreover, a novel concept of the software defined multi-dimensional dimming (SDMDD) is put forward to adaptively implement dimming control with multi-dimensional resource management in order to meet the diverse and changeable requirements from the VLC users.

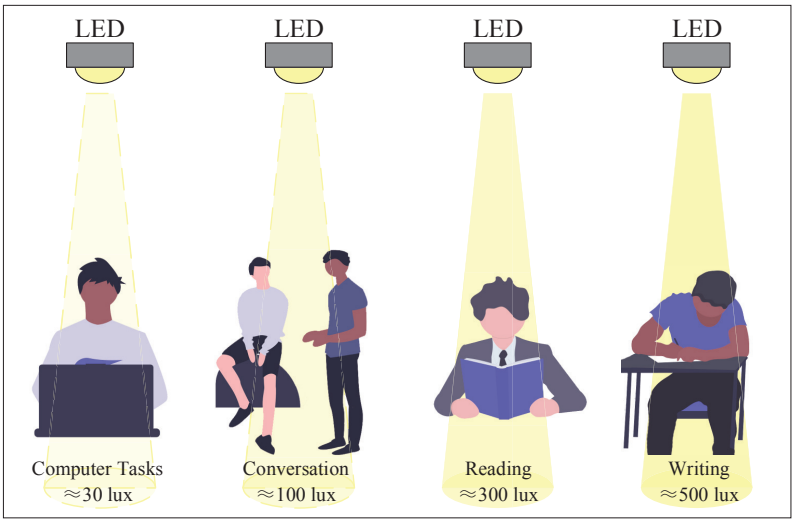


FIGURE 1. Illustration of the human tasks requiring different illumination.

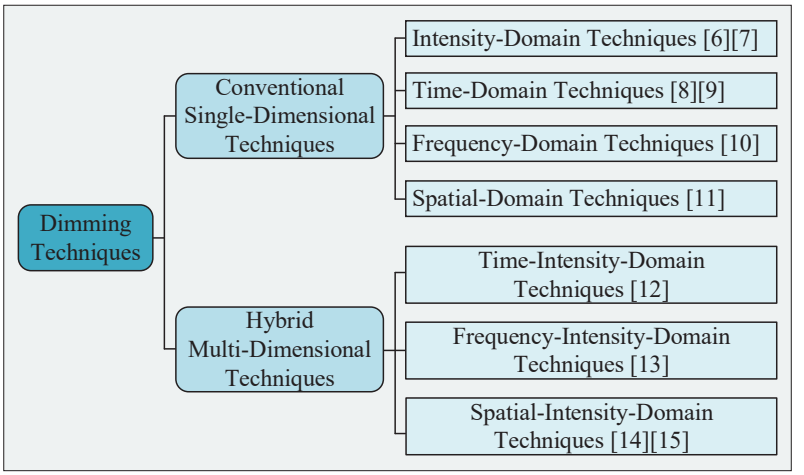


FIGURE 2. The state-of-the-art dimming techniques for the human-centric illumination network.

Conventional Single-Dimensional Techniques

In the literature, several dimming techniques have been proposed to implement the resource management of the human-centric VLC mainly relying on one-domain considerations. We group them into the conventional single-dimensional techniques. Illustrations of these techniques are given in Fig. 3.

Intensity-Domain Dimming Techniques

Among all the conventional dimming techniques, the intensity-domain techniques are the very intuitive ones, since the perceived illumination is influenced directly by the intensity of the LED light. In general, the intensity-domain dimming techniques can be further divided into two classes, that is, the scaling-based intensity-domain dimming techniques and the distribution-based intensity-domain dimming techniques, depending on how the optical intensities are adjusted.

Scaling-Based Intensity-Domain Dimming: Scaling-based intensity-domain dimming is implemented by adjusting the direct current (DC) bias and the scaling factors of the transmitted signals. In the standard IEEE 802.15.7, scaling-based intensity-domain dimming is offered for the single-carrier VLC systems [8]. An illustration of optical signals with scaling-based intensity-domain dimming is given in Fig. 3a, where the OOK modulation is applied as an example. Supposing the "ON" and "OFF" symbols are transmitted with equal probability, 75 percent dimming level as an example can be achieved by raising the DC bias to the middle of the intensity range. The dimming level is defined as the proportion of the actually achieved illumination in the maximum allowed illumination [3].

Scaling-based intensity-domain dimming techniques are intuitive and have little computational complexity. However, the added DC bias reduces the power efficiency, especially when the required dimming level is high. The rising and falling of the DC bias also cause degradation of the usable dynamic range, which decreases the spectral efficiency.

Distribution-Based Intensity-Domain Dimming: Distribution-based intensity-domain dimming techniques control the illumination through adjusting the distribution of the transmitted signals that have different optical intensities. In [6], a distribution-based intensity-domain dimming approach is proposed for the single-carrier OOK-based VLC system. An inverse source coding is applied to adjust the ratio of "ON" and "OFF" symbols to meet the dimming target. An illustration achieving 75 percent dimming target is given in Fig. 3a. Distribution-based intensity-domain dimming can be extended to the multi-carrier scenario as well. The OFDM symbols can be modified to provide

Authorized licensed use limited to: Tsinghua University. Downloaded on August 27,2020 at 08:25:45 UTC from IEEE Xplore. Restrictions apply.

Time-domain techniques implement human-centric communication and illumination mainly depending on time-domain considerations and designs. Generally, they can be further divided into two classes: intra-pulse time-domain dimming techniques that implement dimming controls within the signal pulse, and inter-pulse techniques that add illumination compensation between signal pulses.

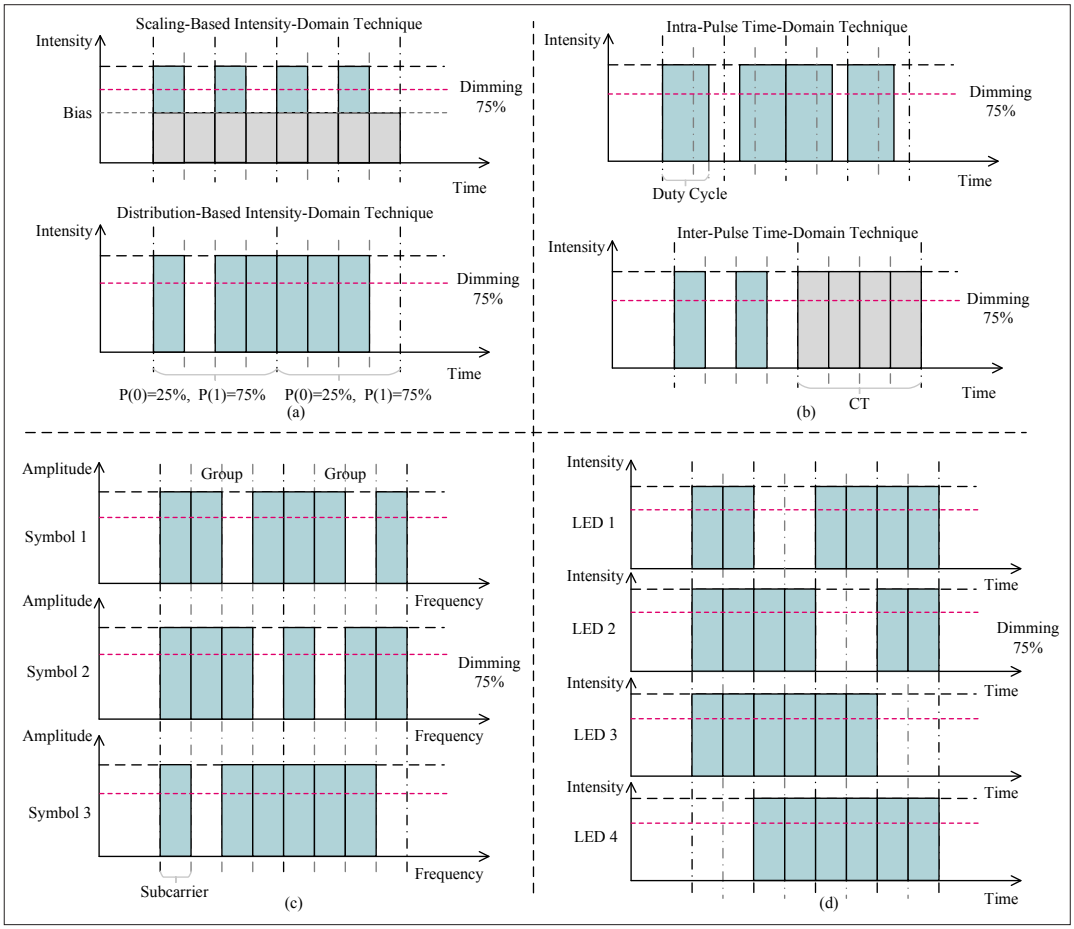


FIGURE 3. Examples of the conventional single-dimensional techniques: a) the intensity-domain approach; b) the time-domain dimming approach; c) the frequency-domain approach; d) the spatial-domain approach.

different average optical intensities. For example, they are modified as the "positive" OFDM symbols and the "negative" ones in [7]. The probability of transmitting different kinds of OFDM symbols can be changed to meet the diversified illumination requirements.

Distribution-based intensity-domain dimming approaches alleviate the degradation of spectral efficiency in the low and high illumination regions. However, additional hardware and computation are needed to facilitate the distribution adaptation.

Time-Domain Dimming Techniques

Time-domain techniques implement human-centric communication and illumination mainly depending on time-domain considerations and designs. Generally, they can be further divided into two classes: intra-pulse time-domain dimming techniques that implement dimming controls within the signal pulse, and inter-pulse techniques that add illumination compensation between signal pulses.

Intra-Pulse Time-Domain Dimming: In the literature, many kinds of intra-pulse time-domain dimming approaches have been proposed, such as the variable OOK (VOOK) approach and the variable PPM (VPPM) approach, which implement dimming controls by adjusting the signal pulse width of OOK and PPM symbols, respectively [8]. An example of the VPPM approach providing 75 percent dimming is presented in Fig. 3b, where the position of the pulse is used for information modulation and the duty cycle of the symbol is adjusted to 75 percent for dimming adaptation. In order to improve the spectral efficiency, an enhanced approach, multiple PPM (MPPM), was put forward in [9], which changes the number of optical pulses within one symbol duration to facilitate precise dimming control.

The intra-pulse time-domain dimming approaches implement dimming controls through careful design of the transmitted symbols in the time domain. Nonetheless, the pulse of the symbols cannot be too wide nor too narrow for accurate detection at the receiver. Thus, this kind of dimming technique suffers from communication performance degradation under high or low dimming requirements.

Inter-Pulse Time-Domain Dimming: Inter-pulse time-domain dimming techniques insert the compensation time (CT) between the data symbols to control the dimming level, which can be applied to both the single-carrier and the multi-carrier VLC systems. The compensation symbols transmitted during CT are only used for dimming adaptation, but not for data transmission [9]. For example, as shown in Fig. 3b, using OOK modulation, supposing the "ON" and "OFF" symbols are transmitted with equal probability, an "ON" compensation symbol is appended after every data symbol to achieve 75 percent dimming level.

The inter-pulse time-domain dimming approaches are simple to be implemented and can be easily applied to almost every kind of modulation

Authorized licensed use limited to: Tsinghua University. Downloaded on August 27,2020 at 08:25:45 UTC from IEEE Xplore. Restrictions apply.

scheme. However, the weakness of this kind of dimming approach is that the appended CT intervals decrease the spectral efficiency of the communication, especially when the dimming target deviates from 50 percent.

Frequency-Domain Dimming Techniques

Generally, frequency-domain dimming techniques are well-suited for multi-carrier VLC systems to support human-centric illumination. In these techniques, the illumination is adjusted by changing the number of activated subcarriers. Fewer subcarriers are activated to transmit data symbols under the low-light requirements and more subcarriers are selected in the opposite situations. In these approaches, the index modulation technique can be involved to improve the spectral efficiency [10]. Due to the principle of index modulation, when a subset of the subcarriers is activated, the indices of the subcarriers that are activated can also be modulated to convey data information [10]. An example of the frequency-domain dimming approach is illustrated in Fig. 3c. The whole bandwidth is divided into groups and each group consists of four subcarriers. It is shown that in each group, only three subcarriers are activated in order to achieve 75 percent dimming target. It is worth noting that the indices of the activated subcarriers are diverse in different groups and symbols, which can be used to convey extra data information.

One of the strengths of frequency-domain dimming techniques is that they are easily implemented in the multi-carrier VLC systems. The division of the whole bandwidth into subcarriers provides an inherent dimension to implement dimming control. On the downside, frequency-domain dimming techniques are not applicable to extreme illumination requirements. Under low-light requirements, only a small number of subcarriers are activated, which causes a serious waste of spectral resources.

Spatial-Domain Dimming Techniques

In recent works, the multiple-input multiple-output technique has been introduced into VLC systems. Multiple LEDs and PDs work together to improve the spectral efficiency, which also provides a new dimension to implement human-centric dimming control. The basic idea of spatial-domain dimming techniques is that the illumination can be represented by the number of glared LEDs, thus the dimming control can be implemented by adjusting the number of glared LEDs [11]. Since not all the LEDs are activated to transmit data symbols, the spatial modulation and generalized spatial modulation techniques can be applied to the VLC system to transmit extra data information through the indices of the activated LEDs. In Fig. 3d, an illumination of a four-LED VLC system using spatial-domain dimming techniques is given. In order to achieve 75 percent dimming, only three LEDs are activated at the same time to transmit data information. Similarly, the indices of the activated LEDs can be modulated to convey information as well.

Since more LEDs are equipped in the system, the multi-LED VLC system can provide a much wider illumination range than the single-LED system. Spatial-domain dimming techniques are easy to implement because there is no need to change the bias, the scaling factor, and the duty cycle of the transmitted signals. The drawback of these approaches is that the achievable dimming level is discrete because the number of activated LEDs is discrete in nature.

Hybrid Multi-Dimensional Techniques

As discussed previously, many of the single-dimensional dimming strategies have their own weaknesses, such as decreased spectral efficiency, inadaptation to the extreme dimming requirements, and additional complexity, which motivate researchers to work on enhanced techniques. Recently, several hybrid techniques are emerging for human-centric VLC, which utilize multi-dimensional resource management to make up for the drawbacks of single-dimensional techniques and improve the communication and illumination performance. In this section, the principles, key features, strengths, and weaknesses of existing multi-dimensional techniques are discussed and compared.

Hybrid Time-Intensity-Domain Approaches

In [12], a hybrid approach is proposed based on both the time-domain and the intensity-domain considerations. In this hybrid approach, a novel signal format, reverse polarity optical OFDM (RPO-OFDM), is proposed by combining the ideas of PWM and OFDM. The dimming control can be implemented by jointly changing the time-domain duty cycles and the intensity-domain scaling factors. The RPO-OFDM symbols are derived by adding or subtracting the OFDM symbols from the PWM symbols. The addition is adopted when the PWM symbol is "ON," and subtraction is adopted otherwise. The time-domain duty cycles of PWM and the intensity-domain scaling factors of OFDM can be adjusted together to reach the required target.

Using the hybrid dimming approach, a more flexible dimming control can be achieved because of the two-dimensional adjustments. Compared to the single-dimensional scaling-based intensity-domain dimming approaches, the hybrid approaches can keep the DC bias in the middle of the dynamic range of the LEDs to make full use of the dynamic range under intermediate dimming requirements.

Hybrid Frequency-Intensity-Domain Approaches

Frequency-domain dimming approaches can be integrated with other kinds of single-dimensional dimming approaches to improve the communication and illumination performance in multi-carrier VLC systems. In [13], a hybrid approach is proposed for the ACO-OFDM VLC system, which makes use of both the frequency-domain techniques and the intensity-domain techniques to implement hybrid dimming control. The block diagram of the system is shown in Fig. 4a. Due to the principle of ACO-OFDM, only the odd subcarriers are modulated to transmit information bits and the even subcarriers are kept zeros. Frequency-domain signals satisfy the Hermitian symmetry, so that the derived time-domain samples after the inverse fast Fourier transform (IFFT) are real, and either the positive part or the negative part of the time-domain samples can be clipped without any information loss. It can be seen that

Using the hybrid dimming approach, a more flexible dimming control can be achieved because of the two-dimensional adjustments. Compared to the single-dimensional scaling-based intensity-domain dimming approaches, the hybrid approaches can keep the DC bias in the middle of the dynamic range of the LEDs to make full use of the dynamic range under intermediate dimming requirements.

Authorized licensed use limited to: Tsinghua University. Downloaded on August 27,2020 at 08:25:45 UTC from IEEE Xplore. Restrictions apply.

In frequency-intensity-domain approaches, the achievable data rate can be optimized under the given illumination requirements by jointly adjusting the two-dimensional configurations. Thus, it can achieve much higher spectral efficiency than that of single-dimensional approaches, especially under the low and high dimming requirements.

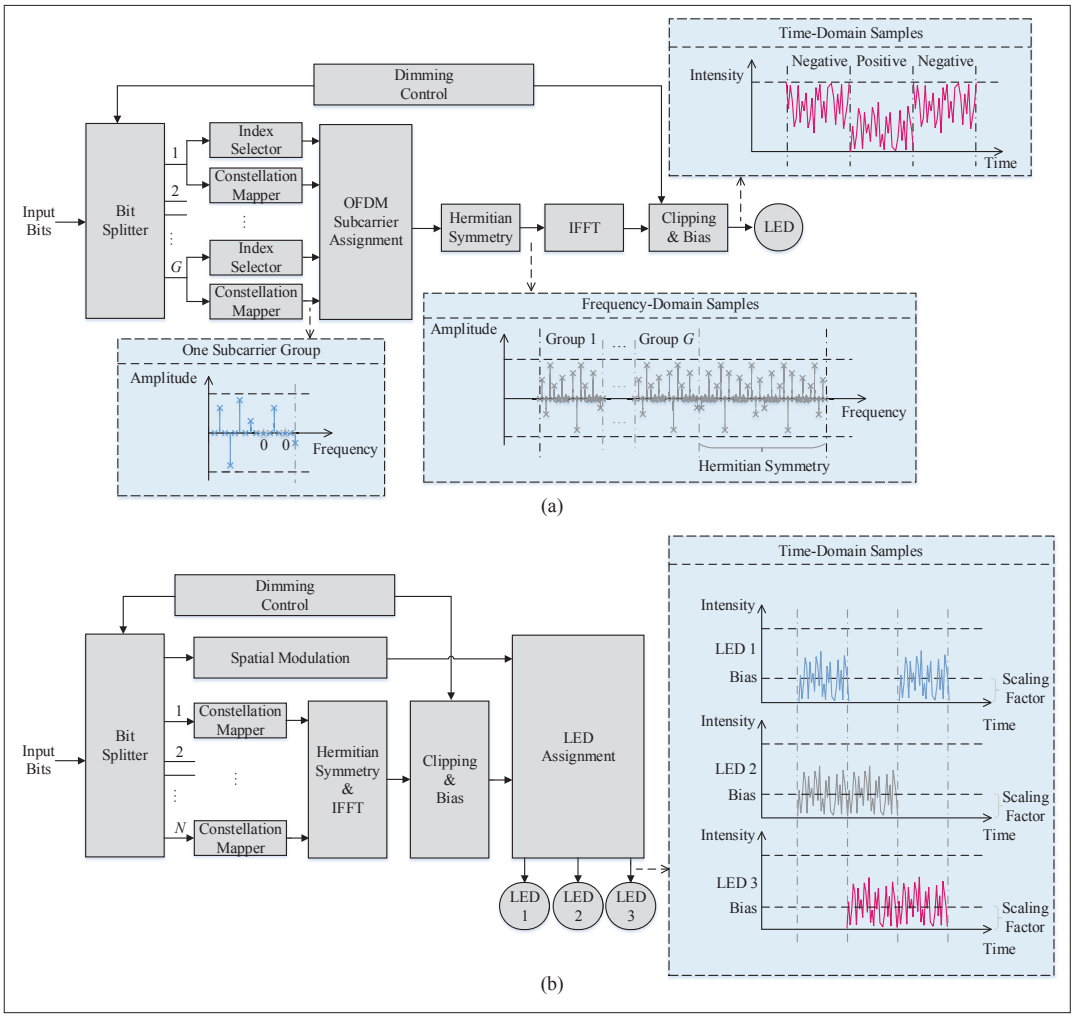


FIGURE 4. The block diagrams of the hybrid approaches: a) the hybrid frequency-intensity-domain approach; b) the hybrid spatial-intensity-domain approach.

the dimming control module controls both the bit mapping and the bias adding to implement hybrid dimming control. On the one hand, the number of activated subcarriers can be adjusted to control the illumination. The subcarriers are divided into G groups and not all the subcarriers are activated in each group. The index modulation technique is adopted to improve the spectral efficiency by transmitting extra information through the indices of the activated subcarriers in each group. On the other hand, the distribution of the transmitted signals can be adjusted to control the illumination as well. Two kinds of OFDM symbols are considered in [13], which are denoted as "positive" symbols and "negative" symbols. The "positive" symbols are generated by clipping the negative part of the time-domain samples and adding the minimum intensity of the dynamic range of the LEDs; the "negative" symbols are derived by clipping the positive part of the time-domain samples and adding the maximum intensity of the dynamic range of the LEDs. Therefore, the distribution of the two kinds of OFDM symbols can be adjusted to control the illumination as well. As a result, the illumination of the system can be controlled by jointly adjusting the frequency-domain activated number of subcarriers and the intensity-domain distribution of the transmitted symbols.

In frequency-intensity-domain approaches, the achievable data rate can be optimized under the given illumination requirements by jointly adjusting the two-dimensional configurations. Thus, it can achieve much higher spectral efficiency than that of single-dimensional approaches, especially under the low and high dimming requirements.

Hybrid Spatial-Intensity-Domain Approaches

In multi-LED VLC systems, the illumination can be adjusted by combining the spatial-domain techniques with other single-dimensional dimming techniques. In [15], a hybrid approach integrating spatial-domain dimming with distribution-based intensity-domain dimming is proposed for the ACO-OFDM VLC system. In this hybrid approach, spatial-domain dimming is implemented by adjusting the number of activated LEDs, and intensity-domain dimming is implemented by adjusting the probability of transmitting two kinds of OFDM symbols, which are denoted as "positive" symbols and "negative" symbols, respectively. The "positive" symbols are derived by clipping the negative part of the time-domain symbols and adding the minimum intensity of the dynamic range of the LEDs; the "negative" symbols are obtained by clipping the positive part of the time-domain symbols and adding the maximum intensity of the dynamic

Authorized licensed use limited to: Tsinghua University. Downloaded on August 27,2020 at 08:25:45 UTC from IEEE Xplore. Restrictions apply.

Approaches	References	Advantages	Disadvantages
Intensity-domain approaches	[6, 7]	Intuitive principles; applicable to both the single-carrier and multi-carrier systems	Limited energy efficiency; increased complexity for distribution-based approaches
Time-domain approaches	[8, 9]	Easy implementation; applicable to both the single-carrier and multi-carrier systems; fixed DC bias	Decreased spectral efficiency under extreme illumination requirements
Frequency-domain approaches	[10]	Improved spectral efficiency through index modulation; well-suited for multi-carrier systems	Limited dimming precision; only applicable to multi-carrier systems
Spatial-domain approaches	[11]	Improved spectral efficiency through spatial modulation; well suited for multi-LED systems; large dimming range	Limited dimming precision; only applicable to multi-LED systems
Time-intensity-domain approaches	[12]	Enhanced spectral efficiency; fixed DC bias; improved dimming range	Increased complexity
Frequency-intensity-domain approaches	[13]	Enhanced spectral efficiency; improved dimming precision	Increased complexity; only applicable to multi-carrier systems
Spatial-intensity-domain approaches	[14, 15]	Enhanced spectral efficiency; improved dimming precision; wide dimming range	Increased complexity; only applicable to multi-LED systems

TABLE 1. Comparisons of the state-of-the-art dimming techniques.

range of the LEDs. Therefore, both the "positive" symbols and the "negative" symbols are positive and within the dynamic range of the LEDs. As a result, the illumination can be controlled by jointly adjusting the number of activated LEDs and the probabilities of the "positive" and "negative" symbols. Another example of the hybrid spatial-intensity-domain dimming approach is provided in [14] for DCO-OFDM systems, which combines the spatial-domain and scaling-based intensity-domain dimming techniques to achieve the dimming target. The difference is that intensity-domain dimming is implemented by adjusting the bias and the scaling factors of the time-domain OFDM symbols. An illustration of the transmitted symbols on the LEDs is shown in Fig. 4b. It can be seen that two out of the three LEDs are activated simultaneously and the biases are decreased from the middle of the dynamic range to provide a much lower dimming level.

Compared with single-dimensional spatial-domain dimming approaches, hybrid dimming approaches can achieve a more flexible dimming control because of multi-dimensional resource management. In addition, the indices of the activated LEDs can be modulated through the spatial modulation technique to transmit more information bits. The summaries of the single-dimensional and multi-dimensional techniques are provided in Table 1.

Challenges and Future Research Trends

So far, although many efforts have been made to design resource management strategies for human-centric VLC with one or more dimensional considerations, there are still many essential problems to be addressed in the future, including the joint optimization of communication and illumination, the joint control of color and intensity, practical implementation and commercialization.

Joint Optimization of Communication and Illumination

Generally, the support of dimming control limits the achievable data rate of the VLC system, especially under the high and low dimming requirements deviating from 50 percent. In future dimmable VLC systems, the full exploitation of multi-dimensional resources and the joint optimization of communication and illumination are of great importance to improve the system performance, including the spectral efficiency, the energy efficiency, and so on. More efforts need to be made for joint optimization of communication and illumination to meet the diverse and changeable requirements from the VLC users.

Joint Control of Color and Intensity

Other than the intensity, the color of the LED light is also an illumination requirement in some use cases, which influences the comfortableness of human eyes. A specific color can be achieved by varying the intensity of monochromatic LEDs of different colors. However, the intensity and the color of the LED light are not independent. The change in optical intensity will cause a slight shift in the light color. And the temperature and the aging of the LED also shift the wavelength of the LED emission. Thus, joint resource management strategies of color and intensity are needed under changes to various parameters, such as temperature and aging.

Practical Implementation and Commercialization

The practical environment of the dimmable VLC system is more complicated than the experimental environment. More factors need to be considered to achieve satisfactory communication and illumination performance, including the ambient light, shot noise, shadowing, junction temperature, computational complexity, and so on. In order to realize practical implementation and large-scale commercialization of dimmable VLC, the current hardware and software infrastructures still need to be upgraded, which requires effort from both the lighting equipment manufacturers and the mobile device manufacturers.

Software Defined Multi-Dimensional Dimming

In order to address the challenges and seize the opportunities for human-centric VLC, we propose the concept of SDMDD in this article. In general, there exists a wide variety of requirements in practical VLC systems. On the communication side, the data rate is required to be high when transferring large files or playing high-definition streaming videos on mobile devices. However, the data-rate demand is not so strong in indoor mobile device positioning and pairing use cases,

Authorized licensed use limited to: Tsinghua University. Downloaded on August 27,2020 at 08:25:45 UTC from IEEE Xplore. Restrictions apply.

There also exist challenges for the SDMDD framework, including the establishment of joint optimization models to satisfy diverse requirements, and the invention of efficient optimization algorithms. Further research is required to bring the concept to practical implementation.

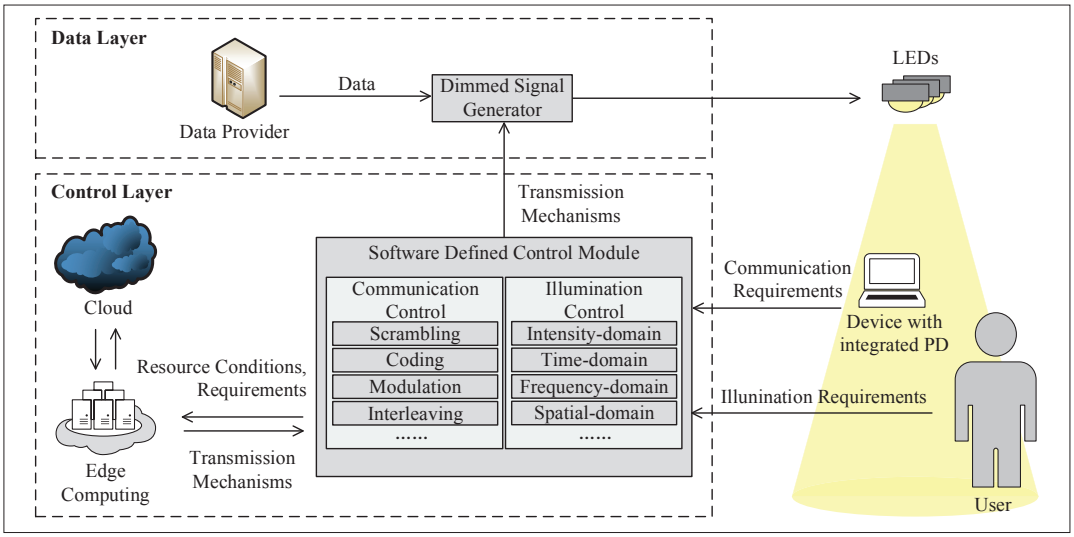


FIGURE 5. The framework of the software defined multi-dimensional dimming for the human-centric illumination network.

where the high-accuracy and low-latency properties are desired. As for the VLC enabled vehicle-to-vehicle communication scenario, reliability and latency are essential demands. On the illumination side, the illumination requirements are different for reading, writing, and computer works in the office environment. According to [5], the requirements of humans are not all the same. The visual requirements of the young, the old, and the disabled may differ greatly. Based on the above considerations, the concept of SDMDD is proposed to facilitate joint management of the communication and illumination resources to meet the diverse and changeable requirements in the VLC systems.

The proposed framework of SDMDD is illustrated in Fig. 5. In this framework, the control layer is separated from the data layer in order to implement flexible resource management. The control layer determines specific transmission mechanisms to satisfy both the communication and illumination requirements, and the data layer is used to provide the desired data information of the electronic devices.

Specifically, the control layer consists of a software defined control module and edge computing equipment. The software defined control module collects the real-time illumination requirements from the users and communication requirements from the devices, including intensity of light, color of light, required data rate, bit error rate, latency, reliability, and so on. Then the control module transmits the requirements and the conditions of the usable multi-dimensional resources to the edge computing equipment. Edge computing can be implemented at the gateway of a room or several rooms in a building to alleviate the load of cloud computing. Edge computing calculates the optimal communication and illumination configurations under specific metrics, such as the maximization of spectral efficiency or energy efficiency to provide real-time feedback of the suggested transmission mechanisms. After that, the decision of the transmission mechanisms is made by the control module and directs the generation of the VLC signals. Finally, the VLC signals are transformed into optical intensities and transmitted through the LEDs.

Big data and artificial intelligence (AI) techniques can also be integrated into the proposed SDMDD framework to enhance the system performance. In future smart cities, billions of devices will connect to the network. The management of the communication requirements of these devices and the optimization of the transmission mechanisms needs huge amounts of data processing. Therefore, the big data technique can be utilized to implement massive data storage and data processing to provide real-time optimization of the transmission mechanisms. AI techniques can be used to adjust the illumination requirements based on the historical information of human behavior and human preference in order to provide personalized services for different users in the future smart home and smart cities.

Under this framework, the adaptive and flexible adjustments on the transmission mechanism can be achieved by joint management of the multi-dimensional resources to meet the various and changeable requirements. According to [3], indoor lighting accounts for about 19 percent of global electricity consumption. Thus, if indoor lighting can be adjusted according to the illumination actually required by humans, it will be good for both global electricity consumption and human health. Moreover, the SDMDD framework is easily integrated with machine learning techniques and other AI techniques to provide intelligent and personalized services, which can be the building blocks of the future smart home and smart cities. There also exist challenges for the SDMDD framework, including the establishment of joint optimization models to satisfy diverse requirements, and the invention of efficient optimization algorithms. Further research is required to bring the concept to practical implementation.

Conclusion

This article reviews the current research progress in dimming techniques of VLC for human-centric illumination networks. Comprehensive comparisons and discussions of the state-of-the-art solutions are provided from a multi-dimensional perspective. In addition, the challenges and future research trends are also carefully addressed. The concept of SDMDD is therefore proposed for the

Authorized licensed use limited to: Tsinghua University. Downloaded on August 27,2020 at 08:25:45 UTC from IEEE Xplore. Restrictions apply.

first time to facilitate joint design and management of multi-dimensional resources. In the future, we believe that dimming strategies will cover not only the physical layer but also the higher layers to further improve the system efficiency and enhance the users' experience. With continuing efforts from academia and industry, it is expected VLC will play a much more important role in post 5G or even 6G wireless communication systems.

Acknowledgment

This work was supported by the National Key Research and Development Program of China (2017YFB0403402).

References

[1] S. H. Lee, S. Jung, and J. K. Kwon, "Modulation and Coding for Dimmable Visible Light Communication," *IEEE Commun. Mag.*, vol. 53, no. 2, Feb. 2015, pp. 136–43.
[2] F. Zafar, D. Karunatilaka, and R. Parthiban, "Dimming Schemes for Visible Light Communication: The State of Research," *IEEE Wireless Commun.*, vol. 22, no. 2, Apr. 2015, pp. 29–35.
[3] J. Gancarz, H. Elgala, and T. D. C. Little, "Impact of Lighting Requirements on VLC Systems," *IEEE Commun. Mag.*, vol. 51, no. 12, Dec. 2013, pp. 34–41.
[4] A. Sears and J. A. Jacko, *The Human-Computer Interaction Handbook: Fundamentals, Evolving Technologies and Emerging Applications*, Boca Raton, FL: CRC Press, 2007.
[5] A. Dix *et al.*, *Human-Computer Interaction*, Upper Saddle River, NJ: Prentice Hall, 1998.
[6] J. K. Kwon, "Inverse Source Coding for Dimming in Visible Light Communications Using NRZ-OOK on Reliable Links," *IEEE Photon. Technol. Lett.*, vol. 22, no. 19, Oct. 2010, pp. 1455–57.
[7] F. Yang and J. Gao, "Dimming Control Scheme with High Power and Spectrum Efficiency for Visible Light Communications," *IEEE Photon. J.*, vol. 9, no. 1, Feb. 2017, pp. 1–12.
[8] S. Rajagopal, R. D. Roberts, and S. Lim, "IEEE 802.15.7 Visible Light Communication: Modulation Schemes and Dimming Support," *IEEE Commun. Mag.*, vol. 50, no. 3, Mar. 2012, pp. 72–82.
[9] K. Lee and H. Park, "Modulations for Visible Light Communications with Dimming Control," *IEEE Photon. Technol. Lett.*, vol. 23, no. 16, Aug. 2011, pp. 1136–38.
[10] N. Ishikawa, S. Sugiura, and L. Hanzo, "50 Years of Permutation, Spatial and Index Modulation: From Classic RF to Visible Light Communications and Data Storage," *IEEE Commun. Surveys Tuts.*, vol. 20, no. 3, Mar. 2018, pp. 1905–38.
[11] Y. Yang *et al.*, "Spatial Dimming Scheme for Optical OFDM Based Visible Light Communication," *Opt. Express*, vol. 24, no. 26, Dec. 2016, pp. 30 254–63.
[12] H. Elgala and T. D. C. Little, "Reverse Polarity Optical-OFDM (RPOOFDM): Dimming Compatible OFDM for Gigabit VLC Links," *Opt. Express*, vol. 21, no. 20, Oct. 2013, pp. 24 288–99.
[13] T. Wang *et al.*, "Spectral-Efficient Hybrid Dimming Scheme for Indoor Visible Light Communication: A Subcarrier Index Modulation Based Approach," *J. Lightw. Technol.*, vol. 37, no. 23, Dec. 2019, pp. 5756–65.
[14] Y. Yang *et al.*, "A Novel Hybrid Dimming Control Scheme for Visible Light Communications," *IEEE Photon. J.*, vol. 9, no. 6, Dec. 2017, pp. 1–12.
[15] T. Wang *et al.*, "Spectral-Efficient Generalized Spatial Modulation Based Hybrid Dimming Scheme with LACO-OFDM in VLC," *IEEE Access*, vol. 6, June 2017, pp. 41 153–62.

Biographies

Tengjiao Wang [S'19] (wangtj16@mails.tsinghua.edu.cn) received his B.S. degree from the Department of Electronic Engineering, Tsinghua University, Beijing, China, in 2016. He is currently pursuing the Ph.D. degree with the DTV Technology Research and Development Center, Department of Electronic Engineering, Tsinghua University. His research interests are in the field of visible light communications, wireless communications, multiple-input multiple-output systems, non-orthogonal multiple access, and sparse signal processing theory. He received the National Scholarship in 2018.

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, Beijing, China, in 2005 and 2009, respectively. He is currently working as an associate professor with the Research Institute of Information Technology, Tsinghua University. He has published over 120 peer-reviewed journal and conference papers. He holds over 40 Chinese patents and two PCT patents. His research interests are in the fields of channel coding, channel estimation, interference cancellation, and signal processing techniques for communication systems, especially in 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 in Broadcasting*) in 2015. He is the Secretary General of Sub-Committee 25 of the China National Information Technology Standardization (SAC/TC28/SC25), and a fellow of IET.

Jian Song [M'06, SM'10, F'16] (jsong@tsinghua.edu.cn) received his B.Eng and Ph.D. degrees in electrical engineering both from Tsinghua University, Beijing, China in 1990 and 1995, respectively, and worked for the same university upon his graduation. He has worked at The Chinese University of Hong Kong and the University of Waterloo, Canada in 1996 and 1997, respectively. He was with Hughes Network Systems in the U.S. for seven years before joining the faculty team at Tsinghua in 2005 as a professor. He is now the director of Tsinghua's DTV Technology R&D center. He has been working in a wide range of areas in fiber-optic, satellite, wireless communications and power line communications. His current research interest is in the area of digital TV broadcasting. He has published more than 200 peer-reviewed journal and conference papers. He holds two U.S. patents and more than 40 Chinese patents. He is also a Fellow of IET.

Zhu Han [S'01, M'04, SM'09, F'14] (zhan2@uh.edu) received the B.S. degree in electronic engineering from Tsinghua University in 1997, and the 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 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 IEEE JSAC) in 2016, and several best paper awards at IEEE conferences. He is a 1 percent highly cited researcher according to the Web of Science since 2017.

In the future, we believe that dimming strategies will cover not only the physical layer but also the higher layers to further improve the system efficiency and enhance the users' experience. With continuing efforts from academia and industry, it is expected VLC will play a much more important role in post 5G or even 6G wireless communication systems.

Authorized licensed use limited to: Tsinghua University. Downloaded on August 27,2020 at 08:25:45 UTC from IEEE Xplore. Restrictions apply.