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Survey paper

# LANET: Visible-light ad hoc networks☆

Nan Cen[a,*], Jithin Jagannath[a], Simone Moretti[b], Zhangyu Guan[a], Tommaso Melodia[a]

[a] Department of Electrical and Computer Engineering, Northeastern University, Boston, MA 02115, United States
[b] Department of Electrical, Electronic and Information Engineering, University of Bologna, Italy

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ABSTRACT

Visible light communication (VLC) is a wireless technology complementary to well-understood radio frequency (RF) communication that is promising to help alleviate the spectrum crunch problem in overcrowded RF spectrum bands. While there has been significant advancement in recent years in understanding physical layer techniques for visible light point-to-point links, the core problem of developing efficient networking technology specialized for visible-light networks is substantially unaddressed.

This article discusses the current existing techniques as well as the main challenges for the design of *visible-light ad hoc networks* - referred to as LANETs. The paper discusses typical architectures and application scenarios for LANETs and highlights the major differences between LANETs and traditional mobile ad hoc networks (MANETs). Enabling technologies and design principles of LANETs are analyzed and existing work is surveyed following a layered approach. Open research issues in LANET design are also discussed, including long-range visible light communication, full-duplex LANET MAC, blockage-resistant routing, VLC-friendly TCP and software-defined prototyping, among others.

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## 1. Introduction

The proliferation of advanced multimedia devices and services is causing significant growth in demand for bandwidth and spectrum resources. While new portions of the radio frequency (RF) electromagnetic spectrum are being made available and are increasingly leveraged to meet this demand, RF communications inevitably suffer from problems including spectrum crunch, co-channel interference, vulnerability to eavesdroppers, among others [1,2]. Moreover, RF-based communications are not always permitted because of the potential dangerous effect of Electromagnetic Interference (EMI), which occurs when an external device generates radiations that affect electrical circuits through electromagnetic induction, electrostatic coupling, or conduction. For example, cellular and WiFi emissions are prohibited in airplanes during takeoff and landing because electromagnetic radiations can interfere with onboard radios and radars; electronic equipment can emit unintentional signals that allow eavesdroppers to reconstruct processed data at a distance by means of directional antennas and wideband receivers.

Optical communications have attracted significant attention as a valid alternative over legacy RF-based wireless communications. Optical communications are classified in two main categories, fiber-based and optical wireless communications (OWCs). Fiber-based systems are frequently employed in the backbone network cabling because of their robustness, reliability and high-rate in delivering large amounts of data. OWCs are rapidly growing in popularity as an emerging and promising wireless technology capable of high speed data transfer over short distances [3,4]. An optical wireless-based system relies on optical radiation to deliver information in free space, with wavelengths included in the Infra-red (IR), visible-light, and ultraviolet (UV) bands. In the last decades, OWCs have been deployed in medium to long communication distance environments, e.g., OWC has been applied for inter-chip connection as short-range transmission while visible light communication (VLC) found applications in medium-range indoor wireless access. Moreover, inter-building connections can be established using IR communications whereas ultraviolet communications (UVCs) have been recently adopted in outdoor non-line-of-sight scenarios and specifically for ad-hoc and wireless sensor networks (WSNs). Recently, satellite communications and deep-space applications based on OWC have been demonstrated, especially for military applications [5]. In particular, the recent rapid increase in the use of LEDs for lightning has paved the way for the develop-

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* Corresponding author.
*E-mail addresses:* ncen@ece.northeastern.edu (N. Cen), jjagannath@ece.northeastern.edu (J. Jagannath), simone.moretti6@unibo.it (S. Moretti), zguan@ece.northeastern.edu (Z. Guan), melodia@ece.northeastern.edu (T. Melodia).

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ment of new communication systems based on leveraging visible light as a communication medium. That is, LEDs can act as illumination devices as well as information transmitters at the same time, thus delivering data by digitally modulating the emitted light beam intensity at a very fast rate [6]. In this article, we discuss *challenges, basic principles, state-of-the-art, open research directions and possible solutions* in the design of *Visible-Light Ad Hoc Networks (LANETs)*, i.e., infrastructure-less (e.g., sensor, ad hoc) wireless networks based on visible light links.

A few survey papers on optical and visible light communications (VLCs) [7–14] have appeared in the past few years, *mainly focused on physical and link layers or specific VLC applications*. For example, in [7] Karunatilaka et al. discuss physical layer techniques to enhance the performance of LED-based indoor VLC systems, including modulation schemes and circuit design, among others. In [8], the authors survey existing VLC channel models and provide insights on the theoretical basis for VLC system design. In [9], Do and Yoo discuss existing VLC-based positioning systems, while in [10] the authors focus on VLC receiver design for automotive applications. In [15], Tsonev et al. survey the development of Li-Fi systems in cellular networks utilizing OFDM as well as link-layer schemes. Similarly, in [11] the authors review transmitter and receiver design for visible light communication systems, physical layer techniques, medium access techniques and visible light indoor applications (e.g., indoor localization, gesture recognition, among others). This article differs from the above-mentioned papers in the following ways: (i) We mainly focus on visible light ad hoc networking, which is substantially unexplored; (ii) we provide a comprehensive review of protocol design at all layers of the networking protocol stack; (iii) we discuss challenges and applications for visible light ad hoc networks; (iv) we discuss a potential software-defined visible light ad hoc network (LANET) architecture and discuss possible solutions to implement each component.

The rest of this paper is organized as follows. In Section 2, we provide a high-level comparison between LANETs and traditional MANETs, and highlight major factors that need to be reconsidered in LANET design, and then discuss enabled applications in Section 3. In Section 4 we discuss available hardware devices and technologies that can be used to build LANETs, and then present the overall architecture of LANET and discuss possible design challenges. Through Sections 5–9, we discuss the state of the art in VLC-based networking and highlight possible open research issues in LANET design following a layered approach, from physical layer up to transport layer. We finally draw conclusions in Section 10.

## 2. LANET: Visible-light ad hoc networks

Visible light ad hoc networks (LANETs) refer to *infrastructure-less mobile ad hoc networks where LANET nodes are wirelessly connected using single-/multi-hop visible light links, configure their protocol stacks in a cross-layer, online and software-defined manner, and adapt to various networking environments (e.g., air/ground/underwater) by switching among different frontend transceiver devices*. Two examples of LANETs are illustrated in Fig. 1 for civilian (e.g., Internet of Things, environmental sensing, vehicular communications, smart homes, disaster rescue operations, among others) and military applications [16], respectively. In this section we discuss major challenges in the design of LANETs, as well as the main characteristics of LANETs by comparing it with traditional RF-based wireless networks.

### 2.1. Main design challenges

Optical wireless communications, particularly visible light spectrum, have found many applications in short-, medium-, as well as long-range communications in the last decade. These include inter-chip connections, indoor wireless access, as well as satellite and deep-space applications, among others [5,12]. However, while there has been significant advancement in understanding efficient physical layer design for visible-light point-to-point links, the core problem of developing efficient networking technology specialized for visible-light networks is substantially unaddressed. One of the main challenges is that VLC relies on optical radiations to deliver information in free space through a substantial portion of unregulated spectrum between 400 and 800 THz, with corresponding wavelengths in the Infra-Red(IR), visible light, and Ultraviolet(UV) bands [12]. This makes VLC substantially different from RF-based communications in terms of *communication range, transmission alignment and shadowing effect, ambient light interference and receiver noise, and VLC ad hoc networking*, among others.

**Short communication range**. Because of the limited propagation range of short-wavelength signals, the transmission range of VLC is relatively short (typically a few meters), compared to RF propagation distances ranging from tens of meters (WiFi) to kilometers (LoRa) [7,11]. When increasing the link distance, for a given desired level of reliability the achievable data rate decays sharply, thus limiting the number of applications where VLC high data rate transmissions can be employed.

**Transmission alignment and shadowing effect**. Because of the low penetration of light, while visible light signals in adjacent rooms do not interfere with each other, this also presents several limitations. First, the transmitter and the receiver must be aligned to each other, especially for line of sight (LOS) short distance communications with small field of views (FOVs), and this is challenging especially if LANET nodes are moving [17]. Second, VLC link quality can be significantly degraded because of shadowing effects caused by obstructing objects, e.g., mobile human bodies [18].

**Ambient light interference and receiver noise**. Noise and interference in VLC are mainly caused by exposure of the receiver to direct sunlight and by the presence of other sources of illumination (*i.e.*, other LED sources, fluorescent and bulb lamps) [19,20] that cause shot noise and consequently decrease the Signal-to-Noise Ratio (SNR). In turn, the receiver can be affected by thermal noise caused by the pre-amplification chain.

**Lack of well-established channel models**. Factors that affect the performance of visible light links include *free space loss, absorption, scattering, scintillation noise induced by atmospheric turbulence*[1] and alignment between transmitters and receivers, among others [21]. Different from RF, channel modeling for visible light links is still largely based on preliminary empirical measurements, especially for outdoor non-line-of-sight (NLOS) environments [14,22]. The applicability of existing theoretical channel models in the design of LANETs still needs to be verified and tested in different transmission mediums [23].

**VLC ad hoc networking**. Existing work on VLC mostly focuses on increasing the data rate for a single VLC link using advanced modulation schemes [24–29]. However, *VLC ad hoc networking* with a large number of densely co-located VLC links (i.e., LANETs) is still substantially unexplored because of the unique characteristics of VLC, including intense modulation/direct detection (IM/DD) channel model, FOV based directionality, low-penetration, among others. To the best of our knowledge, there are no existing architectures and protocols designed specifically for LANETs.

[1] Scintillation noise induced by atmospheric turbulence will affect the performance of outdoor VLC-based applications, such as free-space tactical field applications, ad hoc vehicular communications, disaster rescue applications, among others.

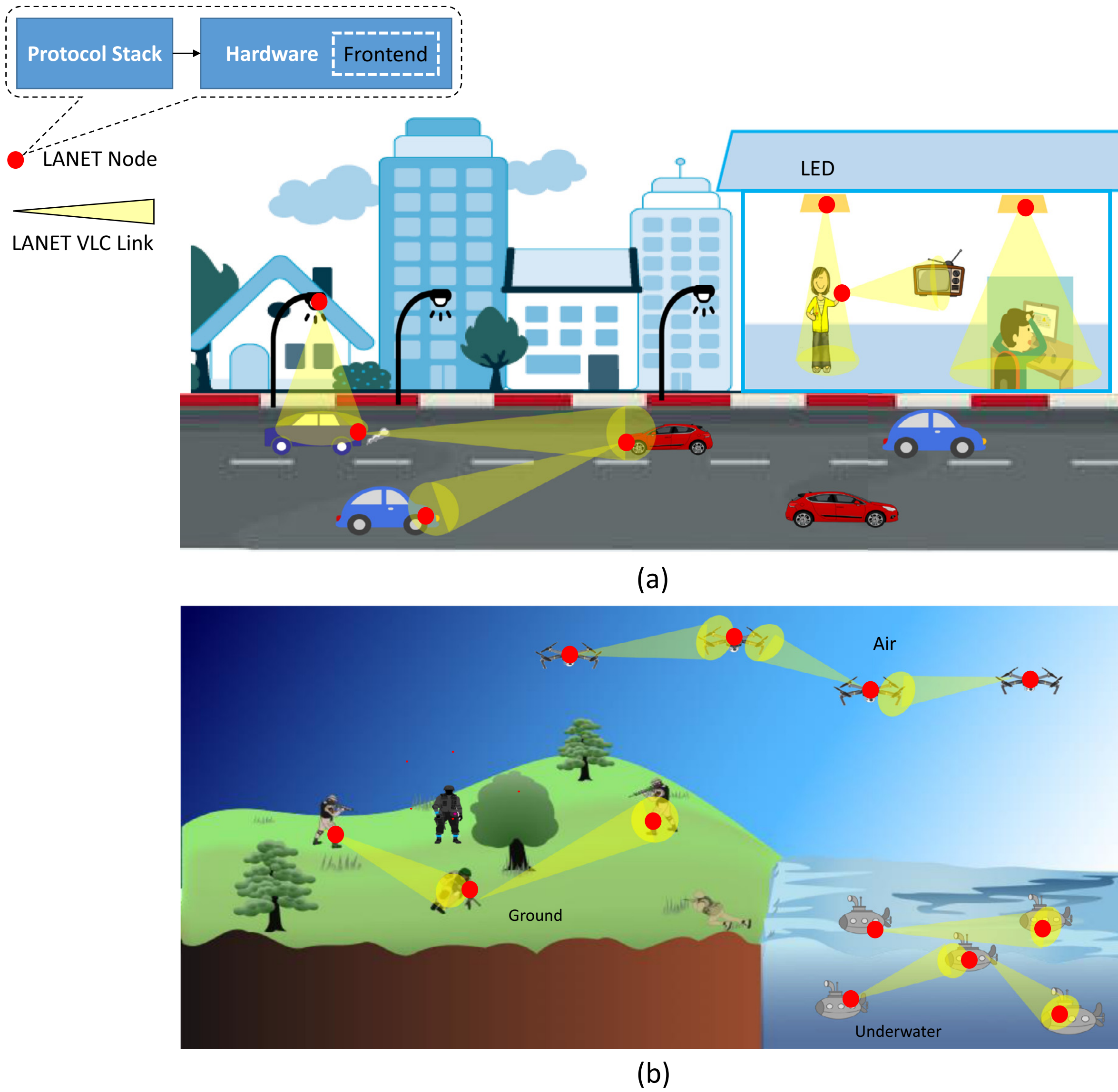


**Fig. 1.** Visible-light ad hoc networks (LANETs) for (a) civilian and (b) military applications.

## 2.2. LANETs vs traditional MANETs

Similar to traditional RF-based MANETs, LANETs also have the ability to self-organize, self-heal, and self-configure. Because of the unique characteristics of visible light compared to RF signals, in LANETs visible light point-to-point links require mutual alignment of transmitters and receivers given the directivity of light signal propagation, which is not easy to obtain with mobile nodes; communication links in LANETs can be easily interrupted by intermittent *blockage* since light does not propagate through opaque materials. In Table 1, we summarize the differences between LANETs and MANETs, in terms of critical aspects including *transmitter and receiver, spectrum regulation, network capacity, spatial reuse, security and costs.*

- *Transmitter and receiver*. In MANETs, the front-end components of each node are typically antenna-based, operating at high frequency. In contrast, simple LED luminaires and photodetectors (PDs) or imaging sensors are typically adopted as transmitters and receivers in LANET. They are relatively simple and inexpensive devices that operate in the baseband[2] and do not require frequency or sophisticated algorithms for the correction of radio frequency impairments, e.g., phase noise and IQ imbalance

**Table 1**
Comparison between LANETs and MANETs.

| Property | MANET | LANET |
|---|---|---|
| Power consumption | Medium | Low |
| Bandwidth | Regulated, limited | Unlimited (400 nm ~ 700 nm) |
| Infrastructure | Access point | Illumination/signaling LED |
| EMI | Yes | No |
| Security | Reduced | Higher |
| Mobility | High | Reduced |
| Line of Sight | Not required | Strictly required |
| Technology | Mature | Early stage |
| Coverage - range | Medium - long | Narrow - short |

[2] Compared to complex passband processing in RF communication, VLCs operate in the baseband domain, which does not require mixers and high-frequency ADC/DAC. This may simplify system design and reduce power consumption.

[12]. As a consequence, SWaP (size, weight, and power[3]) and cost of front-end components involved in LANET systems are often lower than equivalent MANET systems.

- *Spectrum regulation*. The visible light spectrum is mostly unused for delivering information, which implies potential high throughput and an opportunity to alleviate spectrum congestion, particularly evident in the Industrial, Scientific and Medical(ISM) band. The bandwidth available in the visible light portion of the electromagnetic spectrum is considerably larger than the radio frequency bandwidth, which ranges from 3 kHz to 300 GHz. The availability of this mostly unused portion of spectrum provides the opportunity to achieve high data rates through low-cost multi-user broadband communication systems. VLC solutions could be complementary to traditional RF systems and alleviate the spectrum congestion that especially impacts the ISM band.
- *Network capacity*. In MANETs, all the nodes usually operate in a shared wireless channel with a single radio at each node, where the number of channels, the operating frequency, and maximum transmit power are stringently regulated [32], and consequently the network capacity is unavoidably limited and affected by co-located networks. LANETs, instead, can rely on a substantial portion of unlicensed and currently unregulated spectrum as described above, which have the potential to make significant capacity available for networked operations.
- *Spatial reuse*. Visible light cannot pass through opaque objects, thus resulting in *low penetration*. Moreover, in contrast to omnidirectional RF communications, because of predefined limited field of view (FOV) of LEDs, visible light links are typically *directional*. This provides a higher degree of spatial reuse with respect to omnidirectional transmissions typically used in RF. For example, since light cannot propagate outside of a closed room, there is no interference from VLC signals in adjacent rooms. Because of this unique characteristic of VLC, most existing MAC and network layer MANET protocols cannot be directly applied to LANETs and hence need to be redesigned, including neighbor discovery and route selection, among others.
- *Security*. Since they operate in dynamic distributed infrastructure-less configurations without centralized control, MANETs are vulnerable to various kinds of attacks, ranging from passive attacks such as eavesdropping to active attack such as jamming [33]. Differently, in LANETs, the inherent security property that stems from the spatial confinement (low penetration and restricted FOVs) of light beams, will enable secure communications since jammers or eavesdroppers can be easily spotted than in legacy RF communication.
- *Costs*. As discussed above, LANETs are more *cost-efficient* than MANETs because of much simpler front-end devices (e.g., LEDs, PDs) compared to RF solutions for transmitting, sampling and data processing. Moreover, nodes in MANETs are usually battery-powered to enable communications in the absence of a fixed infrastructure. The sensing unit, the digital processing unit and the radio transceiver unit are the main consumers of the battery energy, and therefore more sophisticated energy-efficient algorithms, e.g., energy-efficient MAC or routing schemes [34,35], are needed, which are however challenging in such resource-limited and infrastructure-less MANETs. Differently, LEDs used as transmitters in LANETs highlight themselves by high energy efficiency, longevity, and environment-friendly factor enabled by recent tremendous advances in LED technologies [12]. Moreover, VLC manifests its low-power baseband processing property, which further results in low-cost LED devices compared to high-frequency passband RF front-end antennas.

## 3. Envisioned applications

LANETs have a great potential for enabling a rich set of new civilian and military applications, as illustrated in Fig. 1, ranging from low-latency high-bandwidth indoor communications and outdoor intelligent transportation networking, to highly secure Lower Probability of Intercept/Lower Probability of Detection (LPI/LPD) operations under high network density and jamming conditions, among others. Just name a few examples in the following.

- *Intelligent transport systems*. One of the most promising outdoor applications of LANETs is for ad hoc vehicular communications [36,37], including Vehicle to Infrastructure(V2I), Infrastructure to Vehicle (I2V) and Vehicle to Vehicle(V2V) communications. LANETs can be employed to design intelligent transport systems with better road safety. For V2V, a communication link can be established using head and tail lights or photo-diodes and image sensors at the receiver side, while for V2I the urban infrastructures (e.g., traffic lights, street lights) can be utilized for transmitting useful information related to current circulation of traffic including vehicle safety, traffic information broadcast and accident signalling. Additionally, in vehicular ad hoc networks (VANET), the network topology is highly dynamic and often large-scale. This makes realizing visible-light VANETs more challenging because of the limited FoV, and the relatively short transmission ranges [38]. Moreover, different from legacy RF-VANETs, the quality of visible links can be significantly degraded by weather conditions, including fog and rain, among others.
- *Internet of Things*. The vision of Internet of Things (IoTs) anticipates that large amounts of mobile embedded devices and/or low-cost resource-constrained sensors will communicate with each other via the Internet. To allow networking among a massive number of devices, the communication system must be ubiquitous, low-cost, and bandwidth and energy efficient. Infrastructureless LANETs are a promising choice for communication in the Internet of Things because of its inherent advantages as discussed in Section 2.2, e.g., orders of magnitude available bandwidth, reusing ubiquitously existing lighting infrastructure, low-cost front-end devices, among others. Therefore, LANETs can easily enable a wide range of IoT services, such as localization, smart home, smart city, air/land/navy defense, among others.
- *D2D communications*. Device to Device(D2D) communications are rapidly emerge in recent years [39]. Beyond the crowded RF spectrum, LANETs are a promising candidate to support D2D communications. VLC-D2D applications [40] can use LEDs and PDs or LCD screens and camera sensors. The ubiquitous presence of LCD screens and surveillance cameras in urban environments creates numerous opportunities for practical D2D applications since information can for example be encoded in display screens while camera sensors can record and decode data using image processing techniques [41].
- *Indoor positioning*. Recently proposed VLC-based indoor localization schemes have shown improved performance, in terms of accuracy, given the higher density of LEDs as compared to Wi-Fi access points [42–44]. To set up a light-weight indoor positioning network, LANET-enabled sensors can be organized to form an ad hoc network with a tree-like structure (i.e., having a sensor connected to a LAN as the root node) and a simplified protocol stack only providing basic data transfer and rout-

[3] As we discussed in Footnote 2, the processing power of VLC is lower than RF, and the power consumption [30,31] of the front-end components of VLC and RF are comparable. Therefore, while additional investigation is clearly needed, there is a strong potential for power-efficient LANETs system that would consume less power than legacy RF systems.

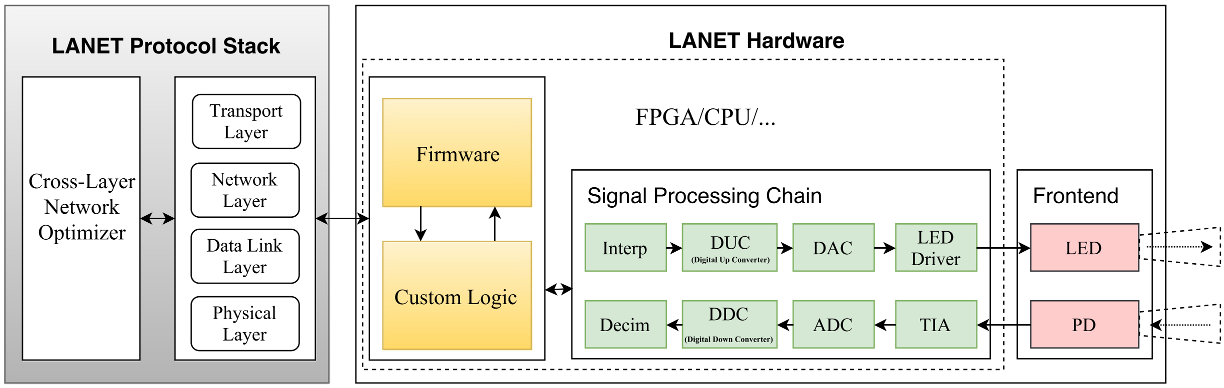


**Fig. 2.** Reference Architecture of LANET Node.

ing functionalities that can be run on devices with limited resources. The authors in [44] design a VLC-based indoor positioning system, aiming at avoiding interference among a large amount of ad-hoc deployed light sources without any explicit coordination. This scheme could be tested in LANET in future.

- *RF-suppressed applications*. LANETs can provide a reliable and accurate solution for data transmission in scenarios where RF communications are suppressed or prohibited, like hospital and climbing/landing airplanes. For example, wireless technology is applied in hospitals for updating information related to patient records, collecting data in a real-time way from handheld patient devices, detecting changes in a patient's condition, and also for observing medical images via medical equipment (*e.g.* ultrasound). There, security and safety are essential to maintain confidentiality of patient records, and to ensure that only authorized personnel have access to the data being transferred wirelessly while limiting the interference to those interference sensitive medical devices like electromagnetic interference (EMI).
- *Military applications*. In last decades, the most common optical/visible light communication for military applications employ IR short-range transmissions [45]. In recent years, the emerging of VLC has shown promising advancements making possible the extensive deployment of VLC for military communication strategies [16]. The use of VLC is turned out to be beneficial in the tactical field with enhanced network capacity and better resistance against adversary jamming, and the research is focused in this direction by military organizations and defense companies. Novel and advanced visible light-based military applications include personal area networks, warfighter-to-warfighter communication, vehicular networks, underwater networks, and space applications including inter-satellite and deep-space links. For example, in underwater, autonomous vehicles will be able to self-organize in a LANET to exchange high-data rate traffic via visible light carriers as a high-rate short-range alternative to acoustics; in ground, marine soldiers can self-organize in a LANET in case of RF interference and be connected to command; finally, in air/space LANETs, nanosats can be connected to a satellite station via VLC and be relay-assisted by other nanosats when in proximity in a delay-tolerant ad hoc network.

## 4. LANET node architecture

In this section, we discuss the two major components of LANET nodes, i.e., hardware and protocol stack as shown in Fig. 2, by describing a general reference architecture for LANET nodes. We first review existing frontend hardware components with a particular emphasis on transmitters and receivers that can be used to develop versatile LANET platforms in different environments, e.g., air/space, ground and underwater.

### 4.1. Node architecture

To date, as we will discuss in Section 4.3, there is no existing testbed fully considering VLC-based networking with cross-layer optimized protocol stack (from physical up to transport layer). To bridge this gap, we discuss a potential solution[4] for VLC ad hoc networking, i.e., a software-defined LANET architecture that supports fully flexible and reconfigurable networking based on visible light communications. As shown in Fig. 2., each LANET node consists of two main modules: (i) *LANET protocol stack*, which includes cross-layer network optimizer and a software-defined programmable visible light networking protocol stack, from physical up to transport layer, and (ii) *LANET hardware*, which consists of fixed firmware and user-customized control logic, signal processing chain circuit and LANET front-end (e.g., LED and PD).

- *LANET protocol stack:* In LANETs, each node is installed a programmable protocol stack, which implements networking functionalities across multiple layers in a software-defined fashion to enable fast and intelligent adaptability. The protocol stack has a modular structure, where different functional blocks, such as timing functionalities, medium accessing functionalities, routing functionalities, among others, can be designed and upgraded independently and conveniently.
  Cross-layer design is an effective way to optimally leverage dependencies between protocol layers to obtain performance gains. In LANETs, the programmable protocol stack is driven using a cross-layer optimizer, which adaptively controls and reconfigures on-the-fly the network parameters based on the results of cross-layer optimization to maximize network utility (i.e., throughput, energy consumption, re-routing, among others), e.g., channel-aware adaption of link layer transmission schemes and multi-user channel access strategies [46–48].
- *LANET hardware:* While different software-defined radio devices have been adopted in existing VLC testbeds, including USRP, WARP and BBB boards (see Table 2), these devices failed to achieve a good tradeoff between fast and flexible prototyping, high-performance signal processing capability and low cost of the device [28,29,49]. To resolve this issue, some new family of software-defined devices can be used in LANET development, e.g., Nutaq MicroZed, which integrates FPGA and ARM processors into a single board to enable real-time signal processing without requiring large-size FPGA (hence with reduced cost)

[4] We are currently working on the proposed software-defined LANET architecture and more details and results will be discussed in our future work.

**Table 2**
Representative existing VLC testbeds.

| Testbed | Hardware | Topology | Layer involved | Remarks |
|---|---|---|---|---|
| Zhang et al. [17] | WARP | Single link | PHY | Data rate 500Kbps to 4Mbps |
| Qiao et al. [29] | WARP | Single link | PHY | ACO-OFDM DCO-OFDM |
| Gavrincea et al. [28] | USRP | Single link | PHY | IEEE 802.15.7 standard based |
| Wang et al. [27,49] | BeagleBone black board | Single link | MAC and PHY | Low cost low data rate |

and without turning to external host (hence with reduced signal processing delay).

As shown in Fig. 2, in LANETs LED and PD are used as transmitter and receivers, respectively. *Medium absorption property* of the networking environment is one of the most important factors in selecting proper transceiver devices. For example, in the atmosphere environment, the absorption is inversely promotional to the wavelength [50], i.e., the absorption of violet/blue light is stronger than red light in air. While Blue LED has been proven to be the best choice for the receiving transceiver because deep ocean water typical exhibits a minimum absorption at this wavelength [51]. The selection of PD will be based on the types of LED selected, the sensitivity of the application requirement, among others.

### 4.2. Front-end hardware

As discussed in Section 1, because of advancements in LED technologies, LEDs outperform conventional light sources or fluorescent bulbs in terms of energy-efficiency, longevity, switching speed and environment-friendliness. All of these advantages motivate the research on visible light communication and enable low-cost VLC systems. To implement the communication function of LEDs, the driver circuit should be modified to modulate data through the use of emitted light, which may help improve the performance [52]. Existing LEDs can be classified into three categories as follows:

- *Phosphor converted LEDs (pc-LEDs)* employ a yellow phosphor coating covered upon a blue LED to produce white light. By modifying the thickness of the phosphor layer, different white colors, such as warm-white, neutral-white or cool-white can be produced. Pc-LEDs are cheaper and less complex compared to other LEDs (e.g., RGB LED, Micro Led, etc.). However, their bandwidth is limited to a few MHz because of the low phosphor conversion efficiency [7].
- *RGB LEDs* utilize three LED chips emitting Red, Green and Blue (RGB) to produce white light. By controlling the intensities of different LED chips, color control can be achieved. Compared to low-cost and low-complexity pc-LED, the cost of RGB LED is higher but with wider achievable bandwidth of 10–20 MHz [53].
- *Micro LEDs ($\mu$ LEDs)* have been used to develop high data rate VLC testbed with much higher bandwidth compared with pc-LED and RGB LED (usually above 300 MHz) and with the resulting achievable data rate up to 3 Gbit/s [54].

For receiving devices, three types of light receivers have been used: PD, imaging sensors and LEDs.

- *Photodetectors (PDs)* are a semiconductor devices that convert the received light signal into electrical current. Currently, basic PIN and more complex, expensive (about four times the cost of the PIN) Avalanche PD (APD) have attracted more interest for the development of visible light testbeds. APDs have been shown to be more suitable for long range communication as a high speed receiver in high bandwidth and bit rates applications since their internal gain can result in higher SNR [55]. However, the high-cost is inevitable compared with PIN PDs. As demonstrated in [26], by using APD the data rate has been almost doubled compared with [25] where basic PIN PD is adopted.
- *Imaging sensor*, aka camera sensor, can also be used to receive light signals. However, to enable high-resolution photography, the number of PDs must be very large, which greatly increases the cost of the resulting testbed. Besides, due to low sampling rate, image sensors can only provide limited data rate (a few kbit/s) [7]. Therefore, image sensors are not suitable to develop cost-efficient LANETs.
- *LEDs* have been used not only as transmitters but also receivers [56,57]. The most compelling advantage of using LEDs as receivers is to further reduce the cost of the systems but with possibly complemented data rate of up to 12 kbit/s and highly limited FoV [27]. For developing visible light networks like LANETs, LEDs as receiver is recommended.

### 4.3. Existing VLC testbeds

As discussed in Section 1, visible light ad hoc networking technologies are still in their infancy, with the core problem of developing flexible networking protocol stacks and resource control algorithms specialized for visible-light networks still substantially unaddressed. To see this, next we briefly review several software-defined VLC-based testbeds available in existing literature [17,27–29,49].

**Software-defined single link VLC testbeds**. A software-defined single-link VLC platform utilizing WARP is presented in [17]. At transmitter side, the AC waveform is generated by OOK modulation scheme on the software-defined modulation on WARP, then fed to a baseband filter and then converted to analog signal by adding a DAC board (EMC150) on WARP. Besides, a Bias-Tee module is used to build the driver circuit to combine the AC signals and DC power to drive the LED. At the receiver side, PD and ADC are used to receive light signal and convert it to real-valued signal for post processing in WARP. The supported bit rate of such single link platform is from 500 Kbps to 4 Mbps. Similarly, [29] also implements ACO-OFDM and DCO-ODFM single-link VLC testbed.

**IEEE 802.15.7 standard based VLC testbeds**. In [28], the authors prototype a visible light communication system based on the IEEE 802.15.7 standard. The transmitter of the low-cost software-defined system consists of USPR platform, an amplification stage, the LED driver circuit and a commercial pc-LED. The transmitted data is modulated in the PC and then delivered to USRP over Ethernet link to do DAC. At the receiver side, PD (e.g., ThorLabs PDA36A) delivers the received signal to the USPR receiving platform, where the signal is sampled and then passed to the PC for demodulation. Similar to above discussed [17,29], only single visible link has been implemented without considering networking development including techniques in the MAC layer, network layer and transport layer.

**Low-cost low-data-rate OpenVLC tesbeds**. [49] presents OpenVLC1.0, an improved version of OpenVLC [27]. OpenVLC1.0 is an open source, flexible, software-defined, and low-cost platform for research in VLC networks. OpenVLC1.0 mainly consists of three parts: i) BeagleBone Black (BBB) board, ii) OpenVLC1.0 cape and iii) OpenVLC1.0 driver. BBB is a low-cost development platform

**Table 3**
Visible light modulation schemes.

| | Modulation | References | Computation complex | Power efficiency | Bandwidth efficiency | Applications |
|---|---|---|---|---|---|---|
| Single Carrier Modulation (SCM) | OOK | [24–26,52,59,60] | Low | Medium | Medium | Low to moderate data rate |
| | PAM | [7,22,61] | Medium | Low | High | Medium data rate |
| | PPM | [14,62–65] | Complex | High | Low | Medium data rate |
| Multiple Carrier Modulation (MCM) | OFDM | [58,66–70] | Complex | Low | High | Multiuser high data rate |
| Color Domain Modulation | CSK | [70,71] | Complex | Medium | High | Multiuser high data rate |

running Linux for implementing quick communication prototyping. The cape is front-end transceiver that can be plugged into the BBB, including hight power LED (HL), low power LED (LL) and PD to be switched to transmit or receive light signals according to application requirements. The driver is used to implements the software solutions for VLC networking, where currently key primitives at MAC and PHY layers are implemented such as signal sampling, symbol detection, coding/decoding, channel contention and carrier sensing. The data rate around 12 kb/s over 4–5 m is validated using the proposed OpenVLC1.0. OpenVLC1.0 can be adopted as a starter kit for low-cost and low-data-rate VLC research.

We summarize the above-discussed representative testbeds in Table 2, from which we can see that most existing VLC testbeds have been focusing on understanding and designing efficient physical layer technology for visible light point-to-point links [17,27–29,49], or designing simple MAC schemes based on the IEEE 802.15.7 VLC standard [27,49]. As discussed in Sections 2.1 and 4.3, unlike protocol design for RF communications, visible light networking technologies are substantially unexplored because of unique characteristics of VLC wireless links. Next, we discuss those enabling technologies and highlight possible open research issues at each layer of LANET protocol stack.

## 5. Physical layer

Unlike RF systems where signal can be modulated in terms of amplitude, frequency and phase, in VLC it is the intensity (aka instantaneous power) of the visible light that is modulated [15], i.e., *intensity modulation* (IM). Correspondingly, demodulation is typically based on *direct detection* (DD), where a photodetector produces an electrical current proportional to the received instantaneous light power, i.e., proportional to the square of the received electric field [58]. This combination of modulation techniques is referred to as IM/DD (Intensity Modulation / Direct Detection). As discussed in the previous sections, LEDs may have dual functions, illumination and communication. Different from indoor communication using visible light spectrum, where illumination is the primary function [14], in LANETs illumination may not be as important as in indoor applications. This means that flicker mitigation[5] and dimming support for comfortable indoor living environment are not core considerations in the modulation process of LANETs.

### 5.1. Existing modulation schemes

In this section, we discuss the state-of-the-art IM/DD modulation schemes adopted at the PHY layer for visible light communication system. As summarized in Table 3, existing VLC modulation schemes can be classified into *single carrier, multi-carrier* and *color domain* modulation schemes. We will compare the main VLC modulation schemes from the perspective of power efficiency, bandwidth efficiency, and implementation complexity.

#### 5.1.1. Single carrier modulation

Single carrier modulation techniques were first proposed for IM/DD wireless infrared communication [72]. For example, on-off keying (OOK), pulse amplitude modulation (PAM), and pulse position modulation (PPM) are easily implemented for LANET systems. In general, single carrier modulation schemes are suitable for LANETs where low-to-moderate data rate are required [70].

**On-off keying (OOK)**. OOK is the most common and simplest modulation technique for IM/DD in VLC, where higher or lower intensity of light represents a 1 or 0 bit [22]. Both OOK non-return-to-zero (NRZ) and OOK return-to-zero (RZ) can be applied. Since OOK-RZ has twice the bandwidth requirement of OOK-NRZ and does not support sample clock recovery at the receiver [59], OOK-NRZ has been more widely used in VLC systems [24–26,52,60]. In [24] the authors present a 10 Mbit/s visible light information broadcasting system with maximum communication distance 3.6 m based on message signboard with four LED arrays. Vucic et al. [25,26] demonstrate a visible light link operating at 125 Mbit/s over a 5 m communication distance by adopting blue-filtering with analogue equalization at the receiver and an improved 230 Mbit/s visible link with OOK-NRZ by using an APD instead of the PIN photodiode, respectively. More recently, in [52] a 300 Mbit/s line-of-sight visible light link using OOK-NRZ over 11 m is demonstrated with 600 nm LED and off-the-shelf PIN PD by proposed 2-cascaded Schottky diodes-capacitance current-shaping drive circuit. In [60], an OOK-NRZ based visible link with maximum transmission speed 477 of Mbit/s over 0.5 m by using a commercially available red LED and a proposed LED driver with a simple pre-emphasis circuit and a low-cost PIN PD is demonstrated.

**Pulse amplitude modulation (PAM)**. PAM is a more generalized OOK (the simplest 2-PAM is namely OOK modulation) [61]. In PAM, multiple intensity levels are defined to represent various amplitudes of the signal pulse. However, multiple intensity levels may undergo nonlinearity in terms of LEDs luminous efficacy, depending on the color of LED emission on input current and temperature [7].

**Pulse position modulation (PPM)**. PPM divides a symbol duration into $L$ equal time slots and a single pulse is transmitted in each of the $L$ slots, where the position of the pulse represents different transmitted symbols. PPM can improve the power efficiency compared with OOK but at the expense of an increased bandwidth requirement and greater complexity [7]. Therefore, to overcome the lower spectral efficiency and data rate limitations, some variants of PPM, e.g., Multi-pulse PPM (MPPM) [62] and Overlapping PPM (OPPM) [63], are proposed. MPPM and OPPM can not only achieve higher spectral efficiency but also provide dimming control. Besides, Variable PPM (VPPM) [14] is another important variant of PPM, adopted in standard IEEE 802.15.7 (which will be discussed later in this section), where the duty cycle (pulse width) of the transmitted symbol can be adjusted according to the dimming level requirements. Recently, other variations based on MPPM, such as OMPPM [64] and EPPM [65] are also proposed to further either improve the spectral efficiency or provide arbitrary dimming control levels. Because of the low data rate of PPM and the low relevance of dimming control in LANETs, we will not discuss PPM-

[5] Flicker mitigation aims to eliminate the phenomenon that human eyes can observe the flickering of the light, which can be avoided by using waveforms whose lowest frequency components are far greater than the flicker fusion threshold of the human eyes (which is typically less than 3 kHZ).

based modulation schemes in detail, interested readers are referred to [7] and references therein for more information.

### 5.1.2. Multi-carrier modulation

Compared to single carrier modulation, multi-carrier modulation can achieve high aggregate bit rates and improved bandwidth efficiency at the cost of reduced power efficiency because increasing the number of subcarriers also increases the DC offset to avoid clipping [22]. *Orthogonal Frequency Division Multiplexing (OFDM)* and its variants, as the typical multi-carrier modulation techniques, are widely adopted in the existing VLC systems.

OFDM is first demonstrated in [73] for visible light communications. OFDM can help combat inter-symbol interference (ISI) and multi-path fading while significantly boosting the achievable data rate over wireless links. To date, the highest data rates achieved in visible light communications by utilizing OFDM is up to 3 Gbit/s over 0.05 m [54] where a single LED is adopted.

Different from original OFDM in RF systems, where complex-valued bipolar signals are generated, in IM/DD based visible light communications only real-valued signals are acceptable. Therefore, conventional OFDM techniques for RF need to be modified for VLC systems. To convert bipolar signals to unipolar, there are two major techniques: i) DC-biased Optical OFDM (DCO-OFDM) [58] and ii) Asymmetrically-Clipped Optical OFDM (ACO-OFDM) [66]. In ACO-OFDM, only odd subcarriers are used to modulate data, while in DCO-OFDM all the subcarriers are adopted by adding a DC bias to make the signal positive. It is shown in [67] that ACO-OFDM is more efficient than DCO-OFDM in average optical power for constellations from 4 QAM to 256 QAM because the DC bias used in DCO-OFDM is less power efficient; but DCO-OFDM outperforms ACO-OFDM in spectrum efficiency since ACO-OFDM uses only half of the subcarriers to carry data. Recently, Unipolar OFDM (U-OFDM) [68] and asymmetrically clipped DC biased optical OFDM (ADO-OFDM) [69] are proposed to overcome the limitations of DCO-OFDM and ACO-OFDM.

### 5.1.3. Color shift keying (CSK)

CSK was defined in the latest IEEE 802.15.7 standard [71] by using multi-color LEDs, which is similar to frequency shift keying in that bit patterns are encoded to color (wavelength) combinations. Specifically, the transmitted bit corresponds to a specific color in the CIE 1931 [74] coordinates.[6] The IEEE 802.15.7 standard divides the spectrum into 7 color bands from which the RGB sources can be picked from, and the picked wavelength bands determine the vertices of a triangle inside which the constellation points of the CSK symbols lie. The color point for each symbol is generated by modulating the intensity of RGB chips. However CSK cannot be used in a VLC system where the source is a pc-LED [7] (which is one of the most common sources of light in an illumination system). Moreover, implementation of CSK requires a more complex circuit structure [7].

### 5.1.4. Standardization of physical layer: IEEE 802.15.7

IEEE 802.15.7 standard [71] has specified at the PHY layer three types of VLC techniques, including in total 30 modulation and coding schemes for different applications with different desired data rates, as discussed as follows.

- *Physical(PHY) I* is designed for outdoor applications with low data rates. This mode uses OOK and VPPM along with Reed-Solomon (RS) and Convolutional Coding (CC) for Forward Error Correction (FEC). The operating data rates vary from 11.67 kbit/s to 266.6 kbit/s with support for 11.67 kbit/s at 200 kHz being mandatory.
- *(PHY) II* has been designed for outdoor applications with moderate data rates. (PHY) II uses the same modulations and Run Length Limited(RLL) code as (PHY) I but supports only RS coding for FEC. PHY II supports data rate ranging from 1.25 Mbit/s to 96 Mbit/s. All PHY II VPPM modes shall use 4-bit to 6-bit encoded symbols(4B6B) encoding, while all OOK PHY II modes use 8 bit to 10 bit encoded symbols(8B10B) with DC balance.
- *(PHY) III* uses CSK for applications equipped with multiple light sources and color filtered photo detectors. The data rates vary from 12 Mbit/s to 96 Mbit/s. (PHY) III supports RS coding for FEC.

[6] The CIE 1931 color space chromaticity diagram represents all the colors visible to the human eyes with their chromaticity values $x$ and $y$.

## 5.2. Open research issues

In the physical layer of LANETs, the following two research directions can be identified to further enhance capacity and power efficiency of visible light communications.

- *High power efficiency.* As discussed in Section 1, besides free space loss, other factors, including absorption and atmospheric conditions, can considerably reduce the intensity of visible light for outdoor applications. Moreover, in ad hoc networking, low energy consumption is often a critical factor since network devices are usually battery powered. Examples include mesh networks of unmanned aerial vehicles (UAVs), sensors or communication devices in disaster recovery scenarios, tactical field devices, among others. Therefore, intuitively, new physical layer techniques enabling *higher power efficiency* are needed. Although Li et al. [75] and Tian et al. [76] have pioneered research on low-power consumption, this line of work for visible-light wireless communications is still in its infancy.
- *Long communication range.* Visible light has the potential to provide high data rate communications. For example, [77] and [54] demonstrated a 4.5 Gbit/s RGB-LED based WDM indoor visible light communication system and a 3 Gbit/s single gallium nitride $\mu$ LED OFDM-based wireless VLC link, respectively. However, the communication ranges are only 1.5 m and 0.05 m. For LANETs, mainly operating in outdoor environments, significantly longer ranges are a key requirement. Chan et al. [78] proposes to use a polarized-light intensity modulation scheme to increase the transmission range, up to 40 meters, with very limited data rate, i.e., 76 bytes per second. Ion [79] and Wang et al. [80] can achieve data rate 210 Mbps and 400 Mbps respectively at bit error rates of $10^{-3}$ over distances in the order of 100 meters, at the cost of increased system complexity. In [79], a collimating lens for optical antennas is designed and optimized by using Taguchi method. In [80], advanced OFDM modulation schemes, pre-equalization, reflection cup, convex lenses, and receiver diversity are adopted to boost the data rate over 100 meter distance. There is clearly a trade-off among the data rate, transmission range and system complexity scintillation noise induced.

# 6. Medium access control layer (MAC)

There has been limited work specifically on Medium Access Control (MAC) for visible light communications. The few existing MAC schemes for Visible Light Communication(VLC), as summarized in Table 4, are mainly based on approaches blindly drawn from RF communications, such as Carrier Sense Multiple Access/Collision Detection(CSMA/CD) (also adopted in IEEE 802.15.7 [71]) or Carrier Sense Multiple Access/Collision Avoidance(CSMA/CA), cooperative MAC and OFDMA, unfortunately without considering specific (VLC) channel characteristics and challenges. Additionally, most of the existing MAC schemes have been designed to enable point-to-point VLC and hence are not easily ex-

**Table 4**
Summary of MAC protocols for VLC.

| MAC Protocol | Medium access method | Topology operation modes | Other comments |
|---|---|---|---|
| IEEE 802.15.7 [71] | CSMA/CA | Peer-to-peer, star, broadcast | Standardzation for VLC |
| SACW MAC [81] | CSMA/CA | Star | Full-duplex |
| Lin et al. [82] | CSMA/CD | Star | Full-duplex |
| Schmid et al. [83] | CSMA/CA | Peer-to-peer | LED-to-LED |
| Cooperative MAC [84] | CSMA/CA | Peer-to-peer | Cooperative relay |
| Broadcasting MAC [85] and supports QoS | TDMA | Broadcast | Frame synchronization |
| OWMAC [86] | TDMA | Star, with unicast, broadcast, & multicast | 84 Mb/s data rates |
| Dang et al. [87] | OFDMA | Star | Comparison of O-OFDMA & O-OFDM-IDMA |
| Ghimire et al. [88] | OFDMA-TDD | Star | Self-organising interference management |
| Chen et al. [89] | DCO-OFDM | Indoor downlink transmission | Spectral efficiency of 5.9 bits/s/Hz |
| Bykhovsky et al. [90] | DMT | Star | Interference-constrained subcarrier reuse |
| Shoreh et al. [91] | MC-CDMA with PRO-OFDM | Star | Handles dimming using PRO-OFDM |
| He et al. [92] | OCDMA with OOC | Peer-to-peer, star | Bipolar-to-Unipolar encoding and decoding |
| Gonzalez et al. [93] | OCDMA with ROC | Peer-to-peer, star | Specific design of OOC, higher complexity |
| Chen et al. [94] used as receiver | OCDMA with Color-Shift Keying(CSK) | Peer-to-peer, star | Mobile phone camera |
| Yu et al. [95] | MU-MISO | Cooperative broadcasting | ZF algorithm using generalized inverse |
| Pham et al. [96] | MU-MISO | Cooperative broadcasting | ZF algorithm using optimal precoding |
| MU-MIMO (BD) [97] | MU-MIMO | Star | Precoding using BD algorithm |
| MU-MIMO (THP) [98] | MU-MIMO | Star | Precoding using THP algorithm |

tendable to LANET. Some of these MAC schemes are discussed below.

### 6.1. Existing visible light MACs

**CSMA-based channel access** [81–83]. In [81], the authors propose a full-duplex Medium Access Control (MAC) protocol with Self-Adaptive minimum Contention Window (SACW) that delivers higher throughput from the central node to the terminal nodes in a star topology. The proposed algorithm still uses the basic slotted (CSMA/CA) mechanism as in [71] with adaptive contention window. The objective of SACW MAC is to allow the central node to monitor the data traffic to increase the probability of full-duplex operation. The authors of [82] also propose a high speed full-duplex MAC protocol based on CSMA/CD by considering a star topology with Access Point (AP) at the center and multiple terminal nodes trying to communicate with the AP. Another example of VLC using CSMA/CA is in [83], which uses LED to transmit and receive to reduce hardware cost and size. This work uses LED charged in reverse bias to receive the incoming light.

**Cooperative MAC** [84]. A cooperative MAC protocol is proposed in [84] to reduce latency and for on-demand error correction. The sender and receiver will initiate a cooperative mechanism to find relay nodes when the direct link does not provide the required bandwidth to meet the Quality of Service (QoS) requirement. Once cooperative mode is initiated, the sender broadcasts a *RelayRequest*. Nodes within range save the sender's identification number. Next, the destination broadcasts a *RelayRequest*. Nodes that receive both *RelayRequests* will broadcast its information to sender and destination if the node decides to be a relay. The relay overhears the sender's packets and saves them till an Acknowledgment (ACK) is received from the destination. If the ACK is not received, the relay transmits the saved packets to the destination.

**Orthogonal frequency-division multiple access (OFDMA)** [87–90]. Recently, OFDM used in the PHY layer of VLC has been extended to enable multi-user access through Orthogonal Frequency Division Multiple Access (OFDMA). In [87], authors compare the Bit Error Rate (BER) performance, receiver complexity and power efficiency of two multicarrier-based multiple access schemes namely, Optical Orthogonal Frequency Division Multiplexing Interleave Division Multiple Access (O-OFDM-IDMA) and Optical Orthogonal Frequency Division Multiple Access (O-OFDMA). The authors of [88] evaluate a self-organizing interference management protocol implemented inside an aircraft cabin. The goal of the work is to allocate time-frequency slots (referred to as chunks) for transmitting data in an IM/DD-based OFDMA-Time Division Duplex (TDD) systems. Another OFDMA technique for indoor VLC cellular networks is analyzed in [89] using Direct-Current Optical OFDM (DCO-OFDM) as multi-user access scheme. In [90], the authors propose a heuristic subcarrier reuse and power redistribution algorithm to improve the BER performance of conventional Multiple Access Discrete Multi-Tones (MA-DMT) used for VLC.

**Code division multiple access (CDMA)** [91–94,99,100]. There have been several contributions aimed at employing CDMA in VLC. A system using Multi-carrier CDMA (MC-CDMA) along with OFDM platform is proposed in [91]. The proposed design uses Polarity Reversed Optical OFDM (PRO-OFDM) to overcome the inherent light-dimming problem associated with using Code Division Multiple Access (CDMA) with visible light. In this design a unipolar signal is either added or subtracted to the minimum or maximum current respectively in the LED's linear current range to provide various levels of dimming. In [92], the authors discuss how Gold sequences and Wash–Hadamard sequences can be adapted for VLC. Optical Orthogonal Codes (OOC) [99] comprising of sequences of 0*s* and 1*s* have also been explored as a prime candidate to establish Optical Code-Division Multiple Access (OCDMA) for visible light communication. Since as the number of users increases in the system, it becomes challenging to generate OOC for each user, Random Optical Codes (ROC) have been proposed as an alternative, even though they do not provide optimal performance [93,100]. There have also been efforts to combine CSK modulation and OCDMA to enable simultaneous transmission to multiple users [94].

**QoS-based MAC.** In [85], the authors propose a QoS based slot allocation to enhance the broadcasting MAC of IEEE 802.15.7 standard. They use a super frame structure similar to the standard. When a new channel wants to join the AP, it sends a traffic request to the access point along with its QoS parameters (data rate, maximum burst traffic, delay requirements and buffer capacity). Optical wireless MAC (OWMAC) [86] is a Time Division Multiple Access (TDMA) based approach aimed to avoid collision, retransmission and overhead due to control packets. In OWMAC, each node reserves time slot and advertises the reservation using a beacon packet. OWMAC also employs Error-Correction Code (ECC) in their ACK to ensure that retransmission are reduced to corrupted ACK packets. This protocol is designed to handle start like topologies.

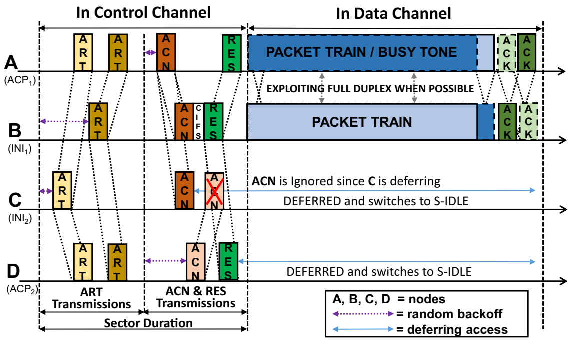


**Fig. 3.** Timing diagram of VL-MAC.

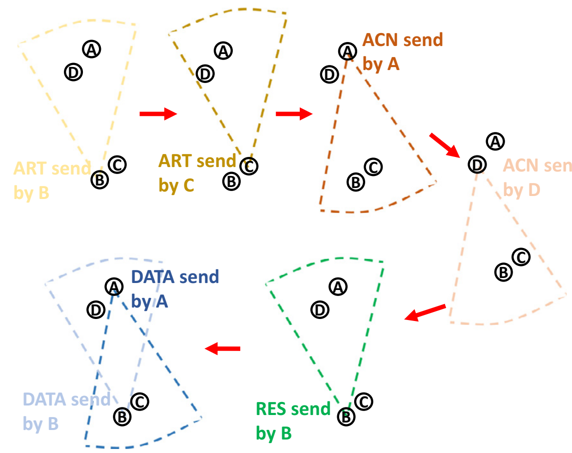


**Fig. 4.** Handshake procedure of VL-MAC.

**MU-MIMO** [95–98,101–103]. An alternative method uses multiple LED arrays as transmitters to serve multiple users simultaneously [95,96]. In contrast to the RF counterpart, the VLC signal is inherently non-negative leading to the necessity of modifying the design of the Zero Forcing (ZF) precoding matrix. In [95], a ZF precoder is chosen in the form of specific generalized inverse of the channel matrix known as the pseudo-inverse. The authors of [96] recognize that the pseudo-inverse may not be the optimal precoder. Accordingly, they design an optimal ZF precoding matrix for both the max-min fairness and the sum-rate maximization problems. Block Diagonalization (BD) algorithm [101] has also been used to design the precoding for Multi-User Multiple-Input Multiple-Output (MU-MIMO) VLC system [97] to eliminate Multi-User Interference (MUI) and its performance has been evaluated in [102]. Finally, Tomlinson–Harashima Precoding (THP) [103] has been utilized in [98] to achieve better BER performance compared to the block diagonalization algorithm in VLC systems.

MAC protocols [81,82,87–90] that are designed for centralized operation in a star topology are not easily extensible to LANETs. Cooperative operations like in [84] can be employed in LANETs but cannot be the primary MAC protocol used to negotiate reliable medium access. Techniques based on CDMA or MU-MIMO are suitable for centralized networks as it may be complex to negotiate different codes for each link in a distributed network. Similarly, QoS-based techniques can be used to improve a stable MAC protocol that has been primarily designed to overcome inherent problems of LANETs such as deafness, blockage and hidden node problem. These problems are described in detail in Section 6.4.

### 6.2. MAC for LANETs

A MAC protocol for LANETs (VL-MAC) is proposed in [104] to alleviate problems caused by hidden nodes, deafness and blockage while maximizing the use of full-duplex links. VL-MAC introduces the concept of opportunistic link establishment in contrast to traditional methods where a forwarding node is chosen before the negotiation for channel access begins. A utility based opportunistic three-way handshake is employed to efficiently negotiate medium access. First, a node chooses the optimal transmission sector, i.e., the "direction" that maximizes the probability of establishing a link even when some of the neighbors are affected by blockage or deafness. Since full-duplex communication is inherent to VLC, the utility function is also used favors the establishment of full-duplex communication links. The full-duplex transmission or busy tone along with power control employed by the proposed MAC protocol is aimed at mitigating the hidden node problem. All these factors contribute towards maximizing the throughput of LANET. The timing diagram and an example of three-way handshake procedure is depicted in Figs. 3 and 4 respectively. The node that initiates communication is called the initiator and the node that accepts communication link is called the acceptor.

Consider four nodes *A, B, C* and *D* as shown in Fig. 4, among which *B* and *C* are the initiators with packets to be transmitted and *A* and *D* are prospective acceptors. Once a node has packets to transmit, it has to choose a sector to transmit such that it maximizes the initiator's utility function ($U_{ini}$). This is a joint function of backlog and the achievable forward progress through the chosen sector. Accordingly, *B* and *C* choose the sector corresponding to their maximum $U_{ini}$. In this example, assume that both choose the same sector. Nodes *B* and *C* choose a random back off depending on their $U_{ini}$ and broadcast an *Availability Request (ART)* packet if the channel is idle. As shown in Fig. 4, both *A* and *D* listen to control packet during the corresponding sector duration. On reception of *ARTs, A* and *D* will calculate their respective acceptor's utility function, $U_{acp}$. Next, *A* and *D* choose the initiator (*B* or *C*), initiator's session and acceptor's session for potential full-duplex communication such that it maximizes their respective $U_{acp}$. As shown in Figs. 3 and 4, *A* transmits a *Availability Confirmation(ACN)* to the chosen initiator (*A* chooses *B* in this case) after a random backoff which is dependent on $U_{acp}$. The initiators *B* and *C* listen for *ACN* from *A* and *D*. In this example, the *ACN* from *A* is received by intended node *B* and overheard by *C*. Accordingly, *B* transmits *Reserve Sectors (RES)* packet to reserve time required to complete the transmission. Node *C* learns that it was not chosen for transmission by overhearing the *ACN*, and hence defers access. Similarly, *D* overhears the *RES* packet and returns idle. Performance evaluation studies show up to 61% increase in throughput and significant improvement in the number of full-duplex links established with respect to CSMA/CA.

### 6.3. Standardization: MAC of IEEE 802.15.7

The IEEE 802.15.7 MAC protocol [71] is designed to support three different topologies, namely peer-to-peer, star and broadcast considered by IEEE 802.15.7, as shown in Fig. 5. In a peer-to-peer topology, each node is capable of communicating with any other node within its coverage area. One node among the peers need to act as a coordinator. This could be determined in multiple ways for example, by being the first to initiate communication on the channel. As shown in Fig. 5, a star topology consists of a single coordinator communicating with several child nodes. Each star network operates independently of other networks by choosing a unique Visible-light communication Personal Area Network (VPAN) identifier within its coverage area. Any new child node uses the VPAN identifier to join the star network. Finally, in the broadcast mode the communication is uni-directional and does not need address or formation of a network. Visibility support is also provided across all topologies to mitigate flickering and maintain the illumination

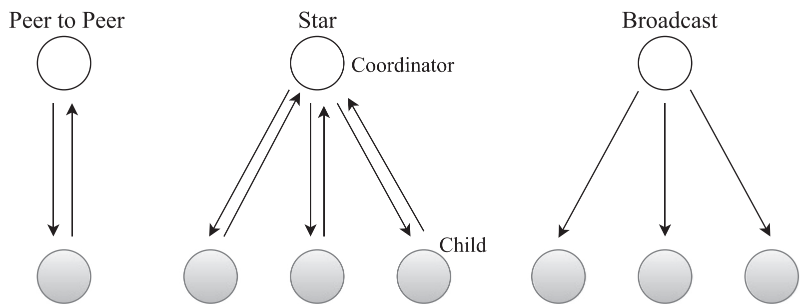


**Fig. 5.** IEEE 802.15.7 supported MAC topologies.

function in the absence of communication or in the idle or receive modes of operation [71].

Active and passive scan are performed by nodes across a specified list of channels to listen for beacon packets and form VPANs. While every node should be capable of passive scan, the coordinator should be able to perform active scan. An active scan is used by a prospective coordinator to locate any active coordinator within the coverage area and select a unique identifier before starting a new VPAN. To perform an active scan over a specified set of logical channels, the node switches to the required channel and sends out a beacon request. Next, it enables the receiver such that only beacon packets are processed. The passive scan is similar to active scan but nodes do not send out the beacon request. The passive scan is envisioned to be used in star or broadcast topologies while the active scan is for peer-to-peer topologies. Beacon packets are also used to synchronize with the coordinator. In VPANs that do not support the use of beacons, polling is used to synchronize with the coordinator.

### 6.4. Open research issues

From the above discussion we can see that existing VLC MAC protocols consider primarily point-to-point link or simple multicast or broadcast access where a master node serves as coordinator. In LANETs, VLC-enabled nodes are networked together via possibly multi-hop visible light links in an ad hoc fashion to support various applications spanning terrestrial, underwater, air as well as space domains, for which the MAC design is more challenging. Several open research issues are identified below.

- *Deafness avoidance*. When the VLC receiver is oriented towards a segment of the space, it is unable to receive from all the remaining segments. This situation is referred to as *deafness*. Thus, a node may try to initiate communication with its neighbor who is experiencing deafness with respect to the node, leading to additional delays during the contention phase. Additionally, the list of instantaneous neighboring nodes may change if the system has a FOV that changes direction. Hence, appropriate synchronization procedures need to be included in the MAC protocol to coordinate between the prospective neighbors.
- *Hidden node detection*. Classic challenges like hidden node problem amplified in LANETs because of directionality. Control packets like Clear-to-send (CTS) transmitted by a receiver may not be received by nodes because of limited FOV. When a node that does not receive the CTS tries to initiate communication with the receiver, it causes interference to the ongoing communication leading to collisions. Furthermore, traditional virtual carrier sensing using Network Allocation Vector (NAV) has to be modified to take advantage of spatial reuse. Because of the above challenges, it is necessary to design channel dependent MAC protocols specifically to leverage the characteristics of VLC.
- *Channel-aware VLC MAC. Directionality* is a key distinguishing feature of VLC. Larger FOV results in more diffused links (i.e., with light reflected by objects between transmitter and receiver), which in turn leads to higher attenuation. Therefore, VLC systems with high-rate transmission cannot have large FOV. Moreover, sudden communication discontinuity (*blockage*) may happen during the contention phase and communication stage. This will result in *frequent re-connect* problem, which will further cause increase in the contention payload and degradation of the effective throughput. VLC devices need to operate at a wide range of power levels to satisfy lighting or other requirements. This implies that a channel-aware MAC protocol is required to negotiate and operate at appropriate configuration (i.e. wavelength, data rates or modulation) to maintain the link under different scenarios.
- *Full-duplex capability*. Unlike typical RF transceiver systems equipped with a single antenna to transmit or receive, VLC devices are usually equipped with a LED for transmission and a PD for reception making these devices inherently capable of *full-duplex* communication. Therefore, MAC protocols designed for LANETs should be able to take advantage and utilize the full-duplex links to improve the network throughput.

## 7. Network layer

Routing at the network layer will play a significant role on the performance of LANETs and have a major influence on the overall network throughput. However, most of the existing work in visible light communication is confined to point-to-point communication or a cooperative relay based communication [83,84]. To the best of our knowledge, multi-hop routing for visible light ad-hoc networking is substantially unexplored. There are two major challenges:

- **Blocking of service**. In LANETs, one of the most important characteristics of visible light communications is that signal penetration through any non-transparent objects is physically impossible. We refer to this problem as *blocking of service*. For example, in traditional routing schemes in RF-based MANET, links with the best quality are generally selected [105,106]. However, best-quality links may not be inside the previous hop's FOV or some objects may appear as obstacles over one link after the routing decision. In these cases, the best routes determined by traditional routing schemes may not be desirable.
- **Limited route lifetime**. Route maintenance is important in any ad-hoc network due to possible route failures caused by impaired channel, node failures, among other reasons. This problem is magnified in LANETs because of blockage caused by obstacles or deafness caused by directionality as described in Section 6. The nodes in a LANET must rapidly adapt to route failures and dynamically find alternate path to the destination.

To address these challenges, we identify three possible research directions in the design of LANET network layer.

### 7.1. Open research problems

- *Proactive LANET Routing*. In proactive or table-driven routing protocols, each node maintains routing information for the entire network. Usually, in an omnidirectional network, the nodes may use broadcast messages regularly to learn changes in topology and routes. In a directional network, this becomes challenging and time intensive due to deafness and the need to exchange messages in every sector. In LANETs, the problem is further aggravated due to the limited route lifetime discussed earlier. Therefore, there is an constant need to update routes but at the same time, it is extremely challenging to learn changes in the network in an efficient manner. All these factors render it extremely difficult to maintain updated routing tables for the entire network.
- *Reactive LANET routing*. In reactive routing protocols, the routes are discovered when a source requires to transmit a packet to a destination and eliminates the need to maintain routing tables at every node. Although reactive protocols reduce communication overhead and power consumption, they lead to higher delays. It is difficult to discover all possible routes due to the narrow FOV and without an adequate neighbor discovery scheme that overcomes blocking. After route discovery, it becomes important to select the optimal route to maximize the overall throughput of the network. Depending on the device, a dynamic routing protocol should consider the interaction between routing and channel selection with help of a cross-layer controller.
- *MAC-aware routing*. Due to the frequent reconnect problem, routing in LANETs relies heavily on MAC layer to maintain the links for uninterrupted transmission. Thus, repeated interaction between the network layer and the MAC layer becomes crucial, inducing the need for a cross-layer controller. While directionality enables spatial reusability, it also poses serious challenges during neighbor discovery and route selection. For example, during the neighbor discovery phase, some nodes may be overlooked due to deafness. This will reduce the number of potential opportunistic routes available to the node in a LANET as compared to a traditional MANETs. Thus, an efficient neighbor discovery technique and a dynamic routing algorithm has to be uniquely designed for LANETs.

## 8. Transport layer

The main objective of transport layer protocols is to provide end-to-end communication services with, among other functionalities, reliability support and congestion avoidance. To achieve reliable transmission, a transport layer protocol, say TCP [107], detects packet loss either caused by transmission errors or network congestion and then sends an ACK to the sender to acknowledge the successful reception of the packet or NACK message to request retransmissions; and regulates the maximum data rate a sender is allowed to inject into the network to avoid congestions.

In past years, transport layer protocols has been extensively discussed focusing on wireless multimedia sensor networks [108], cognitive radio networks [109], delay and disruption tolerant networks [110], and wireless video streaming networks [48], among others. These protocols in existing literature however are not suitable to (at least are not the optimal for) LANETs because of the special characteristics of visible light communications, including *directionality, intermittent availability* and *predictability*.[7] Next, we discuss the applicability of existing transport layer protocols and the necessary modifications to address the unique challenges in LANETs.

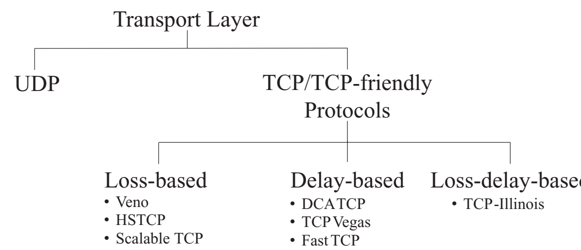


**Fig. 6.** Existing transport layer protocols.

### 8.1. Existing transport layer protocols

Existing transport-layer protocols [111–117] can be categorized into three classes, UDP, TCP and TCP-friendly protocols, and application-/network-specific protocols, as illustrated in Fig. 6.

- *UDP* is a simple connectionless but unreliable transport layer transmission scheme, which provides a minimum set of transport layer functionalities without any guarantee of delivery, order of packets, or congestion control. Because of its timeliness, UDP protocol has been typically used in applications that are delay sensitive but packet loss tolerable, e.g., real-time video streaming, online gaming, and VOIP in wired and radio networks. However, the protocol does not suit well to LANETs due to its indiscriminate packet dropping. Particularly, in mobile LANETs each VLC link can be only intermittently available with link outage at a level of seconds, and the resulting *burst packets dropping* may cause considerable QoS degradation that can be even fatal the dropped packets are key packets (e.g., packets of intra-coded video frames). Multi-path routing can be used to account for link outages, however UDP protocol does not provide any guarantee of receive order of packets.
- *TCP/TCP-friendly protocols*. Different from UDP, TCP protocols provide connection-oriented, reliable and ordered packet delivery [107], and hence it is more favorable to account for the link outages and multi-path routing in LANETs. We discuss three classes of TCP protocols, loss-based, delay-based and their combinations, and discuss their applicability in LANETs. The congestion control in loss-based TCP protocols, including Reno TCP [118] and its enhancements [119,120], has the form of additive-increase/multiplicative-decrease (AIMD), e.g., the well known slow start and exponential backoff mechanisms. While AIMD-based congestion control has been remarkably successful since Reno first developed in 1988, as pointed out in [112], it may eventually become the performance bottleneck in newly evolved wireless networks with high bandwidth-delay product (BDP), such as LANETs. Roughly speaking, if BDPs are high it can be too slow for the transport layer protocols based on AIMD to converge to the optimal transmission size. To date, up to 3 Gbits/s over 5 cm VLC link [54] and 300 Mbits/s over VLC

[7] Unlike radio-frequency-based communications, where the wireless channels can be considerably faded by multi-path transmissions, in LANETs VLC links are largely dominated by LOS transmissions and the resulting wireless channel quality can be much more stable than its RF counterparts and hence is easier to predict. By predicting the channel quality of the links belonging to a route, transport layer protocols can response in a proactive manner to the route outages, e.g., by allocating higher data rate to routes with higher predicated throughput if multiple routes are available.

links of tens meters [52] have been be achieved. By jointly taking the advantages of directionality and predictability of VLC links, LANETs are envisioned to have the potential to unlock the capacity of wireless ad hoc networks, typically resulting in large BDPs.

Therefore, delay-based TCPs are more suitable to LANETs since they have been proven to outperform loss-based TCPs in networks with large BDPs [112]. These protocols adjust the transmission window size based on the measured end-to-end delay: increase the window size if the delay increases and decrease the window size otherwise. Because the network congestion can be indicated more accurately, network resources can be almost fully used with increased network throughput. Main problems of delay-based TCPs are that, they are incompatible with the standard TCPs, and may lead to unfair network resource allocation if it coexists with loss-based TCPs. A possible solution, as in [121], is to design transport layer protocols by jointly considering packet loss and delay.

**Transport layer of LANETs**. To date, there are only few research work focusing on transport layer protocol design and performance evaluation in VLC networks [122–125]. In [122], Mai et al. study the effects of link layer protocols on the performance of TCP over VLC networks. Automatic-repeat request, selective repeat (ARQ-SR) protocol is considered at the link layer, and they find that TCP throughput can be considerably affected by the ISI and reflection of visible light signals, and ARQ-SR could significantly improve the achievable TCP throughput if the number of re-transmissions is properly selected. In [123], Kushal et al. present a visible-light-based protocol to provide reliable machine-to-machine communications. A flow control algorithm similar to TCP has been integrated into the proposed protocol to deal with dynamic ambient brightness. Different from standard TCP, the flow control algorithm there adjusts the packet size based on if previous packets can be successfully delivered. Through experiment results, with given communication distance and angular variation of transmitter, a sharp drop off in packet delivery ratio can be observed if the packet size exceeds certain threshold, which calls for a joint optimization of packet size at transport layer and communication link distance at physical layer. In [124] Sevincer et al. and [125] Bilgi and Yuksel , discuss the effects of intermittent alignment-misalignment behaviors of VLC links at physical layer on the TCP stability at transport layer. They argue that a special buffer should be introduced to make the physical layer more tolerable to the intermittency, and hence mitigate the link-layer packet loss and further make the transport layer protocols less sensitive to the intermittency. Since larger buffer may increase queueing delay, a tradeoff needs to be achieved at transport layer between route connectivity and end-to-end delay.

### *8.2. Open research issues*

The performance of transport layer protocols can be considerably affected by the unique characteristics of LANETs at lower layers, including intermittent link connectivity, transceiver angular variation, and the channel-dependent layer-2 strategies, among others. Next, we identify the following open research issues at transport layer of LANETs.

- *Blockage-aware LANET transport protocol design.* In traditional ad hoc wireless networks, dynamic network topology changes are usually caused by the unrestricted mobility of the nodes in the network, which will further lead to frequent changes in the connectivity of wireless links and hence rerouting at the network layer. If the frequent route reestablishment time is greater than the retransmission timeout (RTO) period of the TCP sender, then the TCP sender assumes congestion in the network, and retransmits the lost packets, and initiates the congestion control algorithm. This phenomenon may be even severer in LANETs because visible light links are easily blocked. Frequent blockage will further introduce dynamic changes of the topology. Therefore, how to design *blockage-aware* LANET transport protocols is challenging and substantially unexplored.
- *Application-specific transport protocols*. LANETs have a great potential to support a diverse set of multimedia applications, and the transport layer protocols can be designed by considering the requirements of specific applications in terms of reliability, throughput, delay, mobility, energy efficiency, among others. For example, to ensure reliable delivery of key frames for video streaming, multiple-path transport protocol can be used and then transmit the packets of key frames through different paths; consequently, the probability of a whole key frame is dropped due to VLC link outage along multiple paths can be considerably reduced.

## 9. Cross-layer design

In previous sections, we have discussed existing research work and remaining open issues at different layers of the network protocol stack of LANETs. The lessons learned from the discussions are that, the unique visible light communications impose both challenges and opportunities in the design of LANETs, and it calls for cross-layer design to address these challenges and to exploit the new opportunities. Next, we first classify existing research activities in cross-layer design in LANETs, and then point out future research directions.

### *9.1. Existing cross-layer research activities*

- *Joint Link and Physical Layers*. The objectives of jointly considering link and physical layer in VLC networks design are to (i) improve the achievable throughput by designing channel-aware link layer transmission schemes [17] and multi-user channel access strategies [126–130]; (ii) mitigate the negative effects of visible light channels on link stability and availability, e.g., use intra-frame bidirectional transmission in favor of easier transmitter-receiver alignment [131], reduce the SNR fluctuations of VLC channels through LED lamp arrangement [132]; and (iii) enable seamless handover in VLC networks by accurately sensing mobile users [133].
- *Joint network, link and physical layers*. Network layer can be designed together with lower layer protocols to mitigate the limitations of VLC in transmission distance and directionality, and hence to extend the coverage and enhance the reliability VLC networks. In [134], Wu design a multi-hop multi-access VLC network, where the source node searches for a multi-hop path if the direct link is blocked; in [135], Liu et al. show that improved end-to-end delivery ratio can be achieved by using multi-path routing to account for the intermittent blockage problem of VLC links in vehicular visible light communication (V2LC) networks. It is shown that the capacity of VLC networks can be considerably enhanced by establishing multiple concurrent full-duplex paths to take the advantage of directional transmissions [136]. In [137], Ashok et al. propose a visual MIMO physical layer transmission scheme that has a great potential to extend the communication distance in mobile visual light networks; challenges imposed by visual MIMO on the design of MAC and Network protocol layers have also been discussed.
- *Joint transport and link layers*. As discussed in Section 8, transport layer has been overlooked in existing literature with only few performance evaluation results reported [122,125], and we

believe it is an important research direction to incorporate transport layer into the cross-layer design of VLC networks.

It can be noticed that cross-layer optimization of VLC networks is still in its infancy, with most existing research focusing on simulation-/experiments-based performance analysis of protocols at different network layers [122,125–128,130], or treating the cross-layer optimization problems heuristically without theoretically guaranteed optimality and convergence of the resulting cross-layer algorithms and protocols [132,134–137]. To date, there is still no mature systematic methodologies that can be used to deign cross layer network protocols for infrastructure-less visible light communication networks, which we believe is a key research direction towards LANETs. Next, we discuss the challenges with cross-layer design for LANETs based on software-defined networking (SDN), a newly emerging network design architecture.

### *9.2. Open research issues: Software-defined LANETs*

The notion of software defined networking (SDN) has been recently introduced to simplify network control and to make it easier to introduce and deploy new applications and services as compared to classical hardware-dependent approaches [138]. The main ideas are (i) to separate the data plane from the control plane; and (ii) to introduce novel network control functionalities that are defined based on an abstract and centralized representation of the network. Software defined networking has been envisioned as a way to programmatically control networks based on well-defined abstractions.

So far, however, most work on SDNs has concentrated on commercial infrastructure-based wired networks, with some recent work addressing wireless networks. However, *applications of software-defined networking concepts to infrastructureless wireless networks such as LANETs are substantially unexplored*. The reasons are multi-fold:

- Essentially, the distributed control problems in LANETs are much more complex and hard to separate into basic, isolated functionalities (i.e., layers in traditional networking architectures). Similar to traditional wireless ad hoc networks [46,47,139,140], as discussed above in this section, control problems in LANETs involve making resource allocation decisions at multiple layers of the network protocol stack that are inherently and tightly coupled because of the shared wireless radio transmission medium; conversely, in software-defined commercial wired networks one can concentrate on routing at the network layer in isolation.
- Moreover, in the current instantiations of this idea, SDN is realized by (i) removing control decisions from the hardware, e.g., switches, (ii) by enabling hardware (e.g., switches, routers) to be remotely programmed through an open and standardized interface, e.g., Openflow [141], and (iii) by using a centralized network controller to define the behavior and operation of the network forwarding infrastructure. This unavoidably requires a high-speed fronthaul infrastructure to connect the edge nodes with the centralized network controller, which is typically not available in LANETs where network nodes need to make distributed, optimal, cross-layer control decisions at all layers to maximize the network performance while keeping the network scalable, reliable, and easy to deploy.

Clearly, these problems cannot be solved with existing approaches, and calls for new approaches following which one can design protocols for LANETs in a *software-defined, distributed*, and *cross-layer* fashion.

## 10. Conclusions

In this paper, we studied the basic principles and challenges in designing and prototyping *visible-light ad hoc networks*. We first examined emerging visible light communication techniques, discussed how VLC can be used to enable a diverse set of new applications, and analyzed the main differences between LANETs and traditional MANETs. We then examined currently available VLC devices, testbed and existing physical and MAC layer protocols and the related standardization activities at these two layers. In network layer, we discussed the challenges in route establishment caused by the directionality of visible light link and its narrow FOV, and in transport layer we compared existing congestion control protocols and pointed out that none of them can suit well in LANETs. Finally, we pointed out that it is essential to develop a systematic cross-layer design methodology towards unlocking the capacity of wireless ad hoc networks via LANETs, and the challenges to accomplish software-defined LANETs were also discussed.

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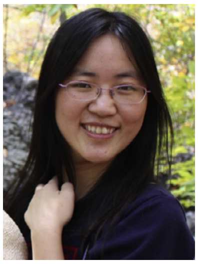
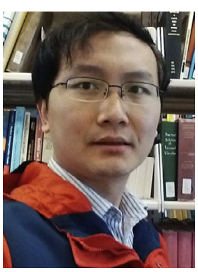


**Nan Cen** (S'09) received the B.S. and M.S. degrees in wireless communication engineering from the University of Shandong, Jinan, China, in 2008 and 2011, respectively, and the M.S. degree in electrical engineering from the State University of New York at Buffalo, Buffalo, NY, USA, in 2014. She is currently working toward the Ph.D. degree in electrical and computer engineering at Northeastern University, Boston, MA, USA. She is currently working with the Wireless Networks and Embedded Systems Laboratory, Northeastern University, under the guidance of Prof. T. Melodia. Her current research interest focuses on wireless multi-view video streaming based on compressed sensing, massive MIMO and visible light communications.

**Jithin Jagannath** is a Ph.D. student in the Department of Electrical and Computer Engineering at Northeastern University. He is currently conducting research in the Wireless Networks and Embedded Systems Laboratory under the guidance of Prof. Tommaso Melodia. He is also an Associate Senior Scientist/Engineer at ANDRO Computational Solutions in Rome, NY. He received his Master of Science degree in Electrical Engineering from University at Buffalo, The State University of New York in 2013. His research interest includes software defined radio, visible light communication, cognitive Networks, underwater sensor network and automatic modulation classification.

**Simone Moretti** was born in Rimini, Italy, on 29 June 1983. He received the Ph.D. degree in Electronic, Telecommunications and Information Technology in May 2016 from the University of Bologna, Italy. He received the Master's degree in Electronic and Telecomunications Engineering in July 2009 from the University of Bologna, Italy. Currently, he is a post-doctoral research fellow at Department of Electrical, Electronic and Information Engineering (DEI) "Guglielmo Marconi", University of Bologna, Italy. His main research interest cover multimedia data processing and communications, radio resource optimization and multi-source wireless communications systems.



**Zhangyu Guan** (S'09-M'11) received the Ph.D. degree in communication and information systems from Shandong University, Jinan, China, in 2010. He is currently an Associate Research Scientist with the Department of Electrical and Computer Engineering, Northeastern University, Boston, MA, USA. He was previously a Visiting Ph.D. Student with the Department of Electrical Engineering, State University of New York (SUNY) at Buffalo, Buffalo, NY, USA, from 2009 to 2010. He was a Lecturer with Shandong University from 2011 to 2014. He was a Postdoctoral Research Associate with the Department of Electrical Engineering, SUNY Buffalo, from 2012 to 2015. His current research interests include cognitive and software-defined Internet of Things (IoT), wireless multimedia sensor networks, and underwater networks. Dr. Guan has served as a TPC Member for IEEE INFOCOM 2016–2017, IEEE GLOBECOM 2015–2017, and IEEE ICNC 2012–2017, and served as a reviewer for the IEEE/ACM Transactions on Networking and the IEEE Journal on Selected areas in Communications, among others.

**Tommaso Melodia** (S'02-M'07-SM'16) received the Ph.D. degree in electrical and computer engineering from the Georgia Institute of Technology, Atlanta, GA, USA, in 2007. He is the William Lincoln Smith Professor with the Department of Electrical and Computer Engineering, Northeastern University, Boston, MA, USA. He is serving as the lead PI on multiple grants from U.S. federal agencies including the National Science Foundation, the Air Force Research Laboratory, the Office of Naval Research, and the Army Research Office. His research focuses on modeling, optimization, and experimental evaluation of wireless networked systems, with applications to sensor networks and the Internet of Things, software-defined networking, and body area networks. Prof. Melodia is an Associate Editor for the IEEE Transactions on Wireless Communications, the IEEE Transactions on Mobile Computing, the IEEE Transactions on Multimedia, the IEEE Transactions on Biological, Molecular, and Multi-scale Communications, Computer Networks, and Smart Health. He will be the Technical Program Committee Chair for IEEE INFOCOM 2018. He is a recipient of the National Science Foundation CAREER award and of several other awards.