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# Guest Editorial: Localisation, Communication and Networking with VLC

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## I. Introduction

We are at the dawn of an era in information and communication technology with unprecedented demand for connected and automated everything. Both Shannon theories and industrial advances have clearly evidenced that more densely packed networks and a much wider operating bandwidth are key drivers for meeting the escalating tele-traffic demands. Recently, there have been substantial research efforts on the exploitation of higher frequency bands, in particular the millimetre wave and optical wireless band. After a decade of active research and developments and along with the maturity of devices, Visible Light Communication (VLC) has emerged as a very promising technology to enable next generation digital innovations and support wide range of applications. This timely special issue is on "Localisation, Communication and Networking with VLC", where the three aspects are purposely selected to reflect the main thrusts of VLC research. The overall aim of this special issue is to inspire multi-disciplinary international communities to work together in order to achieve further research advances. Indeed, a total of 96 high quality papers have been received from both academia and industry. After careful peer-reviewing process, 17 papers have been selected based on their combined novelty, rigour and importance. Owing to the highly selective nature of JSAC, other interesting papers are not included in this special issue, but we hope those papers would be published in equally prestigious venues.

This special issue pays balanced attention to the aspects of localisation, communication and networking. It also puts emphasise on both theoretical and experimental based research. This special issue includes interesting developments of VLC for accurate indoor localisation with practical considerations. Similarly, rigorous studies on VLC under realistic scenarios are also reflected in the physical layer, in terms of dimming control and timing synchronisation. Research on signal processing for VLC has been inspired by new concepts that have advanced the Radio Frequency (RF) communication. It is paramount that these designs remain tailored towards the specifics of VLC transceivers and channels. This special issue has seen this trend continue and it features the latest results from optical Orthogonal Frequency Division Multiplexing (OFDM) and optical Multi-Input Multi-Output (MIMO) research studies. For the networking aspect, interesting papers are included with focuses on multi-element VLC networks, novel cell constructions of VLC and importantly, the physical layer security as well as the reliability of VLC networks. Lastly, this special issue also covers papers addressing a variety of VLC applications, ranging from VLC based energy transfer to VLC for industrial automation, from underwater VLC to camera communication. We believe that these collections are intriguing to the growing research and development activities at the international scale for both the VLC domain and beyond.

## II. Accepted Papers

### A. Localisation

Indoor localisation is one of the most practical uses of VLC, with commercialisation activities now emerging. The paper "Three-Dimensional VLC Positioning Based on Angle Difference of Arrival With Arbitrary Tilting Angle of Receiver" proposes a novel indoor VLC positioning method based on the Angle Difference Of Arrival (ADOA), which is capable of relaxing several pre-existed overly simplified assumptions, particularly the need of confined alignment between transmitter and receiver. The key idea is to exploit the invariability of ADOA in any arbitrarily rotated three-dimensional coordinate systems. This property allows the accurate positioning under arbitrary titling of the receiver. The authors also contribute to theoretically derive the bound of ADOA based positioning and practically design algorithms with both low and high complexity. Both numerical simulations and experiments show centimeter level of positioning accuracy when using the higher-complexity algorithm, whilst decimeter level of positioning accuracy is achieved when using the lower-complexity alternative. These designs will make VLC positioning much closer to its practical use for meeting diverse real-world needs.

Most of the current VLC positioning inevitably require the full knowledge of Received Signal Strength (RSS) values. To relax such a limitation, the paper "A 3D Positioning Algorithm for AOA-Based VLP with an Aperture-Based Receiver" studies indoor VLC positioning based on triangulation method with aperture-based receivers. The author specifically designs these receivers to have beneficial angle diversity, which allows the Angle Of Arrival (AOA) to be extracted by comparing the relative differences of the RSS values from different receiver elements, without knowing their absolute values. To achieve this, an iterative approach is adopted based on maximum likelihood criteria, consisting of coarse positioning estimates and followed by iterative positioning refinements. Accordingly, centimeter level of positioning accuracy is achieved in the entire room as shown by simulation results. This design is thus highly inspiring, particularly in the absence of stable and accurate RSS values of complex indoor scenarios.

Relaxing the need of accurate RSS values advocated in the above paper is achieved by equipping aperture-based receivers.

For conventional receivers, the paper "Coding and Bounds for Channel Estimation in Visible Light Communications and Positioning" designs pilot codes for achieving minimum noise variance of the channel gain estimates in multi-user environments. Under both the maximum and average optical power constraints, the authors contribute to derive the theoretical criteria for optimal pilot codes and propose so-called combinatorial codes as a particular realisation. This paper further studies the bound on trade-off between the noise variance of channel gain estimates and pilot code length. By numerical comparisons, the proposed code is found close to optimal and superior than benchmark, in terms of both the mean square error of channel gain estimates and the positioning performance. The overall contributions of this paper will be highly useful to draw insights when obtaining channel gain estimates for the inter-linked functions of positioning and communication.

### *B. Communication*

VLC has several modulation schemes that are unique and open to design, since they need to take into account dimming control and flickering mitigation, in addition to spectral and power efficiency. To this end, the paper "Hybrid PWM/DPAM Dimming Control for Digital Color Shift Keying Using RGB-LED Array" studies the dimming control issue of Digital Color Shift Keying (DCSK), a unique digital modulation scheme for VLC that alleviates undesirable Light Emitting Diodes (LED) non-linearities. In this paper, a new hybrid dimming control method is proposed for DCSK, by combining Pulse Width Modulation (PWM) and Digitally controlled Pulse Amplitude Modulation (DPAM). This method is shown to be superior than PWM in terms of spectral efficiency and at the same time exhibiting a wider dimming range than DPAM. Indeed, this hybrid design can provide a much higher flexibility than the state-of-the-art and it is also easy to be integrated with RGB-LED array, with zero-touch at the receiver, making the advocated scheme highly appealing.

Different from considering the dimming control, the paper "Robust and Low-Complexity Timing Synchronization for DCO-OFDM LiFi Systems" delves into the under-explored timing synchronisation problem for VLC. Most of the existing papers make idealised assumptions on this aspect, while the authors propose a low-complexity decoupled approach, consisting of frame detection first and followed by joint sampling clock synchronisation and channel estimation for multi-carrier VLC system. Various algorithms are proposed for frame detection and Cramér-Rao Bound (CRB) is also derived. This bound guides the training sequence design to balance the energy efficiency, spectral efficiency, complexity and estimation performance. Simulation results show that the performance of the proposed timing synchronisation is close to that of the idealised case and the proposed algorithms are able to outperform the state-of-the-art. Considering these practical issues will reveal the true VLC system performance, which will impact its real-world adoption.

Continued advances in VLC are inspired by fundamental breakthroughs in signal processing. An excellent example is the paper "Transceiver Design for MIMO VLC Systems with Integer-Forcing Receivers". The authors design the Integer Forcing (IF) transceiver for MIMO VLC system. IF is a new modulo-based non-linear transceiver structure that can achieve a high MIMO channel capacity with low decoding complexity. The authors tackle the challenge of designing invertible integer matrix over one-dimensional lattice, which allows a better performance to be achieved than opting for the conventional lattice reduction methods. Powerful iterative optimisation of the transceiver matrices and the integer matrix is then carried out, by considering the real-valued and non-negative input constraints as well as the optical power constraint. The design is further complemented by a complexity analysis. Simulation results also show great performance gains over straightforward adoptions of IF for MIMO VLC. Indeed, the unique properties of VLC create many open design challenges that lead to exciting signal processing advances.

Depart from the point-to-point VLC system, the paper "Block Precoding For Peak-Limited MISO Broadcast VLC: Constellation-Optimal Structure and Addition-Unique Designs" targets at cooperatively managing multi-user interference by constructing an energy efficient space-time modulation scheme for peak-power-limited multi-user Multi-Input Single-Output (MISO) VLC system. This paper characterises the underlying structure for such design and proposes both linear and non-linear block coded multi-dimensional modulation schemes corresponding to integer and non-integer bit rate requirements, respectively. The resultant codeword exhibits additively and uniquely decomposable property, such that the combined multi-user codeword would be easily detectable from its noisy observation and the constituent individual user's codeword would then be easily retrieved. This design is shown to outperform the classic Zero Forcing (ZF) and Minimum Mean Square Error (MMSE) pre-coding schemes and the orthogonal access scheme, such as the Time Division Multiple Access (TDMA), in terms of average bit error rate. This is indeed an intriguing design by bringing network coding inspired idea into the VLC domain.

Under the same multi-user MISO VLC regime, the paper "Aligning the Light without Channel State Information for Visible Light Communications" proposes an alternative approach to classic transmit pre-coding schemes. Explicitly, the authors design a so-called Blind Interference Alignment (BIA) scheme without the need of transmitter cooperation and it can be operated by dispensing with the channel state information at transmitter. Reminiscent to the reconfigurable antennas in RF domain, a novel reconfigurable Photo-Detector (PD) is devised that is capable of providing linearly independent channel responses to facilitate the BIA. Compared to its RF counterpart, the newly modified scheme is trailered specifically under various VLC constraints, including non-negativity and constant illumination. This paper provides detailed elaborations on the design of reconfigurable PD and BIA under various network topologies. Simulation results show that the advocated design exhibits a more fairly distributed rate per user and provides similar throughput when compared to the conventional pre-coding schemes.

The practice of MIMO-OFDM in RF domain is also highly

relevant for VLC based broadband access. When considering multi-carrier VLC for achieving high throughput, the paper "Biased Multi-LED Beamforming for Multicarrier Visible Light Communications" jointly designs the biasing of multiple distributed LEDs and the beam-forming vector at each sub-carrier for a Direct Current Optical OFDM (DCO-OFDM) system. Typically, biasing and beam-forming are treated separately, while this paper analyses the multi-LED clipping distortion and accordingly derives the underlying beam-forming structure. These theoretical contributions allow the development of a so-called biased beam-forming with optimal solutions in closed-form for flat channels and near-optimal solutions for dispersive channels. Again, simulation results show superior performance of the biased beam-forming when compared to the separate biasing and beam-forming approach previously adopted in the literature, in terms of both data rate and bit error rate.

### *C. Networking*

Similar to the communication aspect of VLC, there are lots of opportunities for the networking aspect. The paper "Multi-Element VLC Networks: LED Assignment, Power Control, and Optimum Combining" considers the joint problem of LED assignment and power control subject to Quality of Service (QoS) constraints and user-fairness. Specifically, the authors employ an efficient computation method to generate the dispersive optical channels and adopt a decoupled approach to solve the above joint optimisation problem. Owing to its NP hardness, several heuristics are thus proposed with significantly reduced complexity. The novelty of this paper becomes more significant when receiver combining is co-designed with the LED assignment and power control, where the authors propose different solutions with or without the knowledge of LED assignment. Simulation results show the effectiveness of the proposed algorithms and demonstrate decent Signal to Noise Ratio (SNR) gains when employing receiver combining. It is worth noting that the authors clearly elaborate on how their algorithms would be implemented, which make their heuristics more plausible for engineering into practice.

Unlike the previous paper on associating LEDs and users in a very structured way, the paper "Joint User Association and Power Allocation for Cell-Free Visible Light Communication Networks" considers the same problem but in a cell-free and user-centric way. The idea is to allow the users to dynamically associate with any transmitters within their Field of View (FoV). The underlying problem is modelled as a non-convex network utility maximisation problem with several VLC specific constraints considered, including the optical power limitations and illumination requirements. An alternating optimisation method is adopted to solve the above problem by iteratively finding the association time fraction and power allocation. Simulation results show that adaptive-cell construction exhibits a higher sum rate than that of the fixed-cell structure and the proposed power allocation is indeed superior than all the benchmarks. An interesting finding for user-centric design is the near-uniform user-rate distribution, which is highly desirable in small cell network designs for both RF and VLC.

Reliability is an important design metric, which is especially true for VLC networking. The paper "In Light and In Darkness, In Motion and In Stillness: A Reliable and Adaptive Receiver for the Internet of Lights" tries to establish a reliable data link for VLC by equipping with two distinct optical receivers, namely the PD and LED, for providing extra diversities. By exploiting the complementary characteristics of these two receivers, for example the distinct optical spectral response and directionality, a greater immunity to blockage, mobility, external lights can be attained. The authors design and implement both the physical layer and link layer of such a dual receiver system. Interestingly, the receiver can switch between configurations dynamically by sensing the illumination environment. Small scale experiments are carried out under various directionality settings and different illumination environments. It is shown that the dual receiver is indeed much more robust than a standalone receiver based either on PD or LED. One additional benefit of the proposed system is its low cost, which is very appealing to the application of internet of lights. More desirably, the authors make both the hardware and software implementations of their design open source to attract further community developments.

Providing secure transmissions is just as important as aiming for high data rate and reliability. The paper "Physical-Layer Security in Multiuser Visible Light Communication Networks" analyses the physical layer security in a multi-user VLC network. Both the Access Points (APs) and users are modelled as Poisson point processes, which allows analytically tractable solutions by using stochastic geometry methodologies. Different from those analysis in RF domain using Shannon capacity formula, a more accurate and tighter channel capacity formula is used for VLC. The authors contribute to derive the security capacity with nearest AP serving strategy and optimal AP serving strategy. Based on these, they also propose a protection zone strategy to enhance the physical layer security. Closed form solutions in terms of outage probability and ergodic security capacity are obtained for non-cooperative AP scenarios, while bounds are obtained for cooperative APs. Numerical results are well agreed with the theoretical findings and the bounds derived are also quite tight. There have been increasing attentions on the physical layer security for VLC and hence this paper will have a wide readership.

### *D. Application*

This special issue features a variety of interesting applications that are key to the future development of VLC. The paper "Visible Light Multi-Gb/s Transmission Based on Resonant Cavity LED with Optical Energy Feed" experimentally demonstrates multi-Gbps data rates when using the off-the-shelf Resonant-Cavity LED (RC-LED), which is previously found only capable of supporting 150 Mbps data rates. This significant data rates enhancement is achieved by using Nyquist FDM and OFDM schemes with powerful bit-loading, where upto 256-QAM is capped at per sub-carrier. The authors further demonstrate 750 Mbps when employing simple on-off keying modulation, in conjunction with frequency equalisation

in analogue domain. In terms of reach, 20m distance is demonstrated using RC-LED to support a real-time High Definition (HD) video playback. In addition to achieve greater rate and reach, the authors also experimentally show the joint data transmission and energy transfer through the same optical channel using RC-LED with dedicated energy feed. It allows the optical receiver to switch between functions and access upto Gbps data rate in burst-mode, which is highly suitable for energy-passive terminals with sporadic data demands.

Another interesting application is VLC for industrial usage as discussed in the paper "Optical Wireless MIMO Experiments in an Industrial Environment". In this paper, the authors carry out channel measurements in BMW's robot testing facility and experimentally demonstrate a MIMO VLC set-up to support communication between industrial robots and the surroundings. VLC is employed thanks to its beneficial security advances, with no information leakage outside the testing facility. Instead of aiming for high data rate, the key performance indicator is determined to be the reliability and hence diversity becomes indispensable. Hence, the MIMO VLC set-up is experimentally demonstrated to be capable of supporting a range of constant movements and manoeuvres of the industrial robots at normal working condition, as otherwise significant loss in signal power and outage would be encountered when performing complex tasks without MIMO. Finally, the authors also elaborate on the design of a 10 Mbps VLC link that would potentially support video transmissions in industrial environment. This paper is pioneering in using VLC for manufacturing and the synergies will be inspiring to a range of important verticals.

As an increasingly promising use of VLC, the paper "Full-Fledged 10Base-T Ethernet Underwater Optical Wireless Communication System" conducts field-trial of VLC for underwater communication. The authors carefully design bi-directional VLC transceivers based on blue LED arrays and commercially available Avalanche Photodiode (APD). This design is first calibrated in a controlled lab condition, where detailed discussions of the optical modem is included and full characterisation of the water turbidity and background noise are recorded. It is then carried out in realistic underwater scenario, i.e. sea harbour, with high turbidity and strong ambient light. This is in contrast to most of the previous experiments under clear water conditions with idealised settings and low channel attenuations. Experimental results show that the advocated design is able to communicate at 10 Mbps at a distance of 7.5m in harsh sea environment. It is also predicted that 40m distance would be achieved at the same data rate in open and deep-water conditions, where lower attenuation and noise floor would be encountered.

The last paper "A Fixed-scale Pixelated MIMO Visible Light Communication System" proposes a fixed-scale pixelated MIMO based camera communication. The novel idea is to place a convex collimating lens in front of the focus of the transmitter and exploit the out-of-focus parts produced by the lens to obtain fixed-scale images at all distances to the receiver. Since the information is transmitted through spatial to angular mapping, this intrinsic design allows imminent use for display to camera communication, supporting moving receivers without the need of re-focusing. The authors carefully tune the design parameters and further use Raptor codes to improve link robustness in case of misalignment and rotation. Experimental results show that the overall design exhibits a higher multiplexing gain and greater reliability with a lower complexity when compared to the state-of-the-art. Upon the advances in consumer electronics, this direction of research would enable novel applications through camera communication.

## III. Future Direction

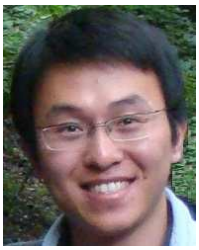
VLC is realized by innovations from novel materials fabricated into devices that become part of larger systems that bridge from end user applications, to networks and to physical communication. Research corresponds to these cross-disciplinary aspects span from small to large. A simple query on "visible light communications" to IEEE Xplore reveals more than 2,500 published papers. In the mean time, the standardization of VLC technologies is also actively ongoing by various international standardization bodies, such as the IEEE 802.15.7r1, ITU G.vlc and ITU G.occ. These activities cover many topics in physical layer communication, media access control layer protocols, networking topologies including the coexistence with WiFi. One could conclude that this area has become saturated with research and the emergence of consumer products signals that the most impactful technical challenges have been solved. When looking into the future, we list open challenges in Table I, which suggest that there is ample work ahead and there are considerable opportunities to advance VLC as a technology that will impact both niche and main-stream communication needs.

## IV. Acknowledgement

The guest editors would like to thank all the authors who submitted their valuable work to this special issue, especially whose papers are not included. Their collective contributions will have a long-lasting impact to the academia community. We would also like to thank all the reviewers for their dedicated time and quality reviews to the success of this special issue, especially in such a short period. We are also indebted to the Editor-in-Chief Prof Muriel Medard, the Executive Editor Laurel Greenidge and the Senior Editor Prof Admela Jukan in the preparation and mentoring process of this special issue.

TABLE I
OPEN CHALLENGES FOR VLC AND THEIR IMPACT

| | Research Area | Opportunities | Potential Impact |
|---|---|---|---|
| Localisation, Comm | LEDs and materials | Faster, more energy efficient materials for producing higher lm/W | Efficacy, energy efficiency, data rates |
| | PDs and materials | Faster, lower noise, more responsive more reliable, more adaptive | Greater flexibility in receiver design |
| | VLC luminaires | Combining lighting with VLC; use of multiple color bands; use of micro-LEDs | Improved control, energy efficiency, color rendering, more data channels |
| | VLC receivers | Supporting multiple WDM, FDM, TDM, SDM channels with a compact device | Greater capacity |
| Communication | Use of MIMO | Reconciling multiple LEDs and multiple luminaires; combined use of WDM | Greater capacity |
| | Beyond IM/DD | Use of coherent media; exploit larger capacity of light signal | Greater capacity |
| | Multiple access | Optimize WDM, TDM, FDM to provide best system performance | Greater user experienced rate |
| Networking | Mobility | Reconciling mobility of user devices, occlusions, user behavior | Greater user experienced rate |
| | Coexistence | Motivate how RF and VLC can complement each other for adoption | Best performance realized from different strengths |
| | Backhaul | Enable high capacity, dense and localized VLC to function in larger system | Continue to enable capacity growth in local network |
| | Internet of lights | Easy-to-integrate solutions for LED; simple modulation; NOMA | Massive connectivity |



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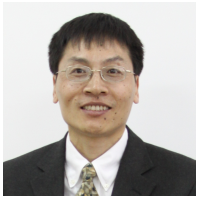

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