LIGHTNETs: Smart LIGHTing and Mobile Optical Wireless NETworks – A Survey

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***Abstract*—Recently, rapid increase of mobile devices pushed the radio frequency (RF)-based wireless technologies to their limits. Free-space-optical (FSO), a.k.a. optical wireless, communication has been considered as one of the viable solutions to respond to the ever-increasing wireless capacity demand. Particularly, Visible Light Communication (VLC) which uses light emitting diode (LED) based smart lighting technology provides an opportunity and infrastructure for the high-speed low-cost wireless communication. Though stemming from the same core technology, the smart lighting and FSO communication have inherent tradeoffs amongst each other. In this paper, we present a tutorial and survey of advances in these two technologies and explore the potential for integration of the two as a single field of study: *LIGHTNETs*. We focus our survey to the context of mobile communications given the recent pressing needs in mobile wireless networking. We deliberate on key challenges involved in designing technologies jointly performing the two functions simultaneously: *LIGHT*ing and *NET*working.**

***Index Terms*—Visible Light Communication, Smart Lighting, Infrared Communication, Free Space Optics**

I. Introduction

RECENT proliferation of wireless technologies and choices available to user applications have triggered a tremendous wireless demand, and the wireless nodes are expected to dominate the Internet soon [1]. The availability of wireless resources as substrates has caused an ever-increasing variety of applications [2]. Recent reports show that usage of mobile Web [3] and WiFi by smartphones is increasing sharply. Accommodating this growing wireless demand with cellular capacity does not seem possible in the long run. Further, the capacity gap between radio frequency (RF) wireless and optical fiber (wired) network speeds will remain huge because of the limited availability of RF spectrum [4]. Though efforts for an all-optical Internet [5] will likely provide cost-effective solutions to the last-mile problem within the wireline context, high-speed Internet availability for mobile ad hoc nodes is still mainly driven by the RF spectrum saturation and spectral efficiency gains through innovative techniques such as hierarchical cooperative [6] multi-input multi-output (MIMO) or orthogonal frequency division multiplexing (OFDM)-supported MIMO [7]. As the RF spectrum is getting scarcer, the push for more wireless bandwidth is driving wireless technologies in alternative spectrum bands into the networking field [8]. Free-space-optical (FSO), a.k.a. optical wireless, communications has been one of these technologies complementary to the traditional RF.

FSO communications is becoming more of a candidate for core networking technology rather than its traditional treatment as a subnetwork. Recent research explored the potential for FSO communication in the several contexts including very high-speed mobile ad-hoc and opportunistic networking, vehicular networks, satellite constellations and as the core subject of this paper in visible light communication (VLC) systems. For most of these applications, required optical components such as Light Emitting Diodes (LEDs) and photodetectors (PDs) are cheap (less than $1), small, low weight (less than 1gm), amenable to dense integration (more than 1000 transceivers possible in 1 sqft), are very long lived/reliable (10 years lifetime), consume low power (100 microwatts for 10-100 Mbps), can be modulated at high speeds (1 GHz for LEDs and higher for lasers), offer highly directional beams for spatial reuse/security (1-10 microrad beam spread) and operate in large swathes of unlicensed spectrum amenable to wavelength division multiplexing (infrared/visible) as depicted in Figure 1. Availability of a large unlicensed optical spectrum and much lower power-per-bit cost of FSO in comparison to RF communications make it a great opportunity for future spectrum-scarce mobile networks and power-hungry sensor networks [9]. VLC with its broad spectral range, relatively cheaper and ubiquitously available components is a fast developing field with many potential applications.

Solid-state (a.k.a. smart) lighting (SSL) is superior to existing lighting technologies due to durability and low-power usage of optoelectronic devices. Recent advances in production of such devices have made solid-state lighting an economically viable technology. Smart lighting devices with multiple LEDs (i.e. multi-element) are heavily getting deployed and commercialized. It is expected that multi-element smart lighting devices will soon outnumber the traditional lighting technologies. The energy gains and long-term cost-efficiency possible with smart lighting devices are very attractive and urge further research work on the VLC technology to realize the potentially higher gains.

Though stemming from the same core technology, the smart lighting and VLC have inherent tradeoffs amongst each

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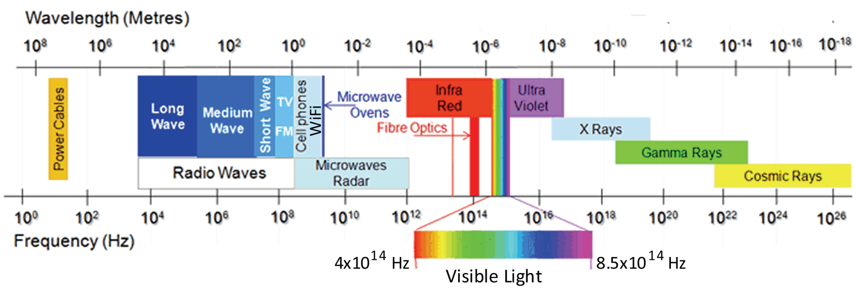

Fig. 1. Electromagnetic spectrum usage (Modified from [10]).

other. The lighting efficiency (e.g., the illuminated area) is maximized when divergence angle of optoelectronic transmitter is high whereas the communication efficiency (e.g., the transmission range) is maximized when it is small. If these tradeoffs are balanced well, there is a high reward opportunity at intersection of the two areas involving unique set of possible applications [11]. Nevertheless, VLC has been investigated primarily for communication purposes in the existing literature, neglecting the needs and constraints for illumination aspects. In this paper, we survey recent advances in these two technologies and explore the potential of their integration into a single field of study: *LIGHTNETs* to research and develop a new technology performing the two functions simultaneously: *LIGHT*ing and *NET*working. It should be noted that there has been not much work in the joint design of lighting and communication systems considering the respective constraints for both purposes. Therefore, we do not focus on the field of joint design issues in this survey, which is currently narrow, but rather, cover the fundamentals of SSL and FSO as much as possible while trying to keep them relevant to *LIGHTNETs*. Furthermore, we narrow our FSO survey to mobility and networking issues and VLC which is a subarea of FSO communication. We believe that the developments in networking and protocols for FSO communication systems can directly benefit the future *LIGHTNETs*. Considering the diverse technical background of the potential readers we also provide a background on both field while keeping the coverage to relevant issues to the extent possible.

The rest of the survey is organized as follows: Section II covers basics of FSO communications and discusses various crucial tradeoffs for FSO-based communication, with an emphasis on mobile networking. Next, Section III covers issues involved in optoelectronic design of multi-element solid-state modules and relates them to VLC systems. Section IV starts with a briefing of FSO communication history in terms of spectral differences in infrared and visible bands, and focuses our survey on recent research in VLC systems along with characteristics of basic VLC channels. Finally, Section V summarizes the survey and embarks a discussion of challenges in designing *LIGHTNETs* technologies that light and network simultaneously.

Different paths exist for readers with varying backgrounds. A reader novice in FSO communication should first read Section II to gain insights into the fundamental issues in FSO communication. Likewise, a reader novice in SSL should start with Section III. Regardless of the background, we think that subsections on mobility and directionality issues in FSO communications (i.e., Sections II-B and II-D) and packaging issues in SSL (i.e., Sections III-B1 and III-B2) are must reads for those who desire to gain insights into the future *LIGHTNETs* where multi-element optoelectronic structures to be utilized for both lighting and mobile communications.

II. Free-Space-Optical (FSO) Communication

The idea of using optical signals for communication is not new. In fact, Bell proposed the idea of "photophone transmitter" and patented it in 1880 [12]. The "photophone" allowed for the transmission of sound via optical signal between two buildings, some 213 meters apart on June 3, 1880. Photophone, however, did not become a reality due to the lack of advanced optical components for reliable communication. Use of optical signal for reliable data transmission become possible only after 1966 when Kao and Hockham demonstrated that glass fibers could be used as transmission lines for light akin to coaxial cables for electrical signals [13]. Later, with the advances in optical emitters and detectors, Bell's idea of optical wireless communication has become a reality in different forms.

A typical optical communication system consists of (i) a transmitter, which encodes a message into an optical signal, (ii) a channel, which carries the signal to its destination, and (iii) a receiver, which decodes the message from the received optical signal as depicted in Figure 2. The transmitter performs as a modulated light source that transmits an optical signal, and a photodetector at the receiving end reproduces the received optical signal and converts to an electrical signal. The medium in between the transmitter and the receiver attenuates or distorts the signal. Fiber-optic communication uses a guided medium known as 'fiber' to propagate the light to the receiver. Optical fibers can carry light signals across greater distances with less loss than metal wires and are immune to electromagnetic interference. Optical fiber has significantly lower attenuation compared to existing copper wire in long-distance high-speed applications. Fiber optic communication systems are widely used in the *wireline* telecommunications industry and have largely replaced copper wires due to their many advantages over electrical transmission, particularly due to the large capacity of the optical spectrum.

A special form of optical communication uses 'free space' as the transmission medium and is known as free-space-optical (a.k.a. optical wireless) communication. As a *wireless* technology, FSO communication has recently attracted significant

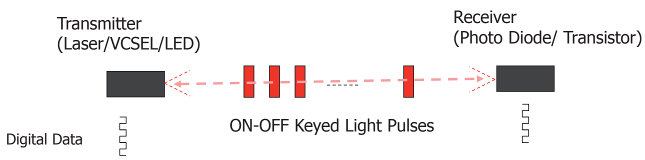

Fig. 2. Simplified schematics of a typical FSO communication system.

interest from telecommunication research and industry, mainly due to the increasing capacity crunch faced by the RF wireless technologies. Among other benefits, FSO communication provides a much larger bandwidth but exhibits very different propagation and channel characteristics than the legacy RF systems.

Until recently, the main focus of FSO communication technologies has been building point-to-point communications using highly expensive materials (e.g., mechanical steering mechanisms and lasers) to reach long distances. There are many FSO communication systems today which are being used in numerous applications, including:

- complementary backhaul to existing wireless technologies [14]
- short-term wireless connection for information exchange between two portables, such as infrared links
- building-to-building connections for high speed network access or wide area networks [15]
- wireless input or control devices, such as remote controls and wireless game controllers [16]
- wireless local area networks (WLANs) [17]
- communication between space crafts and satellite constellation [18]
- inter- and intra-chip communication

The most commonly used components for FSO transmitters are laser diodes (LDs) and LEDs. Compared to LDs, LEDs are cheaper and they have longer lifetime. They can be modulated at high speeds but the optical power outputs are less than LDs. High optical output power of LDs poses potential risks for human eye and, therefore, prevents their indoor use. Laser beams may result in permanent blindness if a human retina is faced with a laser source because LDs are highly directional radiation sources and can deliver very high power within a small area. On the other hand, LEDs consume low power, and they are not highly directional as LDs and are safe at higher power compared to LDs. This is the key reason why LEDs are preferred for most indoor applications. Power consumption is also a big advantage for LEDs. Since LEDs consume much less power than lasers; they are preferred for most applications where power budget is a concern.

A. FSO Propagation Model

The important difference between a fiber-optical and FSO link is the lack of a reliable medium for the propagation of light. In the following subsections, we will cover some of the key characteristics of the FSO propagation.

1) Geometrical Loss: Geometrical loss accounts for the losses that occur due to the divergence of the optical beam originating from the FSO source transmitter, as illustrated in Figure 3. The result of divergence is that some or most of the

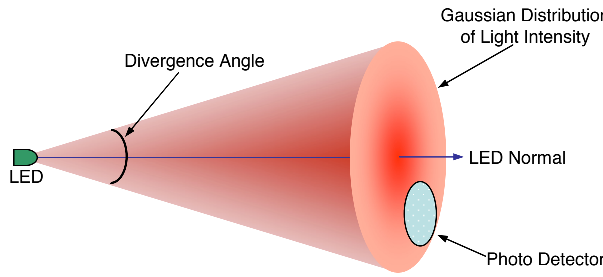

Fig. 3. Light intensity profile of an optical beam.

beam is not collected at the receiving side. The loss can be roughly sketched as the area of receiver relative to the area of the beam at the receiver. We can accurately assume that the cone formed by the beam has a triangular form when viewed from the side. If we measure the diameters in cm, the distance in km and the divergence in $mrad$, the formula for calculating the geometrical loss becomes [19]:

$$\frac{A_R}{A_B} = \left(\frac{D_R}{D_T + 100 * d * \theta}\right)^2 \tag{1}$$

with the following parameters:

	Parameter Descriptions
A_R	Area of the receiver
A_B	Area of the beam
D_R	Diameter of the receiver
D_T	Diameter of the transmitter
d	Separation of transmitter and receiver
θ	Divergence angle

2) Atmospheric Loss: The atmosphere causes signal degradation and attenuation in a free-space-optical link in several ways, including absorption, scattering (mainly modeled as Mie scattering), and scintillation. All these effects vary in time and basically depend on the condition of the weather. The atmospheric attenuation A_L consists of absorption and scattering of the laser light photons by the different aerosols and gaseous molecules in the atmosphere. The power loss due to atmospheric propagation is given by Beer-Lambert Law [20] as:

$$A_L = 10\log(e^{-\sigma R}) \tag{2}$$

where σ is the attenuation coefficient consisting of atmospheric absorption and scattering. Mie scattering occurs because of the particles that are about the size of beam wavelength. Therefore, in the near infrared wavelength range, fog, haze, and pollution caused by the aerosols are the major contributors to the Mie scattering effect. There are also scattering models, but for the wavelengths used for FSO communication, Mie scattering dominates the other losses and it is given by [20], [21]:

$$\sigma = \frac{3.91}{V}\left(\frac{\lambda}{550}\right)^{-q}. \tag{3}$$

In the above formulation of σ, V is the atmospheric visibility in kilometers, q is the size distribution of the scattering particles whose value is dependent on the visibility [19]:

$$q = \begin{cases} 1.6 & V \geq 50\text{km} \\ 1.3 & 6\text{km} \leq V < 50\text{km} \\ 0.583V^{1/3} & V < 6\text{km} \end{cases} \quad (4)$$

The above losses and receiver sensitivity threshold must be taken into account for calculation of the link margin. Once the signal power at the receiver is calculated, error probability is calculated using the received power, subjecting this power value to geometric loss as described in Equation 1, distributing this power with a Gaussian profile around the normal of the transmitter, and using current interference from neighboring transmissions as follows [20]:

$$F_n = F_a/0.9903 \quad (5)$$

$$r = P_{GA}/N \quad (6)$$

$$P_e = erfc(\sqrt{r} * F_n) \quad (7)$$

where F_a is the atmospheric attenuation factor, F_n is the normalized factor, r is the signal to noise (and interference) ratio after signal is subjected to geometric losses, $erfc$ is the complementary error function, and, the resulting quantity, P_e, is the probability of error for a single bit.

B. Directionality: High Capacity via Spatial Reuse

A key property of FSO communications is its directional propagation, which allows high spatial reuse and attain much larger aggregate network capacity. In this section, we survey the FSO literature on using directionality along with related developments in directional RF. We make a comparative discussion of FSO directionality with more established RF technologies. We limit RF-related discussions only to directionality and channel gain tradeoffs, which are inherent in FSO. We also consider the possibility of complementing RF with FSO communication technologies.

1) Divergence Angle and Channel Gain Tradeoffs: The tradeoff between wireless beam directionality and diversity has been an attractive research topic spanning various parts of the electromagnetic spectrum [22]. Compared to an omnidirectional antenna, a directional antenna can provide better transmit and receive gain for a targeted direction while having better immunity to channel interference [23]. In a directional communication scheme, when the mobility of the nodes must be taken into account the directionality must be steered appropriately for the link persistence. Steering must be done in such a way that connectivity can be preserved to the appropriate node seamlessly.

Navda et al. [24] explored the use of directional antennas and beam steering techniques to improve performance of 802.11 links for the scenarios where access points (APs) and moving vehicles are involved to communicate. The aim was to maximize the throughput by selecting the best AP and beam combination for a drive given the information path. In comparison to an omnidirectional antenna, the authors achieved better throughput at an order of 2-4, improved connectivity duration more than a factor of 2, and 15dB improved SNR compared to an omnidirectional scheme. Ramachandran et al. [22] followed with a similar study where they combined both directionality and base station diversity for improving the uplink connectivity of mobile clients. They achieved an uplink increase up to 154% over pure beam-steering and 45% over pure base station diversity. Further improvements were attained by consideration of link layer multicasting with switched beam-forming antennas [25]. For indoor directional communication, phased arrays were to increase spatial reuse by optimizing the placement of directional antennas to achieve maximized overall network capacity [26].

2) Directionality Effects on Higher Layers: In comparison to RF communication characteristics, FSO has critical differences in terms of error behavior, power requirements and different types of hidden node problems. An important FSO communication characteristic is the directionality in communication similar to RF directional antennas. FSO transmitters can be much more directional than directional RF counterparts. Perhaps, the key differentiating property of the directionality of FSO transmitters is the fact that they have much smaller form factors than RF ones, and many of them can be packaged into very small volumes. Different than RF directional antennas, each FSO transceiver can be made to cover a tiny angle as small as a few milli radians.

Such high directionality can be leveraged at higher layers via simple abstractions. For instance, a much better estimation of angle-of-arrival (AoA) is possible by assigning each FSO transceiver to an arrival angle. AoA estimation has not been possible in omnidirectional RF transceivers, and thus the traditional localization techniques used signal strength estimations. Recent work showed that FSO-based localization is possible by using multi-transceiver FSO structures capable of AoA estimation with potentially better accuracy depending on the divergence angle of the used transceivers [27].

In [23], authors design a directional MAC protocol that adapts key ideas from IEEE 802.11 MAC to a hybrid system with both omni and directional transceivers. A node is able to steer the antenna to point to a desired angle. For this *Simple Directional MAC (DMAC)* approach, they implemented RTS and CTS signaling in directional mode. Similar to the Network Allocation Vector (NAV) in 802.11, a directional version is introduced (DNAV) to keep track of allocation of the time domain and *space domain with a local sense of direction*. A node looks up entries from this table whenever it needs to send an RTS to a specific direction. They found that the hidden terminal problem in 802.11 MAC reveals itself in two new forms. First, because the gain of a directional and an omnidirectional antenna with the same transmit power are different (i.e., directional gain is greater), sender and receiver nodes with transmit and receive gains of G^d (directional gain) and G^o (omnidirectional gain), respectively, may be out of each other's range, but may be within range if they both transmit and receive with gain G^d. Secondly, a node that participates in an ongoing transmission (nodes A and B, Figure 4) will not hear RTS/CTS frames (exchanged with C and D) since its antenna is directed to a specific point. Upon completion of its transmission, the two nodes, A and B, are potential interferers to the nodes that are around them (C and D). In their multi-hop RTS based algorithm (MMAC),

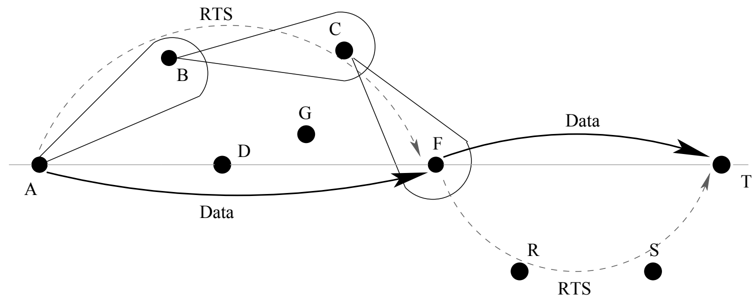

Fig. 4. Multi-Hop RTS [23].

authors propose that when two nodes wish to communicate directly in one hop via their directional antennas instead of through multiple hops via their omnidirectional antennas, the sender node sends out a multi-hop RTS frame through its omnidirectional antenna. A slightly smarter way to select sectored antennas for RTS/CTS exchange is to gradually learn if there are nodes residing in the coverage areas of those antennas [28]. In this approach, only the antennas that can reach an immediate neighbor are included into the signaling.

Additionally, Choudhury *et al.* evaluate the performance of DSR (Dynamic Source Routing) using directional antennas in [29]. They identify issues that emerge from executing DSR (originally designed for omnidirectional antennas) over directional antennas. They observe that route request (RREQ) floods of DSR are subject to degraded performance due to directional transmission and do not cover as much space as omnidirectional transmission. This makes route reply (RREP) take a longer amount of time and this in turn degrades the overall performance of the routing protocol.

Another upper layer implication of FSO communication is that it aids in node localization. The problem of node localization has been tackled by various methods: Using ranging techniques [30], bearing techniques, and combination of the two [31]. Robotics and image community has been working on the localization problem using landmark detection techniques and laser range finders. However those methodologies are less practical for ad-hoc network localization due to either power requirements or lack of a camera in an ad-hoc node. Range-based methods require at least 3 localized nodes (4 in a 3-D setting) to enable localization of a fourth node with varying degrees of quality. Major limitation of range-only methods is that they require high density of nodes to achieve high localization coverage. SpotON [32] and Calamari [30] systems build on the assumption of a simple path propagation model with known parameters for RF whereas this does not hold in practical environments where multi-path propagation is the norm especially in indoor settings to score a 10% error in ranging even after an intense calibration process.

Akella *et al.* proposed a hybrid technique [27] that uses optical wireless (FSO) combined with ranging techniques. They require only one localized neighbor reducing the node density requirement considerably. The method is appropriate especially for low-density and intermittently connected networks with accuracy trade-offs. However, their need for range measurement is, although achievable using signal strength measurements, requires extra computational complexity and it is prone to measurement errors. A key characteristic of the proposed solution in [31] is to use *optical-only techniques* to achieve localization as depicted in Figure 5. Authors found that low-power localization is possible in ad hoc networks with directional optical transceivers if 2-connectedness can be guaranteed with varying accuracy based on the divergence angle of the transceivers.

A key characteristic of multi-element FSO communication that affects transport performance is its highly intermittent connectivity pattern arising from alignment-misalignment periods. Such on-off error behavior is not common in legacy RF channels and can have severely adverse effects on the end-to-end transport performance due to potential confusion of misalignments with congestion indication. We believe that FSO physical layer should be more tolerant to intermittency by retaining packets for possible retransmission in a special buffer [33]. We anticipate that this buffer shall be large enough only to accommodate the intermittency during misalignment periods and present a much smoother physical layer to MAC and upper layers to remedy unintended consequences. With such a buffering mechanism, upper layers observe a higher propagation delay at the physical channel instead of frequent disconnections, and, this alleviates much of the sensitivities of TCP.

3) Capacity Scaling: One of the main motivation of FSO communication is the possibility of high spatial reuse by leveraging directionality of transceivers. The capacity of RF-based multi-hop of mobile ad-hoc networks (MANETs) is known to be not scaling, since the per-node throughput in such networks reduces when there is an increase in the number of actively communicating nodes. RF per-node throughput scales with $\sqrt{n}$ as the number of nodes, n, grows since RF interference dominates the throughput behavior because of the omnidirectional propagation [34]. Kumar et al. showed that the $O(1/\sqrt{n})$ value is achieved for an optimal node placement and communication pattern. Additionally in [35], [36], authors showed that average long-term throughput per source-destination pair can be kept constant under some boundaries such as exploiting mobility to keep data transfer local, and transmitting only when the transmitter and receiver are close

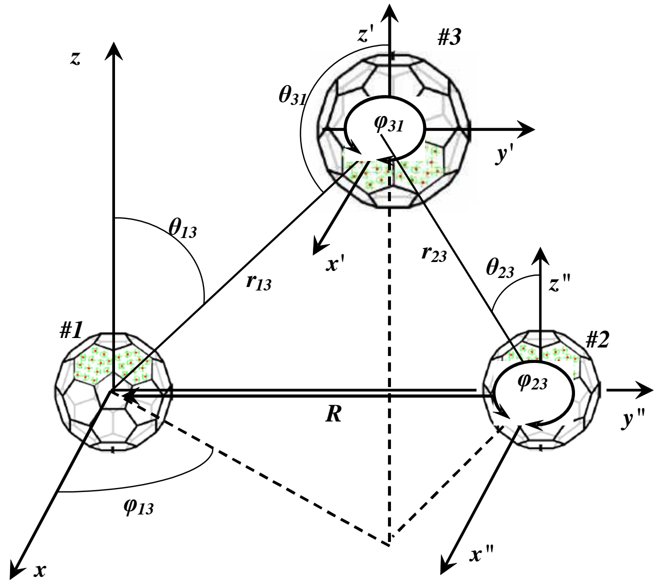

Fig. 5. A third node triangulating using the advertised normals received from two other localized or GPS-enabled nodes.

to each other in such a way that the resource usage and interference can be reduced. Both studies in [35] and [36] showed that per node throughput stays roughly constant as the network size grows, however, with significant constraints on topology or mobility.

Later, in [6], optimal capacity scaling was achieved by using intelligent node cooperation and distributed MIMO (multiple input multiple output). The model used in [6] is based on three key ideas: MIMO for long range spatial multiplexing, local transmit and cooperation to maximize spatial reuse, and intra-cluster cooperation which enables hierarchical co-operation in smaller network. They showed that when small path loss exponent α is in (2,3], hierarchical cooperative communication is order optimal and outperforms the multi-hop communication; and for large path-loss exponents $\alpha > 3$, multi-hop communication is order optimal. Similar work was done by the authors of [37], [38] where capacity scaling is considered for extended arbitrary node placement instead of random extended placement in [6] and [34]. The authors achieved the same results for α being in (2,3], however their results differed for large path loss exponents showing that the scaling depends on the regularity of node placement. Similar works followed by the authors of [39] by considering arbitrary traffic patterns in arbitrarily placed extended wireless networks and define some sufficient conditions for the order of optimality of multihop communications covering all traffic patterns for $n \times n$ dimensional capacity region. Under the conditions of their network and traffic model considering their sufficient conditions they show that for exponential power decay multi-hop communication is order optimal regardless of node placement and traffic requirements.

FSO communication has much more potential for capacity scaling of multi-hop wireless networks or MANETs, as shown in recent studies [33]. Authors perform two different experiments and compare per-node and overall network throughput results with the same RF scenarios. First, they increase the number of nodes in a confined area and keep other parameters same. Second, they increase the area size and keep the number of nodes and all the other parameters the same. In the first scenario they observe that the drop in throughput is much more significant in RF scenario compared to FSO scenario due to the fact that interference starts to dominate the channel accessibility in a highly dense omnidirectional setting. In the second scenario they observe an increase in the throughput while node density is decreasing. This reflects that the initial node density was still high to cause interference which reduces as the area is enlarged. When the area is further enlarged, FSO starts to experience coverage issues and the throughput drops as a result.

C. Stationary Scenarios

The most heavy usage of FSO communication has been in immobile settings where the main focus has been to reach longer communication ranges with higher speeds. A significant part of the existing FSO communication technology is used at high altitudes (e.g., space, satellite, building tops). Though such immobile settings with highly sensitive and expensive FSO components are less relevant to our key theme in this paper, i.e., *LIGHTNETs*, we provide a brief coverage of the pretty large literature in immobile FSO communications. There exists an array of issues involved in bringing the traditionally high-altitude FSO communication technology to the lower altitudes where joint lighting and communications is plausible.

1) Point-to-Point and Mesh Networks: FSO technology has the potential to facilitate intensive bandwidth applications such as high speed data transfer and high definition video conferencing. FSO communication for wireless mesh networks has been mainly considered for roof-top installations where point-to-point or mesh architectures are established and limited spatial reuse or redundancy is achieved through one primary beam and some backup beams. This kind of FSO network is mainly suited for ultra broadband last mile access and residential services [40]. While point-to-point architectures operate at longer distances (2-4 kilometers), mesh FSO architectures operate over shorter distances with less throughput compared to point-to-point systems [41].

Success of FSO for ultra long distances is due to the fact that FSO transmitters are highly directional and can dissipate power in a focused manner rather than omni-directional spread as in RF signals. This directionality comes with a cost of LOS alignment problem, which requires smart mechanisms to manage LOS among transceivers during an ongoing transmission. Traditionally, this has been done via mechanical steering techniques which are very expensive and require high maintenance and sensitive equipment. Further, since they are essentially solutions targeted to solving limited physical movement, mechanical steering techniques are not fast enough to recover from disruptions caused by mobility. Majority of these steering and tracking methods are focused on point-to-point applications: Terrestrial last-mile, deep space [42], and building-top installations. Scenarios involving multi-point-to-multi-point communication are not considered by these mechanical steering approaches since the overall optimization problem becomes much more complicated in selecting which neighbor to align to. Hence, this kind of FSO deployment is typically a mesh network installation where the tracking/steering problem is reduced to maintaining alignment with one other neighbor, which we will delve into in Section II-D1.

Such multi-point deployments are mostly used for establishing a stationary backbone network with high throughput and mobility has been impractical due to unavailability of mechanisms that achieve automatic establishment of LOS alignment among mobile neighbors. Each neighbor has an optical access switch and the building itself provides an additional Ethernet stream. This provides the ability of sending beam to another building which has its own local area network. Buildings can contain multiple FSO systems and direct the beam to other buildings and establish a mesh network. This kind of last-mile FSO usage eliminates the need to lay cable, especially in geographically challenging environments while serving a large number of end nodes, each with little bandwidth requirements. The main problem in such scenarios has been the building sway and vibrations since the FSO communication equipments used for these networks are expected to perform at very high speeds, and thus, are typically very sensitive to misalignments. Various techniques have been developed for stationary deployments of FSO to tolerate small vibrations, swaying of the buildings and scintillation, using mechanical auto-tracking or beam steering [20].

Other research issues for FSO mesh networks have been similar to the ones in traditional mesh networking such as topology control. Most of the topology construction and maintenance techniques aim to optimize a network-wide metric such as network throughput, robustness to failures, or delay. Interesting issues arise when hybrid FSO/RF meshes are to be constructed. FSO networks can be used for the long distances at higher speeds with low interference and high security providing the quality of services required by the end users. The flexibility and scalability of reconfiguration based on the changes in traffic and node positions provides a good advantage of using FSO for wireless backbone networks. However, obscuration due to atmospheric conditions serves as the bottleneck in this scheme. The problem can be solved by using hybrid FSO/RF meshes where RF links serve as the backup when FSO is obscured. In order to achieve such kind of topology deployment, some problems should be taken into consideration: FSO systems are expensive and the deployment should be in an effective way to achieve maximum performance. This consideration brings the problem of topology control in FSO/RF mesh networks. Kashyap *et al.* studied the topology control and routing problems in FSO backbone networks and proposed algorithms that achieve better performance [43]. In their model with a limitation of the number of transmitters and receivers at each node, they assume that for a given transmitter and receiver pair, a transmitter can only transmit to only one receiver at any given point and receiver can only receive from one transmitter. Then goal of the study is to maximize the throughput while routing the traffic profile. They propose different algorithms for both single and multi-path topology structures to obtain near optimal solutions since the problem is NP-Hard. Kyle et al. follow the similar pattern by focusing on a graph theoretic framework [44]. Since their problem space is NP-Hard they propose two different algorithms to increase the delivery of maximal traffic flow across the network. Their algorithms include forming a minimum spanning tree (MST) or traveling salesman path (TSP) to guarantee the network's connectivity and connecting node pairs iteratively based on a recast metric with the constraint of node degree. Their algorithms produce optimal or close-to-optimal solutions. Compared to work in [43], the proposed algorithms outperform in traffic delivery but they have similar performance in network reliability. However, for larger networks these ideas (exhaustive search or an integer programming) become impractical. In the space of realistic dynamic scenarios, Grumani et al. propose a network of hybrid nodes with multiple transceivers and associations [45]. In the case of a failure, reconfiguration takes place with alternate FSO paths where such paths are established and prioritized through multiple associations. This kind of topology mechanism maintains the optical connection for longer periods of time which also increases the efficiency and performance of the network.

In the visible spectrum, FSO point-to-point and mesh networking have also been considered for lighting in smart buildings [46]. NXP Semiconductor and GreenWave Reality recently announced a new line of networked LED light bulbs as an example of such networks [47]. The light bulbs are IPv6 addressable, and their illuminance can be controlled via a WiFi-based wireless link which is based on NXP's networking software, JenNet-IP. Jen-Net-IP is a network layer software that provides an IEEE 802.15.4-based mesh connectivity, specifically targeting low-power networking for residential and commercial applications. The complete system consists of high-quality connected LED bulbs that consume about 80% less energy than traditional incandescent bulbs, a hand-held remote controller to control the illumination, and a gateway for complete remote lighting control. Each bulb has a wireless antenna and a reliable mesh network between the bulbs can be established to strengthen the range of the network supporting up to 500 bulbs. The technology is standardized under IEEE 802.15 which specifies Wireless Personal Area Networks (WPANs).

Task Group 4 standardizes the IEEE 802.15.4 for low rate WPANs, which was the first standardization effort, and it was released in May 2003. The standard is mostly focused on low-cost, low-speed communication between nearby devices and low-power consumption. Since the idea of using VLC for data transmission is new, a mesh network employing a complete visible light system has not been implemented yet. Only hybrid systems combining VLC and IR with a wireless mesh backbone have been proposed [48]. However, the capability of controlling the illumination and assigning IP addresses to the light bulbs and using them for wireless communication [11] is a good start for extending the LIGHTNETs concept to the idea case of point-to-point and mesh networking. Simply, the bulbs can be used to broadcast or transfer data among each other while control frames such as alignment, association or route information are sent through Wi-Fi network. However, such idea will require further optimization to enable both illumination and communication. We discuss these issues in Sections III and IV.

2) Terrestrial Networks: FSO communication technologies use high-power lasers and expensive components to reach long distances. Thus, the main focus of the research has been on offering only a single primary beam (and some backup beams); or use expensive multi-laser systems to offer redundancy and some limited spatial reuse of the optical spectrum [20], [49]. Main target application of these FSO technologies has been to serve commercial point-to-point links which can operate 155 Mbps to 10 Gbps, from 300 meters to 7 kilometers (e.g., [41], [50])in terrestrial last mile applications and in infrared indoor LANs [20], [40], [51]. As an example, Canon [52] manufactures four different models of FSO transceivers capable of communicating 25 Mbps to 1.485 Gbps at 20 to 2000 meters of transmission range with a mechanical auto-tracking system which helps to manage the data transmission due to different environmental conditions such as building sway, wind, and temperature values. Another supplier MRV [15] announced the line-of-sight TereScope 10GE which is a 10 Gigabit Ethernet FSO system. MRV also has previous TS series capable of transmitting at 10 Mbps to 1.5 Gbps with up to a communication distance of 7 kms. Additionally, fSONA [41] and Lightpointe [14] announced different transceiver series that are capable of communicating at 2.5 Gbps with varying distances. Though cheaper devices (e.g. LEDs and VCSELs) have not been considered seriously for outdoor FSO in the past, recent work shows promising success in reaching longer distances by aggregation of multiple LEDs or VCSELs [15]. Compared with lasers or VCSELs, LEDs are modulated at lower speeds (up to 155 Mbps) but they are cheap, small, low weight, consume low power, and have longer life time. Most terrestrial FSO technologies (e.g., enterprise connectivity, last mile access network, and backup links) use infrared (IR) frequency band due to eye safety issues. Infrared wireless is a very simple form of FSO communication technology. Most infrared designs use LEDs as transmitters. Infrared FSO links can be implemented using infrared laser light, but low-data-rate communication over short distances mostly employ LEDs. Maximum range for LED-based terrestrial links is in the order of 2 to 3 km, but the stability and quality of the link is highly dependent on atmospheric factors such as rain, fog, dust, and heat.

D. Mobile Scenarios

1) LOS Alignment: FSO communication cannot penetrate through obstacles and needs line of sight (LOS) alignment. In order for the FSO to become a complementary communication medium for mobile wireless access, the key problem to be solved is its vulnerability against mobility [8]. The key limitation of FSO regarding *mobile* communications is the fact that *LOS alignment must be maintained* for communication to take place successfully. Since the optical beam is highly focused, it is not enough if LOS exists: The transmitter and the receiver must be aligned; and the alignment must be maintained to compensate for any sway or mobility in the nodes. Traditional solution approach to this problem of FSO communications has been to employ highly sensitive mechanical steering and tracking equipment with a powerful single transmitter such as a laser. The mechanical equipment physically rotates the transceiver to maintain the LOS alignment with the other device, which is also applying the same mechanical steering procedure. This approach can achieve establishing a wireless link even if the two communicating devices/nodes are moving with respect to each other. However, it produces device packages that are typically bulky in size, and thus, makes it very hard to develop portable FSO communication devices.

An alternative solution complementary to the aforementioned alignment mechanisms has been proposed in [19]. This solution considers an FSO structure where multiple transceivers are deployed on a soccer ball scheme. Authors implement a small detection and establishment protocol in order to maintain LOS of neighboring transceivers. Their protocol is able to detect the transceivers that are in line-of-sight of each other and assign logical flows to the appropriate transceiver. This mechanism is called "electronic steering" where it stands for an alternative solution to the traditional expensive and heavy LOS alignment mechanisms.

2) Angular Diversity and Diffuse Optics: Mobile communication using FSO is considered for indoor environments, within a single room, using diffuse optics technology [53], [54], including multi-element transmitter and receiver based antennas. Due to limited power of a single source that is being diffused to spread in all directions, these techniques are suitable for small distances (typically 10s of meters), but not suitable for longer distances.

O'Brien *et al.* provides an approach that can be used for in-building optical wireless communication and they argue for the need of an integrated and scalable approach to the fabricating of transceivers [54]. They use devices and components that are suitable for integration.

The tracking transmitter and receiver components(diffuse transmitters and multi-cell photodetectors) have the potential for use in the wide range of network architectures. They fabricated and tested the multi-cell photodetectors and diffuse transmitters, specifically seven transmitters and seven receivers operating at a wavelength of 980 nm and 1400 nm for eye-safety regulations. They designed transmitters and receivers to transmit 155 Mb/s data using Manchester Encoding. They compare optical access methods: a wide-angle high-power laser emitter scattering from the surfaces in the room to provide an optical ether or using directed line-of-sight paths between transmitter and receiver. In the first approach to transmitter design, although a wider coverage area is achieved, multiple paths between source and receiver cause dispersion of the channel, hence limiting its bandwidth. They found that the second approach has spatial reuse and directionality advantages, hence provides better data rates while not achieving a blanketing coverage. They conclude that directional optical communication will be dominant in the future beating non-directional optics and radio frequency communication because of its promising bandwidth. They project to overcome the line-of-sight problems in the near future using high precision micro-lenses and highly sensitive arrays of optical detectors.

The authors of [53] examine improvements obtained in wireless infrared (IR) communication links when one replaces traditional single-element receivers by imaging receivers and diffuse transmitters by multi-beam (quasi-diffuse) transmitters. They consider both line-of-sight (LOS) and non-line-

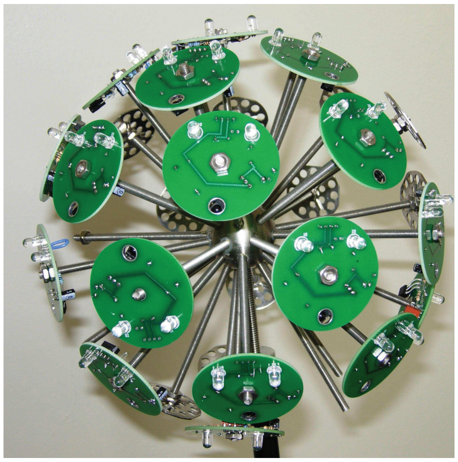

Fig. 6. Picture of a omni-directional free-space-optical antenna. [19]

of-sight (non-LOS) IR links. Obtained power gain is from $13dB$ to $20dB$ while still meeting acceptable bit error rates (10^{-9} with 88% probability) when Space Division Multiple Access (SDMA) is employed in the absence of co-channel interference. The authors encourage usage of quasi-diffuse (i.e., multiple beams) transmitters since they leverage Space Division Multiple Access (SDMA).

3) Multi-Element Designs with Electronic Steering: Recently, there has been some work on the beam coverage in FSO mobile network in order to overcome the misalignment problems caused by severe factors including vibration, motion and atmospheric turbulence by applying fiber-bundle approach to achieve continuous beam coverage at the receiver without the application of mechanical equipments. The authors of [55] apply multiple fibers at the transmitter side with special lens to illuminate a larger area at the receiver side. Again the focus has been on the transmission performance beam steering of the optical link to improve the performance when the misalignments takes place. Optical flow assignment has not been considered to manage multiple different data flows among transceivers during an on going transmission.

The idea of using multiple elements/transceivers in FSO communication has been used in interconnects [56], which communicate over very short distance (e.g., cms) within a computer rack or case. The main issues of such multi-element operation are interference (or cross-talk) between adjacent transceivers due to finite divergence of the light beam, and misalignment due to vibration. Multi-element operation has been suggested not only for increasing the capacity of the overall system, but also for achieving robustness due to spatial diversity in the case of misalignment.

Instead of mechanical steering over powerful and expensive FSO transmitters, a new approach has been proposed so called "electronic steering" over multiple cheap transceivers such as LEDs [19]. A proof-of-concept prototype (see Figure 6 of such a spherical FSO structure with multiple transceivers is presented and performance of such system is evaluated. Unlike the traditional mechanical steering mechanisms for LOS management, authors used a simple handshaking protocol to electronically steer the LOS alignment onto the correct transceiver. The main focus of their study focus on illustrating the feasibility of electronic steering concept by using simple FSO transceivers composed of off-the-shelf components. The experiment results showed that, it is feasible to maintain mobile optical wireless links over spherical multi-transceiver FSO structures.

III. Smart Lighting

SSL technology involves the use of electricity as a fuel to inject electrons and holes into a solid-state semiconductor material. When the electrons and holes recombine, light is emitted in a narrow spectrum around the energy bandgap of the material. Because the light is narrowband, and can be concentrated in the visible portion of the spectrum, it has, like fluorescence, a much higher light-emission efficiency than incandescence. The technology of inorganic semiconductor-based SSL has been reviewed recently [57]. In 1907, light emission from inorganic semiconductors was first observed by Round [58]. The first device to control such light emission was the light-emitting diode, demonstrated by Holonyak et al. at the General Electric Corporation in 1962. The first commercial LED products were introduced in 1968. The initial performance of LEDs was poor, with maximum output fluxes of around one thousandth of a lumen, and only one color, deep red. But steady progress has been made, and efficiencies and brightness have surpassed those of incandescence, while the color range has been extended to the entire visible spectrum. Invention of GaN-based blue LED by Nakamura made the demonstration of high brightness white LEDs (HB-LEDs) possible [59]. High efficiency, low driving voltage, fast switching characteristics and compatibility with networked computer controls enabled LEDs to be subject of a new technology called Smart Lighting with software controlled stability, operating function, adaptation, and energy saving.

Smart lighting is gaining immense popularity due to its advantages over traditional lighting on account of its high lifetime, reliability, energy efficiency and versatility. Smart lighting has become a popular research field because it can be used to facilitate visible light communication. Typically, LEDs last for about 35,000-50,000 hours, which is about three times the lifetime of fluorescent and 50 times that of incandescent sources, cutting the energy used by 25%. Commercial LED light bulbs that use as low as 13W of power to light a room are available [60]. The average brightness of LEDs, which is delivered at a luminous efficacy of 40 lm/W, is much higher than that of a halogen source (15-30 Mcd/m^2 at $\sim$30 lm/W) and not far behind the average effective brightness of high-intensity discharge lamps (60-80 Mcd/m^2 at $\sim$100 lm/W) [61]. SSL enables not only communication, but also the choice of lighting modes, colors, and luminous intensity (see Figure 7) tailored for several applications ranging from baby monitoring to spaceship controls. Researchers in many developing and developed countries have used the advantages of this illumination technology [62].

In order to extract the advantages of LED smart lighting, we have to use them efficiently in an electrical circuit. To this end, several efforts that have come to fruition are summarized in the next subsections.

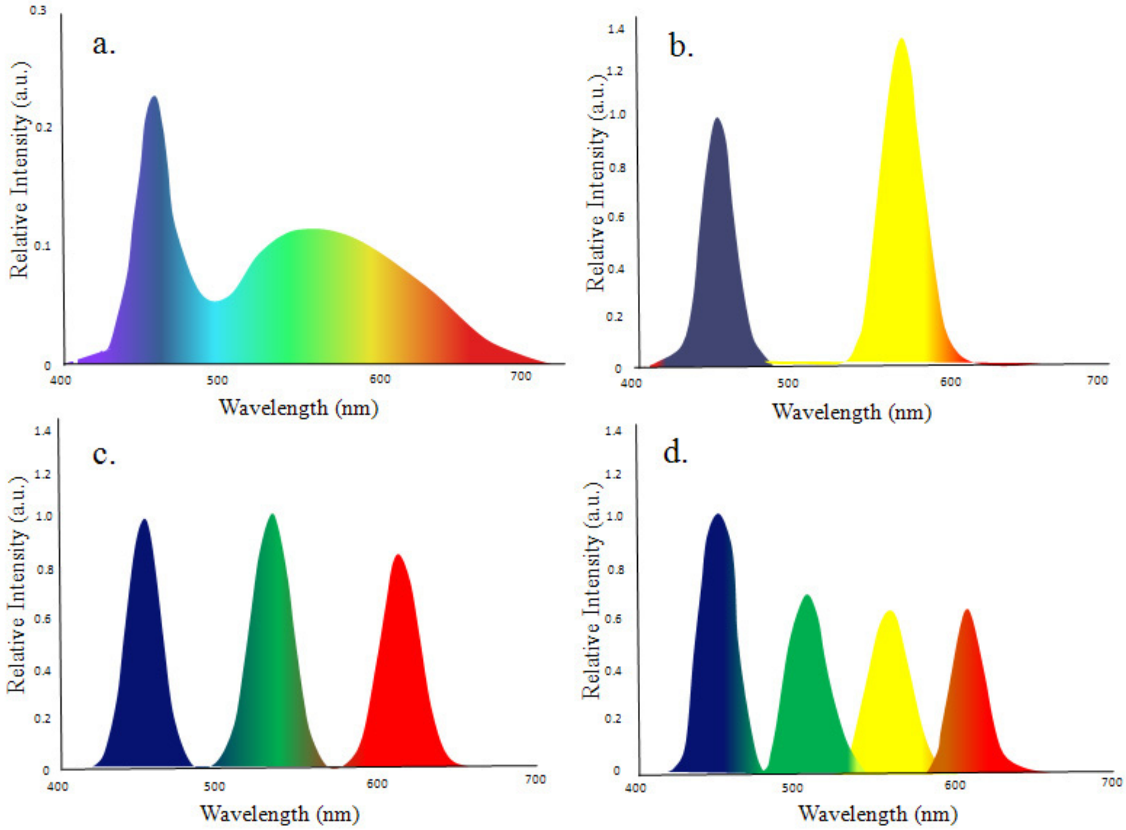

Fig. 7. Different LED Spectra: (a)White Light, (b)Dichromatic LED, (c)Trichromatic LED, (d)Quadchromatic LED.

A. Drivers for SSL

LEDs require DC power to operate, but SSL fixtures are supplied with AC power like conventional lighting. The AC-DC conversion is done in an LED driver chip. The driver then uses a DC-DC converter to step down the line voltage. Traditional LED drivers, which are not dedicated to continuous output applications (i.e., lighting), have had low conversion efficiency and high wastage of thermal and electrical energy. AC-DC conversion accounts for extra heat dissipation due to loss in energy. A 2009 study [63] reported that the lamp efficiency of a commercial lighting LED bulb is only 14% resulting from losses originating in each stage of AC power-light conversion (AC-DC-DC conversion, blue LED pump, phosphor packaging, and the spectral match of the emitted light) in the LED chip/bulb. One of the major concerns SSL technology needs to circumvent and/or eliminate is the heat dissipation incurred from extended periods of lighting and modulation as demanded by VLC. In general, HB-LED drivers must use low power, have long life time, and should be able to use pulse current to drive the LED.

In order to maximize the efficiency, the AC-DC converters in LED drivers must have a high power factor (a dimensionless number representing the ratio of real power to apparent power). One way to maximize the efficiency is to store less energy in capacitors in the drivers as reported in [64], wherein the researchers aim for a power factor of a more realistic 0.9 rather than unity. Designs and prototypes of several driver topologies to achieve efficient current conversion such as single, double, and interleaved switch converters are reported in [65]. A high-power-factor converter for HB-LEDs based on the dependency of voltage conversion ratio on the duty cycle of the driving pulse is proposed in [66]. A quasi power factor correction circuit (AC-DC converter) that supplies a discontinuous power load, and hence operates on modes based on the switching frequency of the following DC-DC converter which actually supplies the LED is prototyped [67]. Seoul Semiconductor has reported power factors of over 0.95 in their Acrich and Acrich 2 lines of SSL bulbs [68]. As advanced as the SSL technology and industry have become in the last decade, power conversion and lamp efficiencies still need further development to accommodate visible light-based communication networks.

Digital modulation techniques that allow dimming without interrupting communication should be accommodated by such drivers. Several companies and researchers are continually investigating the designs and feasibility of LED driving circuits with ample heat sink and compact design suitable for commercial and residential lighting fixtures [69]. Additionally, current regulation must be implemented in a smart lighting system in order to control the wavelength and/or the intensity of the emitted light. This can be achieved by one or more of the following devices: resistors, linear regulators, switching regulators, and the widely used constant current regulators.

B. Thermal Management

Packaging of high-brightness LEDs for illumination requires efficient switching circuits, dynamic deployment of reflectors, phosphor coating, and cooling. Management of an effective heat sink is often the main design criterion as high junction temperatures (of over 125°C) will cause device failure. Packaging requires selection of materials and methods to meet the optical, electrical, and thermal parameters of the design. Additionally, the placement of LEDs relative to reflectors in multi-module packages must be extremely precise to ensure required directionality and diffusion.

1) Single Chip Packaging: Different packaging technologies have evolved for high-brightness LEDs. One of these techniques results in what is called a "bullet head" package. In this package, a 10 mm^2 die is bonded to two lead frame posts, and epoxy molded inside a reflector cup, making its shape look like a bullet. The epoxy, however, has been shown to be an inefficient conductor which increases the risk of device malfunction. Moreover, the reflector is only able to reflect a fraction of the total emitted light in this configuration. Although this particular design is not very efficient, its concept can be used when better materials such as silicone-based ones are available for packaging the LEDs. Some of the advantages of using silicone-based packaging materials are high optical transmittance, variable refractive index, high purity, ease of fabrication, and reliable transparency in the UV-visible wavelength region.

In addition to bullet head packaging, flip-chip based methods are also gaining popularity for surface mount HB-LED packaging. In this method, much like any surface mount CMOS device, the LEDs are mounted atop perforations on the printed circuit board, a surface of which is lined with highly conductive material such as copper. The substrate of the device acts as a heat sink, as shown in Figure 8. One of the advantages of this method is that it can be extended to multi-chip module (MCM) by expanding the size of the substrate and the number of LEDs. A novel method of packaging LED arrays has been successfully prototyped by Lee et. al. This method used flexible printed circuit (FPC) substrate and the LEDs are mounted on a reel-to-reel package using highly precise pick-and-place devices [70]. While this packaging technology looks promising for low-cost mass production, its thermal performance for a large number of LEDs has not been studied.

2) Array Packaging: For MIMO VLC applications, HB-LEDs must be densely packaged as arrays of 10s or 100s of LEDs, which is often problematic due to massive heat dissipation. Arik et al [71] of General Electric and affiliated companies have done comprehensive studies in LED package thermal management, especially at the chip level. They showed that defective solder bumps and poor choice of substrate considerably increase the package temperature. All the components in the LED package contribute to the thermal flux generated and radiated from an operational lighting fixture. These include the chips themselves and materials used in substrate and encapsulation (phosphor, SiC, silicone, or other polymers). The authors of [72] have predicted and described several candidate technologies such as heat sinks, thermo-

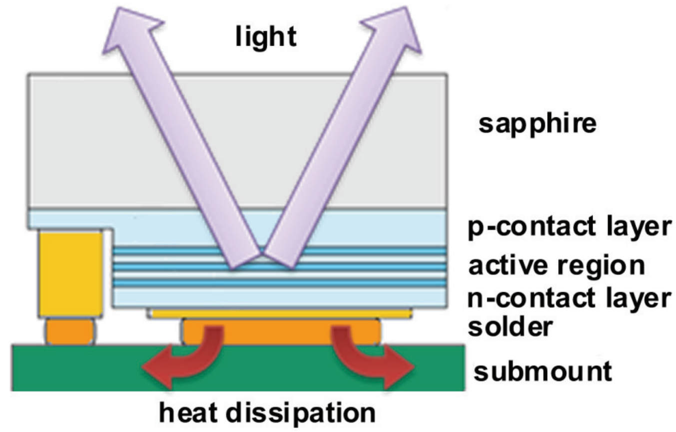

Fig. 8. Cross section of a flip-chip LED

electrics, piezoelectric fans, synthetic jets, and small form factor fans to counter this problem. Synthetic jets, in particular, consume very low power (25mW) at reasonable diaphragm frequencies (20-200 Hz) as shown in [72]. Nuventix, Inc. has deployed the synthetic jets described in [72] as a solution for thermal management for General Electric and other lighting companies using the novel SynJet technology. SynJets are zero-mass flux formed by creating a periodic suction and ejection of fluids (air) through an orifice, generated by an oscillating diaphragm in a cavity surrounding the diaphragm. It means that this process is devoid of ducts, pipes or friction due to fan blades, and its forced cooling by directing the jet stream to the package achieves cooling at a much faster rate than natural convection. Results using SynJet have shown 34 years of 24 hours-a-day, seven days-a-week operation at 60°C [73].

A few other technologies have been developed and successfully used to this end. One of such technologies is called chip-on-board (COB), in which individual LED chips are mounted on the substrate, which is attached to a heat sink (usually metallic) using materials suitable to form thermally conductive interfaces such as Copper-PCB. Such a COB package with 40 LEDs has been implemented and tested with 110V AC power supply and 150mA forward current [74]. A control circuit regulating LED currents is also used to avoid continuous rise of the current with voltage. The LED package was reliable for junction temperatures of up to 80°C, above which problems such as encapsulation expansion and wire bond breakage occur.

Extensive investigations on the effect of the placement of LED chips on a PCB (COB) are presented in [75]. Using thermal modeling and experimental methods to evaluate the thermal interaction between LED encapsulation and PCB material, the researchers proposed an algorithm for LED placement on a PCB facilitating the minimization of dissipated as well as consumed power.

Convection cooling has also been proposed and implemented [76] for a small (2×3) array. In this method, the researchers used thermal conductive silicon grease connecting the substrates and an array of cooling fins aided by a cooling fan. This method showed significant decrease in the tempera-

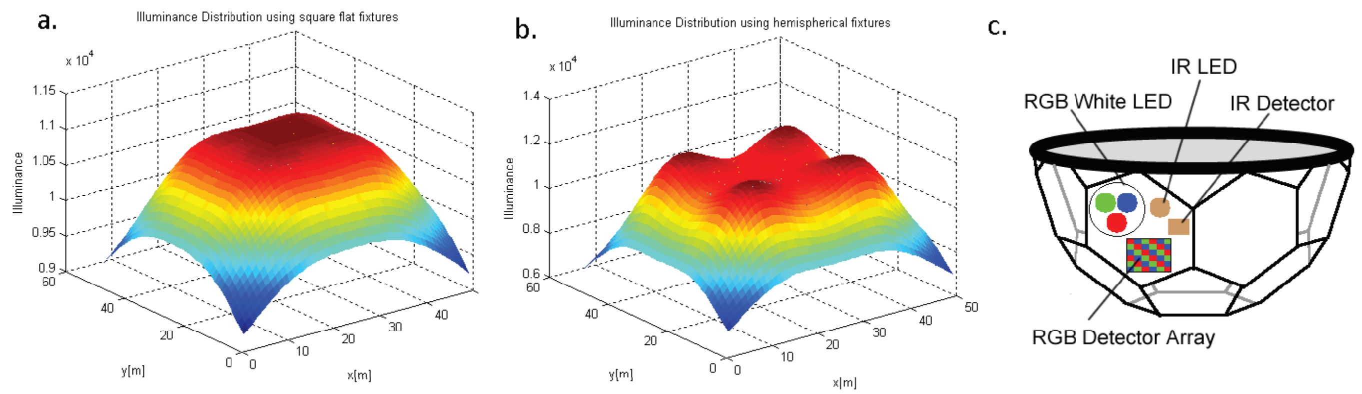

Fig. 9. Spatial illuminance distribution in a 5mx5m room by using (a) perpendicularly aligned LEDs (b) hemispherically aligned LEDs (c) Simplified schematics of a hemispherical transceiver for communications.

ture of the substrates (up to 25 degrees), but its feasibility for high-volume integration has not yet been studied.

C. Indoor Lamp Fixtures and Illuminance

Being the signal carrier (for VLC) and the illumination mean, the temporal and spatial distribution of luminous intensity is of paramount interest in design of novel lighting systems with communication capabilities. Spatial distribution of luminous intensity distribution in a room due to white LED-based lighting elements has been studied by Nakagawa group for communication purposes [77]. Following their formalism, illuminance distribution in a room can be calculated. Luminous intensity is given energy flux per unit solid angle and given by $I = \frac{d\Phi}{d\Omega}$ where Ω is the solid angle and Φ is the luminous flux, which can be calculated by

$$\Phi = V_m \int_{\lambda_1}^{\lambda_2} C(\lambda)\Phi_e(\lambda)d\lambda \tag{8}$$

where V_m is the maximum visibility and $C(\lambda)$ is the luminosity curve. Assuming that the LEDs radiate in Lambertian pattern, illuminance in a spatial point (x, y) can be estimated by $E = I(0)\cos^m(\phi)/L^2\cos(\psi)$, where $I(0)$ is the center luminous intensity of an LED, ϕ is the angle of irradiance, ψ is the incidence angle and L is the distance between the LED and the surface of interest, m is the order of Lambertian emission, and is given by the half-angle at half illuminance of an LED $\Phi_{1/2}$ as $m = \frac{\ln 2}{\ln\cos\Phi_{1/2}}$.

Using the described simple model, we calculated the illuminance distribution in a $5m \times 5m$ room illuminated by 4 fixtures each of which has 60 high brightness LEDs. The Figure 9 shows the spatial illuminance distribution by using two different types of fixtures. In the fixture (a) the LEDs are aligned perpendicularly, whereas in the fixture (b) they are placed on a hemispherical surface as schematically depicted in Figure 9(c). As it is apparent on the Figure 9(b), hemispherical alignment provides better uniformity as well as higher average illuminance. The described model does not include the reflection from the walls.

IV. Visible Light Communication (VLC)

Developments in solid state lighting devices, especially in white LEDs, in the last decade fueled the research expanding the usable spectral region from IR to visible and gave birth to new field of research called Visible Light Communication. VLC technology uses light in the wavelength interval of 380-720nm and offers several advantages over RF communications:

- Virtually unlimited bandwidth of over 350 THz.
- Unregulated spectrum available for immediate utilization.
- Spatial confinement of the light beams provides inherent security eliminating interception or eavesdropping.
- Spatial confinement also allows spatial reuse allowing substantially improved throughput.
- Removal of (or reduced) multipath fading in intensity modulation which degrades the performance of unprotected RF links.
- High brightness white LEDs are becoming ubiquitously available for lighting applications due to their superior efficiencies over conventional lighting technologies and their cost is continuously decreasing.
- Potentially can be integrated with power line communication system which could eliminate the need for a separate data line to LED-based transceiver modules.
- Optical signals do not cause electromagnetic interference (EMI) which limits use of RF technologies in certain environments such as hospitals, airplanes, certain military settings etc.
- Visible light with limited intensity does not pose any health risk and are therefore safe for most applications.

Using LEDs for VLC has recently received particular attention since the advantages of LEDs have drawn interest to VLC research and development. The idea of fast switching of LEDs and the modulation of the visible light for communications was first proposed by Pang et al. in 1999 [78]. This was the first proposal in the context of intelligent transportation where VLC can be incorporated into traffic information systems as an information beacon for the transmission and broadcasting of information [78], [79]. However, the idea has immediately expanded to other application fields, particularly indoor communication systems. VLC has gained prominence in conjunction with lighting and communication [80]. The main focus has been to design a VLC system with white LEDs due to high lighting efficiency, environment compatibility, no out-of-visible-band advantage, better power

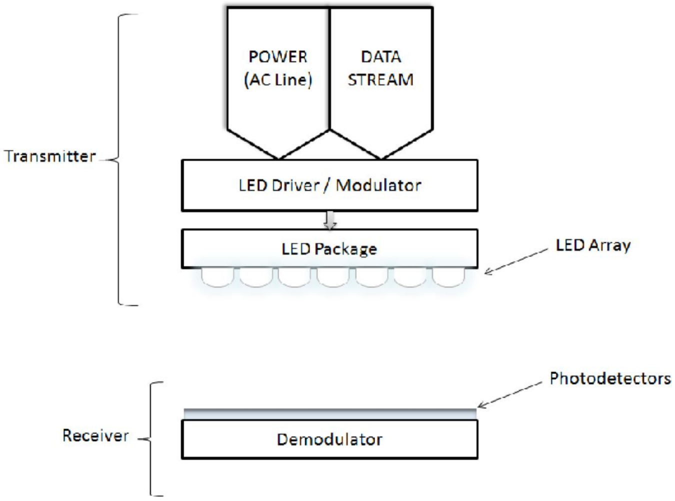

Fig. 10. Simple VLC System

Fig. 11. Example of smart lighting facilitating VLC

efficiency and easy maintenance [81]. A large amount of effort went into increasing the modulation capacity and achieving a transmission of long data range of commercial white LEDs.

Apart from lighting and indoor wireless access points, VLC has been studied for other possibilities such as vehicular signaling and danger notification in traffic systems. The growing use of LEDs in billboards, signs, and location instructions can be leveraged to provide information to nearby handheld devices. PureVLC, a UK based company has recently developed light messaging and *li-fire* VLC HD video transmission using smartphones and laptops [82]. As an effort to ameliorate growing environmental concerns, smart homes and smart lighting are gaining popularity all over the developed world. Smart houses, in addition to being zero carbon emission, have several automated capabilities, the most popular of which is assisted living for the elderly. Such smart houses have been built in Japan, Korea, Europe, USA, Australia and New Zealand. VLC could play an important role in development of these smart homes by facilitating high speed communication.

In November 2003 the Visible Light Communications Consortium (VLCC) was established in Japan, having among its membership major Japanese industrial organizations including Toshiba, NEC, Panasonic, Sony, NTT DoCoMo. It was only in 2008 that the United States and Europe initiated and funded major research projects focusing on this technology. The European Union heavily funded the Home Gigabit Access (OMEGA) project, seeking to develop global standards for home networking, including the use of optical wireless using infrared and VLC technology. In 2009, the IEEE issued a Call for Contributions on IEEE 802.15.7 VLC protocol, and held the first meeting. The IEEE 802.15.7 VLC Task Group is the official authority so far in this area. LVX Systems [83] have claimed to be able to commercially manufacture and deploy VLC systems. As a complement to Wi-Fi, the Li-Fi (Light-Fidelity) Consortium was formed in Oslo, Norway in 2011 [84]. Increased research produced remarkable results in the field including demonstration of multiple-input-multiple-output and integration to power line communication (PLC) [8], [81], [85]. Despite the increased research efforts and noticeable demonstrations, the works reported in the literature focus on one aspect of VLC, typically communication, and ignore the other. Hence there is need for a holistic approach in investigation of *joint-design* of hardware and software protocols considering needs and constraints of both illumination and communication aspects.

VLC can utilize the infrastructure used by power line communications without a major overhaul in the established communication or lighting backbone. LEDs used for lighting can be modulated by data symbols transmitted through the power line itself. This approach is especially useful for indoor broadcasting and/or internet access as a complement to or a replacement of WiFi where a higher security is demanded. With impedance matching, data rates of up to 1 Gbit/s can be obtained [86]. In 2002 Komine and Nakagawa designed and prototyped a PLC/VLC system that could achieve a data rate of 100 kbps [87]. A PLC/VLC system is prototyped in [88], where VLC-enabled power-line modem feeding the LEDs at the transmitter and photodiodes coupled with a microcontroller at the receiver are used to send and receive a simple text string. Another new approach is to replace external PLC modems by PoE (Power over Ethernet) modems, fed by standardized Ethernet cables that can carry power as well as data. Utilizing this technology in VLC will reduce wiring complexity and may improve power efficiency.

VLC leverages the aforementioned advantages from the development of LEDs and their drivers to achieve data rates of the order of several Gigabits per second. A simplistic VLC system architecture is presented in Figure 10. It corresponds to a conventional wireless communication system with an addition of optical driver, which performs the function of electro-optical and optoelectronic conversions. The receiver side uses photodetectors and the transmitter (access point) uses LEDs (with driving and modulating circuits) as the source. In practice, the transmitter is an LED array, usually mounted on a ceiling of a room as shown in Figure 11, for example, and the receiver is a VLC enabled device – a future laptop or a smartphone with photodiodes. Usually, the receivers use direct detection (DD) to absorb incoming radiation. A receiver has a certain field-of-view (FOV), which is the solid angle covering the area that falls within its detection ability. This angle is taken into account while modeling the channel.

In a mixed channel containing both LOS and non-LOS paths, LOS photons (i.e., direct light) arrive at the photodetectors earlier than the non-LOS diffuse light reflected off of walls and other surfaces. *RMS Delay Spread*, or τ_{RMS}, is one measure of the multipath characteristics of the channel. A source of inter-symbol interference (ISI) in optical as well as RF channels, τ_{RMS} is the result of a power delay profile caused by the difference in the power of the light when it reaches the detectors [89]. In an indoor VLC application, the SNR and the arrangement of LED fixtures are directly related. In an office environment, the required level of horizontal illuminance on the working surface recommended by the US General Services Administration is 500 lm/m^2 [90]. The required SNR for reliable data transmission is 13.6 dB [91]. A study made in 2002 [91] suggests that there are only a limited number of LED arrangements are allowed in one fixture given the constraints of acceptable spacings ($< 10\text{cm}$) and directivity (20-50 degrees). Moreover, the SNR and illuminance of an indoor setup is also non-uniform and there are areas with low illuminance and data rates. At the mathematical level, this fact is due to the RMS delay spread, which is dependent on the both the total received power P_T and power received from each working LED P_i [92], and is given by:

$$\tau_{RMS} = \sqrt{\frac{1}{P_T}\sum^{N} P_i\tau_i^2 - \tau_0^2} \tag{9}$$

where N is the number of LEDs, and τ_0 is the mean delay. Section V-A contains a brief account of how this parameter affects VLC.

A. VLC Channel Model and Noise

An indoor VLC channel can be characterized by the optical wireless channel, which was devised as early as 1997 [93]. Although this model was initially used for IR communication, it applies to the visible spectrum as well. In all intensity modulation, the transmitted optical power waveform $X(t)$ is the modulating signal and the channel model $h(t)$ is the baseband linear system. If $N(t)$ denotes the noise model including shot and thermal noise, the communication system can be expressed as

$$Y(t) = RX(t) * h(t) + N(t), \tag{10}$$

where the symbol $*$ is the convolution operator. $Y(t)$ is the received signal at the receiver (instantaneous current), and R is a constant which indicates the detector gain [93].

A simple gain model for visible light communication in an indoor setting is presented in [94]. The total gain consists of a line of sight (H_{LOS}) and diffuse (H_{DIFF}) DC gains (see Figure 12) and is given in the frequency domain by:

$$H(f) = \sum_i \eta_{\text{LOS},i} \exp(-j2\pi f \Delta\tau_{\text{LOS},i}) + \eta_{\text{DIFF}} \frac{\exp(-j2\pi f \Delta\tau_{\text{DIFF}})}{1 + jf/f_0} \tag{11}$$

where i is the total number of paths, η_{LOS} and η_{DIFF} are the efficiencies (gains) of line of sight and diffusion paths, $\Delta\tau_{LOS}$ and $\Delta\tau_{DIFF}$ are the delay in line of sight and diffusion paths. f_0 is the 3dB cutoff frequency of the diffuse-only path. Multipath fading is neglected in optical communications because the area of the detector is about 4 orders of magnitude higher than the wavelength of light, which provides spatial diversity and countermands any multipath fading effects [95]. The efficiencies of the channels are given by:

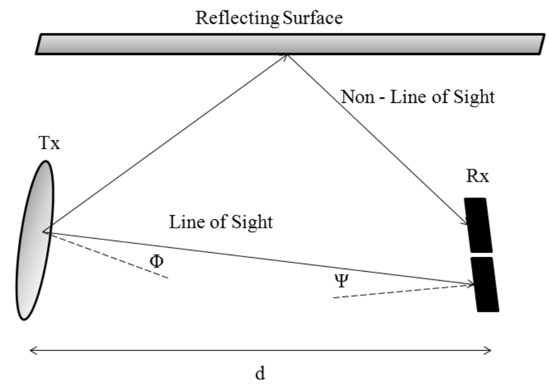

Fig. 12. Illustration of Line-of-Sight

$$\eta_{\text{LOS},i} = A_{\text{R}}(m+1)\cos^m\theta_i \cos\psi_i/(2\pi {r_i}^2) \tag{12}$$

and,

$$\eta_{\text{DIFF}} = \frac{A_{\text{R}}}{A_{\text{ROOM}}}\frac{\rho}{1-\rho} \tag{13}$$

where A_R and A_{ROOM} are the receiver and room area, θ and ψ are angles of irradiance and incidence and r_i is the distance between the ith receiver and ith detector. The average reflectivity of the ambient surfaces is collectively given by ρ and the directivity of the LED source is given by $m = \frac{\ln 2}{\ln cos(hpa)}$, where hpa = half power angle of LED [94].

In all optical communication systems, photodiode shot noise arising from the DC photocurrent due to ambient sources is dominant over the thermal noise [77]. The total noise variance is given by $\sigma^2 = \sigma^2_{shot} + \sigma^2_{thermal}$ as shot noise and thermal noise are uncorrelated [77]. To calculate the signal part of the SNR, the square of the desired power P at the receiver is multiplied some efficiency factor η, which can be a function of the wavelength, lens material, or the processing circuit (in a CMOS imager, for example). The total noise is the sum of the noise due to the channel, inter-symbol interference, and the noise at the receiver [96]. In an indoor environment, neglecting the effects of multi-path fading, the SNR for a received power of P_R, the desired bandwidth B, and photodetector responsivity γ is given as [77]:

$$SNR = \frac{\gamma^2 {P_R}^2}{N_0 B} \tag{14}$$

where N_0 is the noise power spectral density (assumed to be predominantly Gaussian), and is given by

$$N_0 = qRP_{bg} \tag{15}$$

where q, R, and P_{bg} are the electronic charge ($1.6 \times 10^{19} C$), opto-electronic conversion efficiency of the detector, and background light power respectively. [91], [94], [97].

Bit Error Rate (BER), along with illumination, is VLC's main performance metric. Digital communication using visible light has to meet certain BER requirements. For a VLC system to be viable, the BER - the ratio of number of altered (corrupted or lost) bits to the total number of bits transferred - should be less than 10^{-6}. This BER is influenced by various factors including the modulation scheme, transmission and reception powers, channel noise, shot noise at the receptors, ambient light, channel attenuation, wireless multi-path fading, and the potential errors in optical filters. BER can be reduced by using appropriate modulation techniques and transceiver positions. Since the selection of optimal modulation scheme can have a great impact in reducing BER, most of the research in VLC has been to develop and refine new modulation schemes [94], [98], [99].

B. VLC Modulation Techniques and Dimming

Modulation is an essential part of any communication system. However, it is more critical an challenging for *LIGHT-NETs* since the signal modulation for communication directly affect the illumination quality. Hence, one should consider constraints imposed by both columniation and illumination purposes joint design and optimization effort for *LIGHT-NETs*. Several modulation schemes have been proposed by researchers for VLC in order to tailor on various aspects of the medium and devices. LEDs are intensity modulated largely due to the fact that, unlike in RF, VLC does not enjoy the assistance of spatially coherent antennas. A practical VLC system should allow dimming of LEDs and still allow error-free communication whenever lighting is not required. LED junction current is proportional to the brightness, and therefore, dimming can be obtained by controlling the current. However, it should be kept in mind that at any instant the power from an LED cannot be zero, and its time average must not be lower than a ceiling value, which is defined by a dimming factor. There are different modulation techniques to control the required luminous intensity from the LEDs. In particular, pulse modulation techniques are highly convenient and widely used for this purpose.

Pulse Position Modulation (PPM): Most modulation schemes use on-off keying encoding where binary 1s and 0s are coded as presence or absence of carrier (LED on or off). This means that the LED is turned on and off constantly. Fortunately this flickering is too rapid for the human eyes to discern. In cases when the switching frequency is low, a pilot sequence of all 1s can be inserted to hide the off or *dark* periods. PPM is a better way to tackle the flicker problem. In M-ary PPM, the modulating signal is encoded into a possible 2^M slots, where each slot contains a unique bit-combination for each symbol. A modification to this PPM technique is called the Variable-PPM (VPM). In VPM, the pulse width of the different symbols are not the same, and can be adjusted to elongate or shorten dark and light periods, hence increasing or decreasing brightness while carrying the same data.

Pulse Scope Modulation (PSM): Another dimming-friendly pulse modulation technique, called Pulse Scope Modulation (PSM), is described in [100]. In PSM, the modulating signal changes the slope of the leading edge of the pulse, but

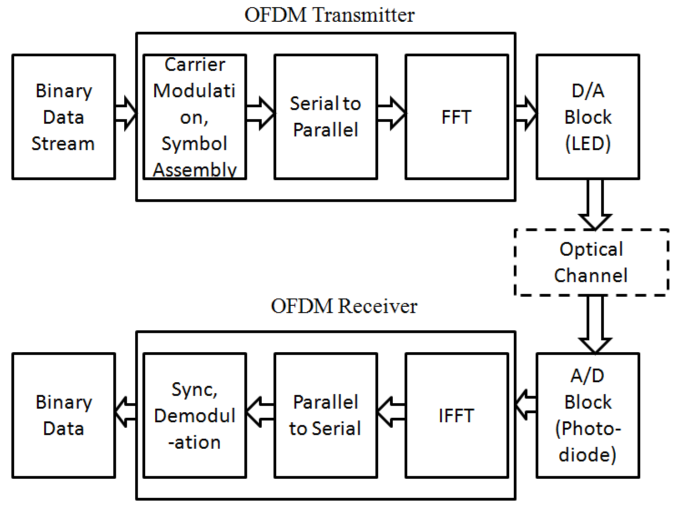

Fig. 13. Orthogonal Frequency Division Multiplexing: Simplified Block Diagram

maintains a constant amplitude and frequency in the carrier. For example, a binary 0 pulse will have a positive slope leading edge, and a binary 1 will have a negative slope falling edge. This technique could be useful in efficient dimming by controlling the rise times and fall times of this non-perpendicular edges. Another benefit of employing PSM could be easy insertion of pulses to subdue inter- and intra-frame flickering.

Pulse Width Modulation (PWM): Garcia et al. proposed that PWM, in addition to luminous flux thermal sensing, can be used to control the output light of LEDs. Using this method, the luminous intensity of an LED changes almost linearly with temperature and reaches a peak at about 110^0C [101]. Another proposed method for efficient dimming uses Multi-path PWM (MPWM). In this method, multiple HB-LEDs are used and the average current through each HB-LED array is pulse width modulated [102]. Recent simulations show that the use of multi-path pulse position modulation can achieve a higher spectral efficiency than previously used OOK techniques, given that perfect synchronization between chip and modulation symbol is achieved [98]. A combination of discrete multi-tone (DMT) and PWM has been shown to not influence the data rates [99].

C. Multiplexing Techniques

Orthogonal frequency division multiplexing (OFDM) is an example of multiple subcarrier modulation. OFDM divides the frequency spectrum into multiple orthogonal subcarriers which are modulated simultaneously to achieve high data rates. This subcarrier orthogonality is achieved by having a minimum frequency spacing between subcarriers to remove crosstalk. Since LEDs are non coherent sources, maintaining the orthogonality is achieved in the encoding level, by introducing guard intervals with cyclic prefix as shown, for example, in [103]. The main advantage to OFDM is that each subcarrier can be modulated independently using single carrier techniques and thus produce a high data rate. Additionally, OFDM is more resistant to a hostile channel, as the channel response

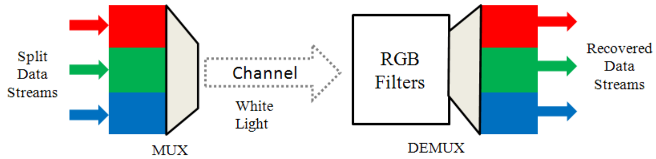

Fig. 14. Wavelength Division Multiplexing

will have considerably lower effect on a multiple subcarrier modulation process compared to single carrier modulation. Since OFDM's output is complex, intensity modulated systems need to generate real OFDM symbols. This can be done by applying inverse Fast Fourier Transform to the transmitter output, which is depicted in Figure 13.

Wavelength Division Multiplexing (WDM) is a technique that allows efficient modulation for optical fiber communications. It is a mature technology that is widely used in optical fiber communication and has begotten several modulation methods over the years. VLC is well suited platform for WDM since combination of three LEDs (red, green and blue, or RGB) on a single chip is a widely adopted technique to to obtain white light. Hence, WDM can be easily implemented in VLC by using multicolor LEDs with various colors being modulated by separate streams of data and multiplexed as white light as shown in Figure 14. Speeds of up to 803 Mbit/s using these multicolor LEDs have been achieved using WDM [104]. Wang et al describe a variant of WDM using tetra-chromatic LEDs and receiver tilting to achieve a improved spectral efficiency [105].

In all the reported VLC WDM studies, the only goal has been the efficient utilization of the channels through different modulation schemes. The change in correlated color temperature of the resultant white light due to the modulation of its components has not been addressed theoretically or experimentally. An important attribute of a lighting source is its apparent color when viewed directly, or when illuminating a perfectly white object. This attribute can be quantified through use of chromaticity coordinates (x, y) on the CIE 1931 chromaticity diagram shown in Figure 15. The area enclosed by the contour comprises the coordinates of all real colors. Inside the contour, a locus of points for blackbody radiators of different temperatures (Planckian locus) is shown. The region in the vicinity of the blackbody radiator locus (starting at approximately 2,500K) defines the white color. Red, green, and blue hues reside within regions that span from the white region toward the corresponding comers of the diagram. Sources with chromaticity coordinates very close to the Planckian locus may be described by color temperature (CT). If the chromaticity of a source is not exactly equal to any of the chromaticities of a blackbody radiator, a correlated color temperature may be assigned to the source using chromaticity match with isotemperature lines [106]. The 1931 CIE chromaticity diagram provides a simple means of color mixing. The principle of color mixing follows from the makeup of the diagram. A set of n primary sources with the chromaticity coordinates (x_i, y_i) and radiant fluxes ϕ_{ei} will produce a color with the chromaticity coordinates

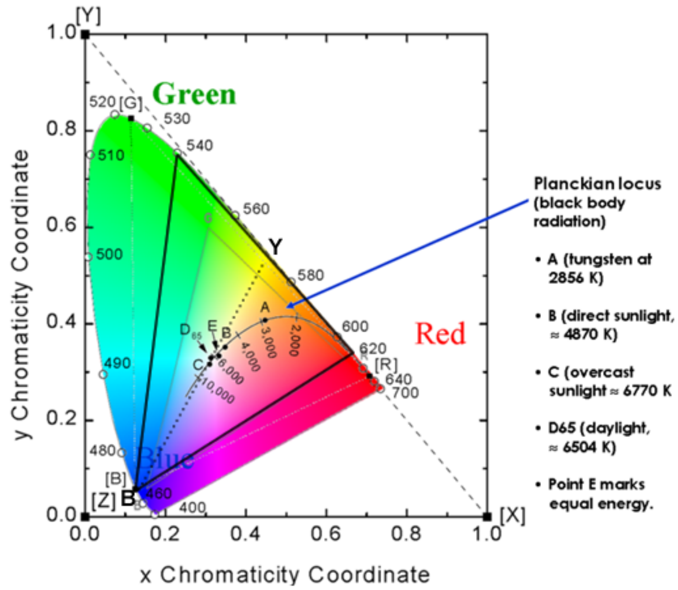

Fig. 15. Chromaticity Diagram (1931 CIE)

$$x_e = \left(\sum_{i=1}^{n} x_i \phi_{ei}\right) / \left(\sum_{i=1}^{n} \phi_{ei}\right) \quad (16)$$

and,

$$y_e = \left(\sum_{i=1}^{n} y_i \phi_{ei}\right) / \left(\sum_{i=1}^{n} \phi_{ei}\right) \quad (17)$$

For two primary sources, any color with the coordinates located on a straight line that connects the coordinates of the sources can thus be imitated. For instance, white color (standard source C) may be composed of two colors (blue and yellow; see the dotted line in Figure 15). For three and more sources, the resulting coordinates can be produced within the top-area polygon with the apices at the coordinates of the primary sources. Again, the chromaticity of the standard source C may be obtained from three colors (red, green. and blue; see solid triangle in Figure 15), and so on.

This property of color mixing can be applied on a PWM system where the duty cycle of each channel is altered externally to produce varying levels of luminous intensities. A new challenge would be to automate this process, i.e., the continuous monitoring of the average intensity of each channel and controlling the duty cycle by some microprocessor. [107]

D. MIMO in VLC

Multiple-Output-Multiple-Input (MIMO) is an attractive method for achieving high data rates in optical communication systems. It has been shown that adaptive equalization of MIMO systems can be used to reduce inter-symbol interference in optical fibers. Optical MIMO has been used and proposed in several implementations such as on-chip communication, but we limit this discussion to VLC uses.

In VLC systems, optical MIMO uses two- or three-dimensional LED arrays as well as multiple receptors to allow parallel (and hence fast) data transmission. A non-imaging optical MIMO system, as opposed to an imaging MIMO

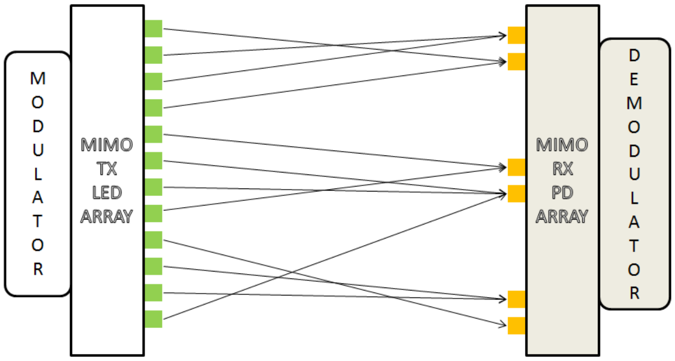

Fig. 16. Visualization of a MIMO VLC structure with fewer photodetectors than LEDs.

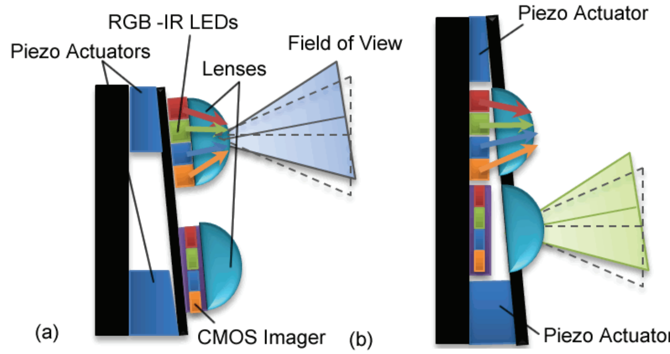

Fig. 17. Beam Steering using piezoelectric actuators

system, is not consistent and depends on the symmetry (or lack thereof) of the receivers, but an imaging MIMO system *learns* the orientations and operates under all foreseeable conditions [108]. MIMO receivers and transmitters may not be allowed equal power; instead methods have been proposed to allocate optimum power, modulation rates, and intensity offset values in order to obtain better performance [109].

VLC is a technology that can potentially benefit from the high speed and high responsivity of complementary metal oxide semiconductor (CMOS) imagers. The use of CMOS visual detector arrays in a VLC receiver has been studied using 35 μm CMOS process. The system is able to identify different light sources based on the brightness of each using a C++ computer program (processing is done off-line).This process achieved photodetector responsivities of 0.8 A/W, 0.66 A/W, and 0.61 A/W for red, green, and blue lights respectively [110]. The ability of CMOS imagers to incorporate circuitry has been exploited to create *smart pixels* and is now widely used for imaging and high definition display.The number of transmitting LED sources need not be equal to the number of photodetectors at the receiver (Figure 16), because the same photodetector can be used for different incoming light signal by using time-division.

E. Beam Steering in VLC

Beam steering methods are primarily used in FSO systems. In VLC the concept can be utilized to provide mobility and concentrate the optical intensity on desired receivers on a MIMO system. Like laser communications, a beam array can be affected in VLC by using electronically controlled micro-mirror arrays, piezoelectric actuators and/or liquid crystal embedded in the transmitters and receivers. The main challenge to effectively manipulate the light sources is that VLC extensively uses the diffusion property of light for illumination. Therefore future designs need to address the tradeoff between such mobility for high-data areas and alteration in the illumination portfolio. A solution might be to selectively steer some receivers and transmitters in an event of extreme misalignment.

One inexpensive method for beam steering would be to tilt LED emitters and CMOS imagers using piezoelectric actuators which can be electronically controlled. These actuators are made of materials that incur strain, hence motion when the voltage across them is changed. This process would require an integrated control circuitry within the envisioned system. Two different schemes of piezo-actuator integrated transceivers are shown in Figure 17. In one scheme (Figure 17(a)) the plate on which both the emitter and receiver systems are placed can be controllably steered by the piezo-actuators. In the scheme pictured in Figure 17(b), only the lenses on the emitters and detectors can be tilted by the same method. The change in the viewing cone due to steering is shown as triangles with solid and dashed lines. The later one has the advantage of zooming-in and out allowing change the size of field of view and thereby, making fine and coarse search and alignment.

F. Uplinks

VLC in full duplex mode requires the aid of a hybrid technology, such as infrared uplink or even RF. The researchers at the Nakagawa laboratories in Japan have implemented a full-duplex VLC system based on carrier sense multiple access with collision detection (CSMA/CD). The choice of the CSMA/CD method targets compatibility with wire line LAN communications such as Ethernet networks and PLC. Such a prototype achieving bi-directional data rate of up to 100Mbps has been shown in [111]. Few more remedies to the uplink issue have been proposed in literature. Corner cube modulation using reflectors to avoid shadowing has been proposed in [112]. 125kbps infrared uplink using sensor network suitable for low uplink rates has been proposed in [113]. Cognitive networks with cooperation from RF uplinks have been proposed in [114]. However, improvements need to be effected in terms of packaging these transceivers for a portable technology.

V. Summary and Future Challenges

As the RF spectrum is getting scarcer, we urgently need innovations that will enable leveraging of new wireless spectrums and technologies in order to respond to the exploding mobile wireless traffic demand. FSO communication with its various forms is a promising approach to respond this emerging need. On the other hand, there is a strong momentum for energy efficient lighting systems with the goal of reducing their share in total energy consumption. There lies an opportunity at the intersection of these two trends merging communication and lighting which we dubbed as a new field:

LIGHTNETs. We surveyed the constituent technologies, i.e., FSO and SSL, of this new field with a focus on recent trends (e.g., mobility, multi-element packaging) and issues related to joint design of communication and lighting.

We covered basics of FSO communication technologies, and made a detailed coverage of recent trends in the last decade to reach a general purpose communication paradigm to complement RF. Among these recent issues are maintaining LOS alignment, achieving high spatial reuse via directionality of the FSO beams, and handling mobility via multi-element designs. To give a better context, we related our discussions to the RF literature whenever possible, e.g., interactions of beam directionality and multi-access designs. We also covered some of the traditional FSO communication technologies which mostly includes infrared stationary scenarios with roof-top deployments, mesh networks, and satellite or space communications. Most of the experience in the legacy FSO communications tools, techniques and protocols will be instrumental in realizing *LIGHTNETs* in the visible spectrum.

In the SSL technology, despite the tremendous developments in the last decade, power conversion and heat dissipation still pose serious challenges for the envisioned *LIGHTNETs* technology. Heat sinks designed for high brightness white LEDs are still as large as several cubic centimeters that is orders of magnitudes larger than the actual LEDs. More efficient and compact AC/DC converters need to be developed especially for multi-element *LIGHTNETs* nodes.

We made a detailed survey of VLC technologies based on various types of LEDs which have shown considerable development and attracted great deal of interest of industrial players in the last decade. A simple search for the patents with the terms 'visible light communication' returns more than 100 patents and more than 350 recent patent applications. However, almost none deals with the lighting aspect of the claimed VLC technologies. Moreover, mobility-related issues such as handover and beam-steering in VLC have not been adequately addressed. This clearly shows that joint design and optimization for communication and lighting requirements largely overlooked and need to be researched more extensively. Our brief survey highlights the fundamental trade-offs as well as technological challenges in such joint design efforts, which if addressed meticulously, may turn *LIGHTNETs* into a high reward opportunity.

We conclude with the brief discussion of such challenges as a guide for the audience interested in further research in the promising field of *LIGHTNETs*.

A. Challenge 1: Illumination vs. Communication

It is reported in [91] that the RMS delay spread in an indoor VLC system is proportional to the spacing between the LEDs. This linear relation is replaced by a constant RMS delay when the spacings approach 0.5cm - 10cm depending on the field of view. In other words, in order to minimize the RMS delay, the spacings between the LEDs and their fields of view must be as small as possible. One one hand, smaller spacings and field of view mean more LEDs are needed to illuminate the room, and on the other hand, more LEDs imply a higher RMS spread as given by equation (9). Moreover, high data rates require impedance matching at the receiver, which gets more complicated as the number of sources increase.

B. Challenge 2: Mobility and LOS Alignment Management

Multi-element FSO modules with many cheap transceivers/elements open the new direction of research on handling the mobility and LOS tracking issues of FSO communications. While such multi-element designs have the potential to integrate spatial reuse and angular diversity in the same devices, it is a challenge to design protocols that can seamlessly and efficiently select transceivers (or elements) so that several objectives can be satisfied at the same time. These transceiver selection and management protocols will have to be achieving high throughput and low energy consumption.

When designing LOS alignment protocols, the key resource to optimize for is the opportunity for alignment with a neighbor node. Since LOS alignment availability (i.e., a short opportunity when two transceivers on two neighbor nodes are aligned and in LOS) is the period when a node can send data, they should be treated carefully. One particular viewpoint is to perceive each FSO transceiver as a channel and cast the problem of LOS alignment detection as the traditional channel selection problem in legacy RF, a.k.a. "cognitive radio". Unlike the frequency-separated RF channels, FSO transceivers/channels have the unique and different properties of being unlicensed and separated on space. However, just like the scarcity of bandwidth on RF channels, LOS alignment availability is a scarce resource in mobile FSO and calls for cognitive methods to treat it preciously, i.e., *Cognitive Optical Wireless (COW)*.

C. Challenge 3: Higher-Layer Integration

Recent work showed that the characteristics specific to FSO communications present a great opportunity for improving efficacy of higher layer protocols such as routing [115], [116]. In general, directionality and spatial (Euclidean) correlation of neighboring FSO structures pose challenges and opportunities in updating layer 2 and layer 3 of the protocol stack.

The fact that transmission between two FSO transceivers requires directional LOS alignment opens interesting abstraction possibilities. For example, it is possible to make directional forwarding [117] among multiple transceivers of the same node. That is, if a signal is received at transceiver i, it is possible to forward it at transceiver $i + 180^0$ so that the signal moves along a line. This *local sense of directionality* is possible due to the directional transmission in FSO communications and the availability of multi-element designs on the same node. This understanding of directionality is weaker than a *global sense of direction* which requires availability of a compass or gyroscope. It is also weaker than the *location* information which requires availability of positioning systems. The challenge is to use this weaker form of information in scaling and enhancing higher layer protocols like routing in a highly dynamic environment like MANETs. Recent work showed a great potential in this line of work [115], [116].

On a similar vein, multi-element FSO modules may be used to improve localization systems. The unique ingredient coming with FSO is the capability of detecting *angle-of-arrival*, which is not possible in legacy RF. Traditional positioning systems use RF signal strength and requires at least three anchor neighbors to uniquely localize a node. 3-D positioning requires four anchors using signal strength. Angle-of-arrival is a much stronger information than signal strength which only allows an estimation of the distance to the anchor. Recent work showed that multi-element FSO modules can be used to detect angle-of-arrival and thus reduce the complexity of the localization problem to two anchors in 2-D space and three anchors in 3-D [31]. More research is needed in further understanding how such multi-element FSO modules can be used to localize a large-scale network involving multiple obstacles and a heterogeneous set of angle-of-arrival detection capabilities among the nodes.

D. Challenge 4: Solid-State Device Design

Legacy solid-state lighting device design assumes that larger divergence angles are better. Since the emitted light is being used to illuminate, we cannot at all decrease the divergence of the light beyond a prescribed threshold in order to meet residential and commercial requirements [118]. Although larger divergence angles are better for lighting efficiency, devices with smaller diver angles can attain better communication efficiencies with longer ranges and smaller bit error rates. For high speed optical communication in *LIGHTNETs*, ways of adjusting beam-width of the transmitted signal is necessary. In traditional (radio) communication, this is done by a directional antenna, but we do not have the luxury of using antennas to manipulate directionality of visible light. Further, this adjustment of beam-width must take the lighting efficiency into account, and seek to find the balance on the tradeoff for the two conflicting goals: lighting and communication.

This problem needs to be addressed primarily in the design and packaging of transmitting devices, namely LED arrays. An initial effort to meet this challenge is presented in [119], where the authors describe the maintaining of *white hot spots* within a room illuminated by a VLC capable system. These are the spots where the intensity and modulation (and hence data rates) of light is made high enough to provide for faster communication capabilities. This, however restricts mobility, the cornerstone of *LIGHTNETs*. Novel modulation schemes and/or illumination capabilities need to be explored to meet the mobility aspect of this challenge.

As mentioned earlier, the solution to the divergence problem begins at the transmitter design, which will inevitably lead to power and thermal considerations. Higher data rates and uniform illumination will incur higher device temperatures. Therefore, thermal management is also an issue tied to this challenge of illumination-communication tradeoff. An ambitious approach would be to try to incorporate multiple modulation schemes according to the data and illumination demand, which will invariably warrant automation. Therefore, this multi-faceted challenge is perhaps the most staggering roadblock to the evolution of *LIGHTNETs*.

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