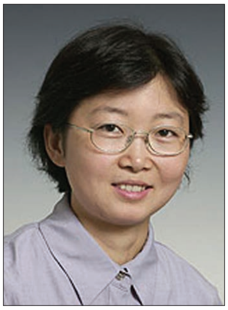
Guest Editorial

Visible Light Communications: Demand Factors, Benefits and Opportunities





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Visible light communications (VLC) is an emerging field of optical communications that focuses on the part of the electromagnetic spectrum that humans can see. Much existing work in optical communications exists, mainly optimized for capacity and transmission performance in fiber and free-space with biases toward spectrum that minimizes attenuation in the medium. However, the use of the visible spectrum has gained interest due to its availability and the ease at which it can be modulated using light emitting diodes (LEDs). Recent demand factors due to the burgeoning mobile industry and the rapid evolution of LED-based lighting are also driving this interest. Here, and in this special issue, we outline the context of VLC, its unique benefits, and describe the state of the art research contributions of the assembled papers.

Demand Factors

The potential for VLC is being driven by the increasing adoption of mobile electronic devices. The demand for wireless capacity as predicted most recently by Cisco (Cisco VNI, Feb 2015) indicates a 10x growth in mobile traffic over the next five years. But over the same time period, mobile carrier speed is predicted to grow by only 9 percent. Because more than 70 percent of all mobile traffic occurs indoors, and much occurs at fixed locations, there is a huge opportunity to offload traffic to localized access points as WiFi or small cells. Key to this technology is the placement of access points where mobile users are active but also to reconcile contention caused by these populous indoor spaces. The problems with contention are where VLC can provide significant benefits over RF technologies. VLC can provide very high data rates when used directly as a directional medium. When combined with a lighting mission — providing light — VLC is ideally suited for where humans exist in these indoor spaces because they consume light at the same time that they consume data.

Basics of VLC and Benefits

In its basic form, VLC uses light that is intensity modulated to transmit data. LEDs are inexpensive, fast, and are widely adopted in lighting, and hence VLC is and ideal match in lighting systems using LEDs. Because of their efficiency as compared to other lighting sources, LEDs appear in many applications in lighting and display including traffic lights, flat panel displays, and instrumentation. In this sense, any LED-based applications fall into the category of "green" technologies.

In terms of communications, LEDs are "fast" in that they can be intensity modulated very quickly (order of MHz), much faster than conventional lighting. At a receiver, the signals are sensed as intensities via "direct detection" using a photo detector that can be very inexpensive. Modulation formats in VLC vary extensively, and their optimization under different application scenarios is an active area of research. This work is unique because unlike RF modulation, optical signals are unipolar due to the nature of the intensity-modulated signal.

VLC has some interesting characteristics that are unique to optical communications systems. Light-based systems are confined by opaque walls and thus improve security and enhance reused of the channel in densely packed cells (e.g. adjacent rooms in an office). However, this does not mean that VLC is a strict line-of-sight technology; it has been shown that VLC also works when the light in a room is severely obstructed. Nor does VLC interfere with RF; VLC can be added to an existing network without introducing new interference. Moreover, in cases when RF signals are perceived as a hazard, for example, in hospitals, airplanes, mines, or as RF "pollution," VLC can be applied as a practical alternative. Due to its directionality and containment properties, VLC is also a good candidate for near field communications (NFC). VLC is also a contender for providing "indoor" GPS. Light-based positioning and localization is being explored by a variety of researchers as potentially more accurate and more easily deployed than RF or acoustic techniques.

Future and Summary

What does the future hold for VLC? While traditionally VLC had been conceived as a point-to-point, cable replacement technique, there are many works that highlight that VLC has the potential to augment cellular communications by providing a means to decrease the cell sizes in cellular communications even further without incurring significant installation cost by piggy-backing on existing lighting infrastructure. This is especially important as current research into 5G suggests that typical cell sizes will be around 50 m, which will pose severe challenges on backhaul and infrastructure deployment. As LEDs increasingly displace incandescent lighting over the next few years, general applications of VLC technology are expected to include Internet-of-Things, wireless Internet access, vehicle-to-vehicle communications, broadcast from LED signage, machine-to-machine communications, positioning systems, and navigation. The long lifetime of LED lights means infrequent replacement of lights, resulting in the need for new business models in the lighting industry, and we see light-as-a-service (LAAS) being introduced, especially as it relates to the adoption of new integration of lighting as controllable devices, each with its own Internet address.

ARTICLES

However, there are still many unsolved issues. The objective of this Feature Topic is to present a collection of articles focusing on the state of the art in visible light communications. Our Call for Papers attracted many submissions worldwide. After a rigorous review process, 13 papers were selected that best fit the theme of this Feature Topic. These cover a broad spectrum of research topics including network protocol and network architecture for VLC, practical applications with VLC systems, new modulation methods for VLC systems, and new materials, components, and devices for VLC.

In the first article, "Visible Light Communications in Heterogeneous Networks: Paving the Way for User-Centric Design" by Rong Zhang *et al.*, the authors introduce the user-centric design of VLC for heterogeneous networks (HetNet), with special emphasize on three key aspects, namely its signal coverage quality, system control, and service provision. Both the traditional and the user-centric VLC cell formation are discussed. Additionally, the user-centric design of VLC in the holistic HetNet environment and a range of open challenges are discussed.

In the second article, "A Practical In-home Illumination Consideration to Reduce Data Rate Fluctuation in Visible Light Communication" by C. W. Chow *et al.*, the authors investigate joint illumination and communication systems to provide an in-home lighting and VLC system. The illumination constraints set by different lighting conditions are analyzed considering different kinds of commercially available luminaries, beam angles, LED lamp arrangements and reflections by different materials and colors. Besides, a white-light phosphor-based LED adaptive data rate VLC system is proposed and experimentally demonstrated. Based on the experimental results, an environment with reduced VLC data rate fluctuation can be achieved.

In the third article, "Grouped Modulation Scheme for LED Array Module in a Visible Light Communication System" by Aiying Yang *et al.*, the authors propose grouped modulation to generate multiple-level optical signals and enhance the data rate for LED array module based indoor visible light communication systems. The concept of grouped modulation is dividing the LEDs in an array module into smaller size groups and driving each group with a separate circuit. The results of the experiments on 2-grouped modulation demonstrate that the data rate can be enhanced and the performance of a VLC system can be improved. Furthermore, more groups and other modulation formats such as pulse position modulation (PPM) and overlapping pulse position modulation (OPPM) can be considered.

Although VLC is capable of concurrently providing communication as well as illumination, to make commercial implementation of VLC feasible, it is necessary to incorporate dimming schemes. The fourth article, "Dimming Schemes for Visible Light Communication (VLC): The State of Research" by Fahad Zafar *et al.*, presents the latest concepts and methodologies involved in dimming control of a VLC system. It gives a detailed overview of trending dimming schemes based on modulation and coding techniques. Adaptive techniques are described that can be implemented to enhance communication capacity together with the concepts involved in developing the driver circuitry that would facilitate the practical implementation of such schemes. Finally, future prospects along with the key areas requiring attention and improvement are characterized.

Many physical devices used in VLC systems exhibit nonlinear effects which can significantly degrade overall system performance. The fifth article, "Nonlinear Distortion Mitigation in Visible Light Communications" by Kai Ying *et al.*, summarizes topics related to the LED nonlinearity distortion mitigation in VLC systems. The authors present the modeling of LED nonlinearities followed by two major approaches for their mitigation: a waveform-specific mitigation and a waveform-agnostic mitigation. For the latter, optimal nonlinear mapping is considered for dynamic-range-limited nonlinearities together with the linearization approaches. Finally, challenges of nonlinear distortion mitigation in VLC are highlighted.

Advanced modulation formats are becoming increasingly important in VLC systems. In the sixth article, "Multi-band Carrier-less Amplitude and Phase Modulation for Band-limited Visible Light Communications Systems" by Paul Anthony Haigh *et al.*, the authors introduce a new modulation scheme into the VLC domain: multi-band carrier-less amplitude and phase modulation (m-CAP) and describe in detail its performance within the context of band-limited systems where m-CAP's considerable potential in achieving higher spectral efficiency is demonstrated.

In the seventh article, "DC-Informative Modulation for Visible Light Communications Under Lighting Constraints" by Qian Gao *et al.*, DC-informative modulation schemes are introduced as viable alternatives to conventional none DC-informative counterparts for multi-carrier visible light communication systems for the purpose of boosting the system energy efficiency. Optimal constellations are constructed either in time-domain or frequency-domain by compact sphere packing. Then several DC informative system architectures are proposed and compared. Finally, challenges in technical implementation are also discussed.

In the eighth article, "A High Performance Blue Filter for White LED Based Visible Light Communication System" by Shao-Wei Wang *et al.*, the authors introduce a high performance blue filter, which has a very wide stopband (500–1050 nm), high transmittance passband (average 97.5 percent in the blue signal range of 430–485nm), and sharp and precise cut-off edge. Employing this blue filter, BER performance of white LED VLC systems is shown to improve by two orders of magnitude compared with the no filter case.

The ninth article, "An Analog Modulator for 460 Mbit/s Visible Light Data Transmission based on OOK-NRZ Modulation" by Honglei Li *et al.*, describes an analog modulator that consists of modulation, metal oxide semiconductor field-effect transistor (MOSFET) drive, and pre-emphasis circuits for high-speed VLC application systems. The analog modulator successfully combines pre-emphasis and AC-coupled modulation technologies together. With the combination of blue-filtering, the proposed analog modulator extends the 3-dB bandwidth of VLC system from 3 MHz to 175 MHz, which allows on-off-keying non-return-to-zero (OOK-NRZ) data transmission up to 460 Mbit/s with bit-error-ratio (BER) below 10–9 under a 1 m radial distance.

In the tenth article, "Size- and Current-Density-Controlled Tunable Wavelength in GaN-Based LEDs for Potential Dense Wavelength-Division Multiplexing Application" by Dongdong Teng *et al.*, the authors design and fabricate an array of mLEDs with hybrid pixel sizes from 30mm~60mm. Wavelength shift accompanying the size and current density variations are investigated. A wavelength tunable range of 20 nm is obtained, which endows the device potential as a tunable light source to enable dense wavelength division multiplex (DWDM) technology for visible light communication (VLC) application. In addition, the full width at half maximum (FWHM) of the complex spectrum broadens from 16 nm to 45 nm which can increase lighting quality.

In the eleventh article, "Ubiquitous 3-D Positioning Systems by LED-based Visible Light Communications" by Jaechan Lim, the author presents a brief overview of positioning approaches in VLC systems, and shows enhancements in positioning performance by employing an iterative maximum likelihood approach using a least-squares solution as an initial guess. This work shows the possibility of obtaining MSE performance of the iterative ML approach that is similar to the Cramer-Rao bound.

In the twelfth article, "Efficient Coding Modulation and Seamless Rate Adaptation for Visible Light Communications," by Min Wang *et al.*, an analog rateless code (ARC) modulation scheme is proposed for VLC in a hybrid VLC-RF system, which can simultaneously improve spectral efficiency and enhance robustness in dynamic lighting scenarios. The author analyzes how to select a good weight set and design a mapping matrix. A new weight set suitable for VLC systems is given. Finally, simulation and experiment results show the proposed weight set and mapping matrix achieve obvious gain, and the proposed adaptive scheme works well in practical VLC systems.

In the thirteenth article, "An Open-Source Research Platform for Embedded Visible Light Networking" by Qing Wang *et al.*, an open-source research platform called OpenVLC is introduced based on software-defined implementation. It offers a basic physical layer, a set of essential medium access primitives, as well as interoperability with Internet protocols. OpenVLC is designed to demystify VLC and lower the barriers to entry to VLC research for embedded system researchers.

BIOGRAPHIES

NAN CHI (nanchi@fudan.edu.cn) received the BS degree and Ph.D. degree in electrical engineering from Beijing University of Posts and Telecommunications, Beijing, China in 1996 and 2001, respectively. From July 2001 to December 2004, she was an assistant professor at the Research Center COM, Technical University of Denmark. From January 2005 to April 2006 she was a research associate at the University of Bristol, United Kingdom. In June 2006 she joined Wuhan National Laboratory for Optoelectronics, Huazhong University of Science and Technology, where she worked as a full professor. She joined Fudan University in June 2008, in the School of Information Science and Engineering. She is the author or co-author of more than 200 papers. She has been the chair of the APOC 2007 OSRT workshop and ACP 2010. She has served as the technical program committee member of many conferences such as APOC 08, ICAIT09, ACP 2011, WOCC 2012, ACP 2013, and IWOO 2014. She has been awarded the New Century Excellent Talents Awards from the Education Ministry of China, Shanghai Shu Guang scholarship, Japanese OKAWA intelligence Fund Award, Pujiang talent of Shanghai City, and Ten Outstanding IT Young Persons awards of Shanghai City. Her research interests are in the area of coherent optical transmission, visible light communication, and optical packet/burst switching.

HARALD HAAS received the Ph.D. degree from the University of Edinburgh in 2001. He currently holds the Chair of Mobile Communications at the University of Edinburgh. His main research interests are in optical wireless communications, hybrid optical wireless and RF communications, spatial modulation, and interference coordination in wireless networks. He first introduced spatial modulation. He was an invited speaker at TED Global 2011, where he coined the term 'Li-Fi.' His talk has been watched online more than 1.5 million times. He is co-founder and chief scientific officer (CSO) of pureLiFi Ltd. Professor Haas holds 31 patents and has more than 30 pending patent applications. He has published 300 conference and journal papers including a paper in *Science*. He was co-recipient of a best paper award at the IEEE Vehicular Technology Conference in Las Vegas in 2013. In 2012, he received the prestigious Established Career Fellowship from the EPSRC (Engineering and Physical Sciences Research Council) within Information and Communications Technology in the UK. He is the recipient of the Tam Dalyell Prize 2013 awarded by the University of Edinburgh for excellence in engaging the public with science. In 2014 he was selected by EPSRC as one of ten RISE (Recognising Inspirational Scientists and Engineers) Leaders.

MOHSEN KAVEHRAD completed his Ph.D. degree at New York University Polytechnic (formerly Brooklyn Polytechnic Institute), Brooklyn, New York in electrical engineering in November 1977. Between January 1978 and March 1989 he worked on telecommunications and networking problems for Fairchild Industries, GTE (Satellite and Labs.) and AT&T Bell Laboratories. In 1989 he joined the University of Ottawa Electrical Engineering Department as a full professor. Since January 1997 he has been with the Pennsylvania State University Electrical Engineering Department as the W.L. Weiss Chair Professor and founding Director of the Center for Information and Communications Technology Research. He is a Fellow of the IEEE for his contributions to wireless communications and optical networking. He received three Bell Labs awards for his contributions to wireless communications, the 1990 TRIO feedback award for a patent on an optical interconnect, the 2001 IEEE VTS Neal Shepherd best paper award, three IEEE Lasers and Electro-Optics Society best paper awards between 1991 and 1995, and a Canada NSERC Ph.D.-thesis award in 1995 with his graduate students for contributions to wireless systems and optical networks. He also received the 2009 DesignCon Paper Award in the High-Speed and RF Design Category, and the Paper of the Year Award from *ETRI Journal* in December of 2009. He has close to 400 published papers, several book chapters, books, and patents in these areas. His research interests are in the areas of communications networked systems of all types. He is a former technical editor for *IEEE Transactions on Communications*, *IEEE Communications Magazine*, and the *IEEE Magazine of Lightwave Telecommunications Systems*. He served as the General Chair of leading IEEE conferences and workshops. He has chaired, organized, and been on the advisory committee for several international conferences and workshops.

THOMAS DC LITTLE received his BS degree in biomedical engineering from RPI in 1983, and his MS degree in electrical engineering and Ph.D. degree in computer engineering from Syracuse University in 1989 and 1991, respectively. Currently a professor in the Department of Electrical and Computer Engineering at Boston University, he is also Associate Dean for Educational Initiatives for the college, and serves as associate director of the National Science Foundation Smart Lighting Engineering Research Center, a collaboration of Rensselaer Polytechnic Institute, the University of New Mexico, and Boston University. His recent efforts address research in pervasive computing using wireless technologies. This includes video streaming, optical communications with the visible spectrum, and applications related to ecological sensing, vehicular networks, and wireless healthcare. He is a successful entrepreneur and most recently nurtured the spinoff of Bytelight, a company focused on indoor positioning with lighting. He is a Senior Member of the IEEE, a member of the IEEE Computer and Communications Societies, and a member of the Association for Computing Machinery.

XIN-LIN HUANG [S'09, M'12] received the M.E. and Ph.D. degrees in the Department of Information and Communication Engineering from Harbin Institute of Technology (HIT), Harbin, P. R. China, in 2008 and 2011, respectively. He is currently an associate professor in the Department of Information and Communication Engineering, Tongji University, Shanghai, P. R. China. His research focuses on cognitive radio, cognitive networks, machine learning, VANET, OFDM technology, and massive MIMO feedback. He has published over 40 research papers, two patents, and three book chapters in these fields. He was a recipient of Chinese Government Award for Outstanding Ph.D. Students in 2010, Best Ph.D. Dissertation Award from HIT in 2013, Shanghai High-level Overseas Talent Program in 2013, and Shanghai "Chenguang" Scholar Program in 2014. From August 2010 to September 2011 he was supported by the China Scholarship Council to do research in the Department of Electrical and Computer Engineering, University of Alabama (USA), as a visiting scholar. He was invited to serve as session chair for IEEE ICC2014. He also serves as IG leader for the IEEE ComSoc-MMTC. He is a paper reviewer for *IEEE Transactions on Wireless Communications*, *IEEE Transactions on Signal Processing*, *IEEE Transactions on Vehicular Technology*, *IEEE System Journal*, *IEEE Communications Letters*, *Computer Communications*, *Wireless Personal Communications*, and the *International Journal of Communication Systems*.