Visible Light Communications for 5G Wireless Networking Systems: From Fixed to Mobile Communications

Shaoen Wu, Honggang Wang, and Chan-Hyun Youn

Abstract

Visible light communication, considered as a potential access option for 5G wireless communications, is gaining extensive attention. VLC has strengths in energy efficiency and ultra wide bandwidth, but also has weakness in transmission range and obstacles in transmission paths. This article aims to provide a conclusive investigation of the latest progress in research on VLC, which can be used as part of 5G wireless communication systems. This work highlights the strengths and weaknesses of VLC in comparison with RF-based communications, especially in spectrum, spatial reuse, security and energy efficiency. The article also investigates various lighting sources proposed for VLC systems. It summarizes the literature work on VLC networking into two categories: fixed and mobile VLC communications.

Fifth generation (5G) wireless systems represent the next phase of mobile telecommunications beyond the current 4G standards. The next generation technology is not very clear, but could be focused on higher system spectral efficiency, data rates, network capacity, scalability and reliability of communications, as well as lower battery consumption, cost, and so on. There are still debates about the direction of future 5G technology. However, 5G technology should be significantly different from current communication technology standards.

Traditional radio frequency (RF)-based wireless communication has arrived at a bottleneck to meet these needs. First, there is a shortage of RF spectra: most of them have been allocated. The bandwidth of each allocation is somehow limited. Second, various exploitations of RF frequency utilization have been studied for decades, and the potential to exploit more is limited. Third, although the low-power integrated circuit (IC) innovations helped improve power consumption, it is still severe in RF communication. Researchers are searching for new wireless commutations alternatives to RF. Visible light communications (VLC), also known as Li-Fi or optical wireless communication (OWC), wireless technology offers such an option and has gained increasing attention. While the current RF networks serve outdoor users or users in fast moving vehicles, VLC can serve indoor environment communications in future 5G systems because of four factors:

- There is no interference between the indoor user and the outdoor user at all due to different spectra.
- Because there is no interference, an RF base station can transmit with low power.
- Scarce wireless link resources are used most efficiently.

Shaoen Wu is with Ball State University.

Honggang Wang is with the University of Massachusetts Dartmouth.

Chan-Hyun Youn is with KAIST.

Therefore, VLC is an ideal complement to RF systems in future 5G technologies [1]. VLC has developed rapidly in the last few years. Although extensive work has been performed on VLC, there is no survey work on the research literature. This work is inspired to update the achievement in VLC research in literature.

In this article, we present a summary of investigation on VLC research in the literature. First discussed are the advantages and challenges of VLC. Then we present an investigation of light sources used in VLC communication. Next, we summarize current work on VLC into two categories: VLC-based fixed and mobile communication. We discuss VLC-based fixed communications that have been widely studied; some of the technologies are well established. We also study the existing work on VLC indoor applications and intersymbol interference (ISI) mitigation technologies. Recently, VLC-based mobile communications has spurred considerable research interests and applications, which are presented. Finally, we conclude the article.

Characteristics of VLC

VLC has its own strengths, but also weaknesses. This section summarizes its characteristics, which are overviewed in Table 1. These characteristics deserve special attention in designing architectures and protocols for VLC communications and networking.

VLC offers several advantages over RF, which are summarized in the left column of Table 1. First, it has unregulated spectrum, specifically from 428 to 750 THz, which provides huge communication bandwidth to deliver license-free extremely high data rate services such as large files and super high definition video transfer. Compared to RF communications, VLC offers hundreds of terahertz of license-free bandwidth, 10,000 times more than the entire RF spectrum up to 30 GHz. Besides the transmission speed, reported at 3.5 Gb/s currently [2], allowed by the huge bandwidth of VLC, the ultra wide bandwidth is also more robust to multipath fading

 0890-8044/14/$25.00 © 2014 IEEE

Advantage	Challenge
Wide unregulated spectrum	Low mobility
High spatial reuse	Light interference
Security	Eye safety
High energy efficient	

Table 1. Advantages and challeges of VLC.

Fixed applications	Mobile applications
System architecture	Spherical LED
ISI mitigation	Camera-based visual MIMO

Table 2. Summary of articles on mobile solutions.

in various environments. In a 2011 TED talk, Hass successfully demonstrated the transmission speed of 1 Gb/s for HD video streaming. Second, the energy cost for data transmission of VLC is considerably lower than that of RF, which enables it to become a promising candidate for green communication. This is because lighting is on most of the time, so the energy used for communication would be close to zero if data is piggy-backed on illumination. Even if lighting is not on, energy-efficient intensity modulation (IM) techniques would allow data communication [2]. Third, VLC spectrum can be reused densely. Visible light wave, as a media for data transmission, cannot penetrate walls and obstacles. Therefore, the information cannot be received unless a receiver sees a transmitter. As a result, in indoor cases, the coverage of VLC is restricted in one room. This exact property enables dense spatial reusability, because the same spectrum can be reused in other rooms. Fourth, VLC provides high secrecy. Its narrow beamwidth and line of sight (LOS) constraint protect the communication from eavesdropping.

Challenges

Regardless of the fact that VLC has many attractive characteristics to support a wide range of demands for wireless communication, several challenges cannot be overlooked, which are summarized in the right column of Table 1. First, one of the most important limitations is having maintain LOS between transmitters and receivers. As has been discussed, a VLC transmission cannot be fulfilled unless the receiver can see the transmitter. This requirement places a tight restriction on the mobility of communication, which is one of the basic advantages of wireless services. Therefore, most current VLC applications focus on fixed point-to-point links. The lack of mobility is due to the feature of narrow beamwidth of light sources. To address the problem of mobility, a diffused light source can be employed. Second, VLC suffers from solar and artificial visible light interference that degrades the performance of the system. Third, for indoor environments, signals such as infrared can present hazards to human eyes. For outdoor environments, the effect of adverse atmospheric conditions on optical wireless links definitely deserves attention.

Light Sources

Light source is substantial in VLC such as antenna to RF-based communications. Its propagation pattern affects not only the quality of communication, but also the illumination. With the rapid development of high-brightness light emitting diode (LED) materials in the context of solid-state lighting, particularly white LEDs, LED-based illumination devices are a promising replacement to traditional incandescent-based and compact fluorescent-based illumination devices in the near future. Due to the advantages of LEDs, such as good light quality, low energy consumption, small size, and long lifetime, they have been deployed in many countries around the world as indoor illumination, display devices, and traffic lights. Nowadays, some of the attractive properties of LED make it particularly proper for wireless communication. On the transmitter side, the signal is easy to modulate by on-off keying modulation to achieve high data rate. On the receiver side, photodiodes are able to convert the optical signals to electrical signals at very high rates. In addition, due to the feature of diffusion, it is more widespread than a narrow beamwidth lighting source to provide ubiquitous wireless communication. In sum, it is expected to be an opportunity to combine illumination devices with wireless communication devices to achieve both green communication and energy-saving illumination.

VLC-Based Communication

VLC was originally developed for indoor last mile wireless service delivery. Since its inception, the system architectures have been established over the years. Some specific designs of systems and components have even been demonstrated in practice. From this experience, the concept of VLC has been proved to be feasible for indoor fixed applications. However, the problem of how to provide mobile applications over VLC is still quite open. Currently, many research groups focus on the design of VLC mobile communications. This section presents a summary of both fixed and mobile VLC communication. An overview of various VLC solutions is given in Table 2.

VLC-Based Fixed Communication

The performance of fixed VLC communications is between RF-based wireless and wired communication [3]. Because of the narrow beamwidth in light waves, they are hard to be used for mobile communications. However, it can provide energy efficiency and high-speed outdoor point-to-point links and indoor last mile applications. For outdoor applications, high-power laser-based equipment is designed for stationary building-to-building transmission links. Because of the high power, the transmission range is enlarged and proper for outdoor environments. For indoor application, LED is employed as the signal source to provide short distance data transmission within a room [4], which is expected to be a desired design for next generation indoor wireless communications. LED lighting sources have very low requirements for power and are therefore energy friendly.

Indoor VLC

In indoor VLC, today, LEDs serve as sources of both illumination and communication. As for illumination, the brightness of LED determines the luminous intensity of illumination. For communication, it determines the transmission power of the signal source, which is the key factor in the signal-to-noise ratio (SNR) and the coverage of wireless service. The network of indoor VLC is a WLAN consisting of uplink and downlink. For uplink, plural white LEDs with a wide range of transmission are deployed on the ceiling. For downlink, white LEDs with narrow-range transmission are employed. Compared to conventional laser-based VLC, LED is more suitable for indoor applications because it is safe for eyes and inexpensive, although the available bandwidth is less than that of laser, which can achieve a data rate up to gigabits per second. As far as the coverage is concerned, service requires the communication cover the entire room. Unlike the highly focused laser source, LED is a diffuse source that is capable of providing adequate coverage in a room.

The light source of an LED-based VLC system is normally configured by placing lots of small LED elements on a panel. Basically, the brightness of illumination grows along with the power of the signal. The goal of green communication and illumination is achieved by using the minimum number of LED elements to support the brightness and transmission power. The direction and placement of LED elements are key factors that affect the efficiency of illumination and communication. In [5], the author proposed an LED panel model that can place LEDs at some angle, and analyzed the effect of various LED directions on the illumination and SNR. Based on their channel model and analysis, the optimal direction was formulated.

One of the main reasons for replacing incandescent and fluorescent lighting with LED is its low energy cost. To fully explore this feature and further improve the energy efficiency, the illumination system should be capable of brightness control. Specifically, the brightness of LED should be adaptive to the brightness of the environment. However, when illumination is combined with communication, this adaptation must consider the effect on the performance of communication, because low brightness leads to low signal transmission power, which directly decreases the SNR. Therefore, VLC calls for new brightness control techniques to determine the trade-off between illumination and communication. In [6], two brightness control methods are developed based on pulse width modulation (PWM) and changing modulation depth. The simulations demonstrate that it is able to control the brightness from 0 to 87.5 percent maintaining the communication performance with PWD over 60 kHz frequency. Besides, the best performance can be achieved from 12.5 to 87.5 percent.

In an indoor VLC system, the LED light source is normally deployed on the ceiling. To set up the VLC on the existing illumination system, the infrastructure, such as circuits and cables, must be installed over the ceiling, which restricts fast and inexpensive deployment of VLC in indoor environments. In [7], a VLC using existing power line communication is proposed to achieve a simple composition and economic VLC. In this integrated system, a VLC system is connected directly to the existing power line. It emits the baseband signals of power line by LED elements in the room. Simulation results show the feasibility of the proposed system in terms of the illumination and SNR performance. The demonstration presents a data rate up to 100 kb/s.

Nowadays, there are various personal devices that demand data communication services, such as smart phones, tablets, and laptops. Most of these devices are Wi-Fi-capable. However, there is no standard interface to access services offered by VLC, which limits the wide adoption of VLC in practice. Aiming to design an interface that can be used by different user terminals, a VLC wireless USB interface is proposed [8]. The interface contains an LED transmitter, a photodiode receiver, and a USB interface adapter. The entire interface is controlled by a field-programmable gate array (FPGA).

The support of bidirectional communication is essential to network interfaces that can significantly improve network performance in multiple access and networking. In [9], the authors propose the design of a full-duplex network interface for multiple access embedded in ceiling lighting. The duplex communication system consists of two simplex channels where the two sides are identical: seven LEDs around the perimeter of the reflector and three photodiodes in the center. The problem of is this full-duplex design is the crosstalk between LEDs and photodiodes.

ISI Mitigation Technologies

Unlike outdoor point-to-point links, indoor VLC requires coverage of an entire room. Therefore, a diffuse light source such as LED is employed. However, a diffuse signal source suffers from ISI. In an RF-based system, receiver diversity is an effective way to address this problem based on the fact that it is unlikely that all independent signal paths are in deep fading. Therefore, combining these multi-path signals can reduce the effect of fading. Diversity is also feasible for LED-based VLC to mitigate the problem of ISI. Because there are a number of LED elements sending signals on the LED panel, receiving devices have various signal sources to combine. This can be considered transmitter diversity. In [10], the author investigate the performance gains of diversity on VLC network performance. It is found that this diversity is able to improve the performance of VLC system in terms of received power gain and bit error rate (BER) reduction. Specifically, gains of a bout 45 nW (0.1 dBm) can be obtained at high modulation bandwidths over 3 GHz. In addition, the simulation shows nearly 0 BER over 100 MHz in most areas of the room, except the corners, where BER is as much as 0.16.

Developing high-speed and reliable links is one of the goals of research on communication systems. Multicarrier modulation is an effective technique offering high data rate as well as mitigating ISI. The core idea is to divide the data stream into several substreams and dividing the frequency band into multiple subbands. Substreams are transmitted over independent subbands. Orthogonal frequency-division multiplexing (OFDM) is the most popular multicarrier technology that can be applied to VLC for high data rate and ISI mitigation. Especially for VLC with multiple transmitters, OFDM is one of the best choices to tackle the problem of ISI. In [11], an experimental system is implemented for LED-based VLC with intensity modulation in an indoor environment. The system is demonstrated with low BER within a range of 1 m. The performance could be better if error control coding was used in the experiment. Although OFDM has lots of advantages, it suffers from high peak-to-average ratio (PAR) due to the nonlinear attribute of LED, especially using intensity modulation. High PAR leads to a large dynamic range that hurts the energy efficiency at the receiver side. More important, it may hurt eyes. To alleviate this problem, clipped OFDM is derived from a bipolar OFDM waveform. To achieve the target BER of 2.5×10^{-5} with 3/4 channel coding rate at 1.7 V bias point, using binary phase shift keying (BPSK) can achieve 2 dB power backoff, and using 64-quadrature amplitude modulation (QAM) can achieve 5 dB power backoff [12].

In sum, these works try to overcome the high PAR problem by adopting signal processing technologies. Others tend to use approaches of other OFDM, such as single-carrier frequency-division multiple access (SC-FDMA), an uplink multiple access scheme for the Third Generation Partnershop Project (3GPP) Long Term Evolution (LTE) standard. SC-FDMA is applied to VLC as an alternative to OFDM to overcome the problem of high PAR. SC-FDMA has comparable BER performance to OFDM, while outperforming OFDM with low PAR.

VLC-Based Mobile Communication

LED-based fixed communication has been widely studied. The concepts have been demonstrated to work in practice. Many commercial products have even appeared in the market. However, LED-based mobile communications is less developed. Maintenance of LOS and alignment between transmitter and receiver are required in VLC systems to sustain data transmission service. In fact, these requirements are double-edged in that on one side, they achieve large coverage range and keep the communication from eavesdropping; on the other side, it is not proper for mobility applications. Since the light source of VLC is highly directional and has narrow beamwidth, it is extremely difficulty to maintain these VLC requirements in mobile scenarios. In this section, the problems of applying LED-based VLC to a mobile environment are presented, and existing solutions are discussed.

Spherical LED

Spherical LED is a design in which a node covered with multiple transmitters and receivers in order to enable LED-based mobile communications. In [13], they propose a spherical free space optical (FSO) that maintains optical links and enables mobility by covering spherical surfaces with inexpensive multiple transmitters (e.g., LED) and receivers (e.g., photo-detector, PD) modules and an auto-configuring circuit. A spherical FSO node provides angular diversity in three dimensions, and hence provides LOS at any orientation as long as there are no obstacles between the communicating nodes. The auto-configurable circuit monitors the LOS between two nodes, and regulates the LEDs to maintain an LOS path.

There is a basic restriction for LED-based VLC, where the communication system has to keep LOS between the transmitter and receivers. However, when it comes to the mobile environment, two cases will break the restriction. One is that the transmitter does not point to the receiver; the other one is that obstacles appear right on the LOS path. For RF, the omnidirectional antenna or antenna with wide beamwidth solves this problem. For LED-based communication, one of the solutions is to resemble the omnidirectional antenna by allocating multiple transmitters and receivers on a sphere node. Nevertheless, developing an omnidirectional-like node is not perfect. It suffers from low energy efficiency, since power is radiated in all directions equally, but only a few directions have users' requests for services. To reduce the energy cost in an RF system, smart antennas with automatic adaptation of beamforming are developed. In [14], with a similar idea to adapt the beamforming of spherical FSO nodes, they propose an auto-configurable circuit to monitor the LOS between two communicating spherical FSO nodes. In addition to the support of mobile communication, the design of spherical LED also extends the system coverage. In a 5 m/s mobile setting, a spherical node with four transceivers can achieve throughput close to 1000 Mbytes/s. In 0.2 km visibility setting, the throughput is about 500 Mbytes/s.

Camera-Based Visual MIMO

Camera-based visual multiple-input multiple-output (MIMO) is a novel solution developed recently for mobile VLC [15, 16]. To understand the motivation of this solution, some fundamental properties of RF and VLC should be considered. The main difference between them is that RF has wide beamwidth, but VLC's beamwidth is narrow. The beamwidth highly affects the system's mobility. Since RF has wide beamwidth, receivers have a wide range of angles of view that enable them to receive the signal in the mobile environment. On the contrary, LED receivers with narrow beamwidth have limited angles of views, so a small misalignment between a transmitter and a receiver can easily disrupt the communication.

The approach of spherical LED helps in that the beamwidth is enlarged in every direction by multiple transmitters and receivers employed around the node. However, the by-product problems of spherical LED are the loss of security and reliability inherent in narrow beamwidth. Some solutions attempt to keep the property of narrow beamwidth by using a steering mechanical system to track the transmitter and maintain alignment. Nevertheless, the steering system is usually too expensive to deploy in the public communication system. For the development of advanced electrical technology and computer vision, a camera-based receiver with a computer vision enabled steering system provides a novel solution.

To overcome the limitation of VLC in a mobile environment, in [15], the authors propose a visual MIMO system with a camera receiver and LED transmitter arrays for VLC. Compared to a photodiode receiver array, a camera receiver provides far more highly directional receiver elements to achieve highly dense MIMO, because each pixel can serve as one element of the receiver. Although the frame rate of the camera limits the transmission speed, the large number of camera pixels can alleviate this limitation by offering multiple channels for parallel transmission. Instead of using complex mechanical steering, computer vision provides low-cost tracking with high processing speed. With wide use of LEDs in vehicles and traffic lights, an application of visual MIMO for automotive safety with warning message display is demonstrated in practice [16].

Conclusion

This article provides an investigation of modern research progress on VLC for future 5G communications. These literature works are categorized into two portions: VLC-based fixed and mobile communications. For VLC-based fixed communications, we summarize the current VLC indoor applications and ISI mitigation technologies. For VLC-based mobile communications, we present the challenges of using VLC in a mobile environment and summarize recently proposed solutions. This work also reviews the strengths and weaknesses of VLC systems, and investigates the lighting sources that have been proposed for VLC networking.

Acknowledgment

This work was generously supported by the National Science Foundation through awards ECCS#1408165, CNS#1429120, and CNS#1451629. Any opinions, findings, and conclusions or recommendations expressed in this article are those of the author(s) and do not necessarily reflect the views of the National Science Foundation. This research was supported by "The Cross-Ministry Giga KOREA Project" of The Ministry of Science, ICT and Future Planning, (GK13P0100, Development of Tele-Experience Service SW Platform based on Giga Media), Korea.

References

[1] M. Chen *et al.*, "A Survey of Recent Developments in Home M2M Networks," *IEEE Commun. Surveys and Tutorials*, vol. 16, no. 1, Feb. 2014, pp. 98–114.
[2] D. Tsonev, S. Videv, and H. Haas, "Light Fidelity (LI-FI): Towards All-Optical Networking," *SPIE OPTO*, Int'l. Society for Optics and Photonics, 2013, pp. 702–900.
[3] H. Willebrand and B. S. Ghuman, *Free Space Optics*, 1st ed., Sams Pubs, 2001.
[4] T. Komine and M. Nakagawa, "Fundamental Analysis for Visible-Light Communication System Using LED Lights," *IEEE Trans. Consumer Electron.*, vol. 50, 2004, pp. 100–107.
[5] D. Tronghop *et al.*, "Modeling and Analysis of the Wireless Channel Formed by LED Angle in Visible Light Communication," *2012 Int'l. Conf. Info. Networking*, 2012, pp. 354–57.
[6] Y. Tanaka *et al.*, "Brightness Control Methods for Illumination and Visible-Light Communication Systems," *Proc. 3rd Int'l. Conf. Wireless and Mobile Commun.*, 2007, pp. 78–84.
[7] T. Komine and M. Nakagawa, "Integrated System of White LED Visible-Light Communication and Power-Line Communication," *IEEE Trans. Consumer Electron.*, 2003, pp. 71–79.

[8] —, "Visible Light Communication Systems Conception and Vidas," *IETE Tech. Rev.*, vol. 25, 2008, pp. 359–67.
[9] T. D. C. Little *et al.*, "Using LED Lighting for Ubiquitous Indoor Wireless Networking," *Proc. 2008 IEEE Int'l. Conf. Wireless and Mobile Computing, Networking and Commun.*, 2008, pp. 1/1–1/6.
[10] G. B. Prince and T. D. C. Little, "On the Performance Gains of Cooperative Transmission Concepts in Intensity Modulated Direct Detection Visible Light Communication Networks," *2010 6th Int'l. Conf. Wireless and Mobile Communi.*, pp. 297–302, 2010.
[11] M. Z. Afgani *et al.*, "Visible Light Communication Using OFDM," *Proc. IEEE TridentCom*, 2006, pp. 134–38.
[12] H. Elgala *et al.*, "Predistortion in Optical Wireless Transmission Using OFDM," *9th Int'l. Conf. Hybrid Intelligent Systems*, 2009, pp. 184–89.
[13] B. Nakhkoob *et al.*, "Multi-Transceiver Optical Wireless Spherical Structures for MANETs," *IEEE JSAC*, 2009, pp. 1612–22.
[14] M. Yuksel *et al.*, "Free-Space-Optical Mobile Ad Hoc Networks: Auto-Configurable Building Blocks, Wireless Networks," *Wireless Networks*, 2009, pp. 295–312.
[15] A. Ashok *et al.*, "Challenge: Mobile Optical Networks through Visual MIMO," *Proc. ACM MobiCom '10*, 2010, pp. 105–12.
[16] —, "Demo: Visual MIMO Based LED — Camera Communication Applied to Automobile Safety," *Proc. ACM MobiCom '11*, 2011, pp. 383–84.

Biographies

SHAOEN WU [M'09] (swu@bsu.edu) received a Ph.D. in computer science in 2008 from Auburn University. He is presently an assistant professor of computer science at Ball State University. He has held an assistant professor position in the School of Computing at the University of Southern Mississippi, a researcher scientist position at ADTRAN Inc., and a senior software engineer position at Bell Laboratories. His current research is in the areas of wireless and mobile networking, cyber security, cyber-physical systems, and cloud computing. He is a recipient of Best Paper Awards at IEEE ISCC 2008 and ANSS 2011. He has served as Chair, and on the committees and editorial boards of several international conferences and journals. More information is available at http://www.cs.bsu.edu/~swu

HONGGANG WANG [SM'12] (hwang1@umassd.edu) received his Ph.D. in computer engineering from the University of Nebraska-Lincoln in 2009. He is an assistant professor at the University of Massachusetts, Dartmouth and is an affiliated faculty member of the Advanced Telecommunications Engineering Laboratory at the University of Nebraska-Lincoln. His research interests include wireless healthcare, body area networks, multimedia sensor networks, mobile multimedia and cyber security, wireless networks, and cyber-physical systems. He has published more than 90 papers in his research areas, including more than 30 publications in prestigious IEEE journals. He is the winner of the Best Paper Award of WCNC '08. He has served as an Editor and a Chair for a number of international journals and conferences.

CHAN-HYUN YOUN [S'84, M'87] (chyoun@kaist.ac.kr) received his B.Sc. and M.Sc. degrees in electronics engineering from Kyungpook National University, Daegu, Korea, in 1981 and 1985, respectively. He also received a Ph.D. in electrical and communications engineering from Tohoku University, Japan, in 1994. Since 2009, he has been a professor with the Department of Electrical Engineering at Korea Advanced Institute of Science and Technology, Daejeon, Korea (KAIST). Currently, he is an associate vice-president of the Office of Planning and Budget at KAIST and also a director of the Grid Middleware Research Center, respectively. He was an Editor-in-Chief for the Korea Information Processing Society, is serving as an Editor of the U.K. *Journal of Healthcare Engineering*, and served head of the Korea branch (computer section) of IEICE, Japan (2009, 2010).