

Driving Visible Light Communications Towards the Tipping Point for Broad Scale Adoption

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ABSTRACT

Over the last decade, Visible Light Communications (VLC) has been the focus of considerable optimistic discussion as a potential candidate for high data rate communications in next generation wireless networks. Much of the discussion has focused on the strengths, benefits, and unique characteristics in order to motivate research and commercial adoption. In this paper we describe some of the misconceptions about the technology and overview what we believe to be critical research barriers that must be addressed in order to drive the technology beyond the tipping point for broad-based adoption.

CCS CONCEPTS

• **Networks** → *Network architectures; Hybrid networks; Wireless access networks;*

KEYWORDS

Visible Light Communications, Optical Wireless Communications, Heterogeneous Networks, Commercialization

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1 INTRODUCTION

VLC has attracted a great deal of research focus in recent years due to its promise as an emerging technology for indoor wireless connectivity [10, 11, 15, 22]. Let's enumerate the usual claims:

- (1) "Free," unlicensed spectrum
- (2) A secure and private wireless medium
- (3) 1000x performance gain over WiFi
- (4) Communication via LOS and/or NLOS channel
- (5) Contention free communications
- (6) Low cost communications
- (7) "Green" communications

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We are all guilty of making these claims. Let's try to be more objective in considering each of the above.

(1) *Free Spectrum*: Yes, to a large extent light is unregulated; but solutions must satisfy eye safety and lighting code requirements. As lighting research continues to evolve, VLC systems should also satisfy emission constraints related to the spectral-power distribution (e.g., temporal restrictions on blue emission) [23]. In addition, with increased use of the optical spectrum, enforcement of protocol use will be required for interoperability and non-interference of devices, just like we have for RF [19].

(2) *Secure and Private*: The argument here is that RF emits indiscriminately and therefore the RF signal is susceptible to eavesdropping. However, light can leak out of interior spaces through windows, doors or even key holes [8]. Accordingly, network protocols for privacy and security in RF networks should also be incorporated into VLC networks. The properties of light can provide an additional layer of physical security; however use of light as a wireless medium should not be considered as a panacea.

(3) *1000x Performance over WiFi*: Indeed, the frequency of light is in the THz; but low-cost components are unable to exploit coherent optical signals in the THz range. Instead, VLC is typically implemented via intensity modulation and direct detection (IM/DD) such that baseband modulation techniques are used and the frequency response of the optical channel is limited by the speed in which the light intensity can be modulated. Moreover, the electronics in the population of electronics devices that are used today are not capable of digesting data at these rates. The good news: in the long term, light-based systems have more theoretical capacity to pursue. Two key research areas that will drive the technology towards its potential spectrum utilization are (a) sources capable of high speed intensity modulation [12, 14], and (b) parallel transmission via wavelength division multiplexing (WDM) [7, 13]. In addition to massive available spectrum, a key focal area regarding performance gain of VLC relates to the area spectra efficiency (ASE) [22] and the spatial multiplexing potential of the optical medium [4]; however, ultra-dense access point deployments imply additional challenges for data distribution and coordination across multiple distributed VLC transmitters.

(4) *Communication via LOS or NLOS channel*: The availability of a line-of-sight (LOS) connection improves performance for individual links whereas non-line-of-sight (NLOS) solutions improve coverage and the ability to target multiple users. Both implementations have been demonstrated; however seamless transition between the two operating modes is not straight forward. Specifically, the transition from a LOS connection to a NLOS connection will generate a signal degradation of multiple orders of magnitude [5] and NLOS signals

inherently experience temporal spreading that leads to higher inter-symbol interference (ISI) [6]. As such, there is no one-size-fits-all solution here. A point-to-point link capable of realizing the full potential of a LOS signal and maintaining connectivity with a NLOS signal must adapt its modulation and coding scheme to account for the channel differences. In addition, a multi-cell / multi-user system implementation with NLOS capabilities must adapt to the various potential interference scenarios that dynamic environments will have on the NLOS connections.

(5) *Contention Free Communications*: Light, if sequestered, can realize low crosstalk, high speed, and excellent propagation (e.g., fiber optic communications and free space optics). One can imagine a network of narrow beams, free of contention (e.g., optical switches); however implementing such networks in free space with mobile devices requires dynamic emission, signal acquisition, and tracking capabilities [17]. For indoor wireless networks with dynamic user devices, spatial coverage must be such that the outage probability (i.e., likelihood that a device has no viable connection) is low. Accordingly, static cell deployment innately leads to a coverage/contention challenge similar to dense RF networks. NLOS links and/or broader emission transmitters can be used to improve coverage; but path loss and signal divergence reduce the optical power incident on the receiver. To overcome path loss and divergence, high signal powers can be used; but the total transmit power is constrained by eye safety regulations. These transmission modifications will also increase the contention from interfering sources. Complex receiver design can be used to isolate the desired optical signal and mitigate contention. The practical challenge here is that the coverage requirements imply a need for redundancy via multiple receiving elements or dynamic receivers in order to avoid outages caused by translational and rotational motion of the user devices.

(6) *Low Cost Communications*: Existing RF access points (e.g., WiFi) have emerged to be inexpensive due to their massive market and the ability to serve a modest range (e.g., 100m radius) from some strategic location. A single centralized unit is relatively easy to deploy (connect, power, install, and maintain); whereas densely deployed lights as VLC access points will require an extensive backhaul / access network along with many instances of the control and modulation electronics. This is an unsolved problem for wireless access, for supporting IoT, and for indoor lighting and HVAC control. Even as VLC hardware decreases in cost with an economy of scale, the primary system expense will be dominated by the cost of the access network and the efforts related to deployment and maintenance.

(7) *“Green” Communications*: VLC typically is envisioned with energy efficient lighting sources such as LEDs or, more recently, laser diodes (LDs) that are often characterized as “green.” However, producing light for illumination is inherently energy-intensive. If not for the need for illumination, one would be less inclined to exploit the visible spectrum. Thus, energy efficient VLC is a byproduct of the use of light which is already needed to meet the lighting mission – even in the absence of communications. In other words, relating VLC energy consumption to that of an RF device is not a direct comparison. Rather, RF energy consumption should be compared with the energy difference between a basic luminaire and VLC-enabled luminaire. In addition, the operational energy expense

of a VLC system should also account for any modifications to the access network that will be needed for ultra-dense distribution of VLC access points. As is the case with any lighting system, the use of appropriate control algorithms is also necessary to conserve energy when the light (or communications) is not being utilized.

But all is not lost. There continue to be good arguments in support of VLC solutions, particularly in use cases where RF is restricted or performs poorly and where VLC can be used as a supplementary technology that addresses various limitations of omnidirectional communication technologies. Regarding the monetary price and energy consumption of VLC systems, we envision that improved manufacturing and packaging will make VLC more competitive as the technology continues to move from testbed implementations to commercial products. We also see the growing adoption of network connected Smart Lighting systems as an opportunity to share the cost of the access network. In the following, we highlight some of the open challenges and opportunities for elevating the role of VLC in future wireless networks.

2 CHALLENGES AND OPPORTUNITIES

Over the last decade, the research community has shown that VLC is more than capable of high data rate point-to-point wireless communications. Looking towards commercial viability on a broad scale, we believe that there are still unanswered questions that must be resolved before the “tipping point” is reached and VLC systems become adopted by the masses. The major challenges and future research opportunities, as we see them, are as follows:

- (1) Access point deployment and backhaul connectivity
- (2) Practical uplink connectivity for mobile devices
- (3) Seamless connectivity in dynamic environments
- (4) Network adaptation and dynamic data distribution
- (5) Coexistence strategies within heterogeneous networks
- (6) Energy efficiency and “lights off” communications
- (7) Adaptation to novel wireless communication paradigms
- (8) Integration, packaging, and design for scale

Many of these challenges relate to the transition from static links to dynamic *systems*. Some aspects of these challenges are engineering problems; but we believe that there are still many open questions that require further research and thorough analysis.

(1) *Deployment and Backhaul*: As indicated in Section 1, the access network and system deployment are often considered “free”. Accordingly, theoretical analysis of VLC networks will often focus on the connections between a set of distributed VLC access points and the end user devices. In order for VLC systems to be commercially viable for indoor wireless Internet connectivity, the access network connecting the VLC access points to a gateway must be accounted for. The access network should be configured so that it does not become a bottleneck in the overall system while avoiding over-provisioning to the point where it is cost-prohibitive. From a cost perspective, we expect that shared use of the network infrastructure for intelligent lighting systems will help to make the deployment and operational expenses more reasonable [16]. Stringent synchronization will also be required if the VLC network is to use distributed transmission techniques like cooperative multiprocessing (CoMP), multiple-input multiple-output (MIMO), or spatial modulation (SM). This is further discussed in point (4).

(2) *Practical Uplink Connectivity*: Visible spectrum is not ideal for providing data uplinks for several reasons including the energy cost for producing a sufficient signal from a user device, achieving alignment with the uplink receiver, and the presence of visual glare. As with the access points, a broader emission profile can simplify alignment at the cost of additional optical power; but the additional power does not improve the link quality due to signal divergence. Compared to broad emission VLC access points, this inefficient energy usage is more impactful in battery operated devices and the unused optical power from a user device does not have the benefit of contributing to the desired light field. Steerable user device emission can redirect the transmitted optical signal towards an access point; however such solutions are relatively complex when accommodating highly mobile devices. As an alternative, asymmetric techniques with both both RF and IR uplinks have been demonstrated [9, 21]. VLC uplinks tend to be complex and/or inefficient while also resulting in increased contention and interference; however asymmetric routing techniques present their own challenges related to hardware and network configuration [20].

(3) *Seamless Connectivity*: In indoor environments where wireless data traffic is dominant, user devices such as smart phones are highly mobile and undergo changes in orientation while dynamic obstructions in the environment can cause LOS connections and be occluded. In a practical system, the handover amongst different potential connections should be seamless such that the user does not notice any disruption in service. The key question is: how can a LOS technology work with the mobile devices that increasingly dominate data consumption? At one extreme, dynamic VLC transmitters can be redirected to follow the path of user devices while horizontal handover techniques reroute traffic amongst VLC access points whenever a connection becomes unreliable. At the other extreme, highly mobile traffic can be assigned to broader coverage technologies in multi-tier heterogeneous environments while VLC is reserved for quasi-static devices (i.e., wireless devices such as laptops that are typically operated in a static position). In practice, we expect that the optimal solution will land somewhere in between.

(4) *Adaptive Networks and Dynamic Data Distribution*: Existing RF deployments (e.g., WiFi) aggregate traffic requirements over a larger area and can be provisioned based on experience demand on the order of 10 to 100m radius. The large radius and multiple users establishes required rates. For smaller cells with radius on order of 1-10m, there is a high risk of under or over provisioning. Schemes that can dynamically re-provision or adapt to user devices and traffic are a possible solution. Also needed are effective multiple access techniques for when cells become skewed or overloaded. Considering the network configuration, adaptive networks and software defined network (SDN) techniques are needed to dynamically switch between multi-user scenarios where VLC access points are assigned to different users and CoMP, MIMO, or SM scenarios where distributed VLC access points are aggregated to form a single high data rate network connection.

(5) *Coexistence Strategies within Heterogeneous Networks*: The natural emergence of multiple competing technologies has led to methods to exploit availability of multiple media. Offloading of traffic from mobile telephony to WiFi is familiar whereas carrier aggregation leverages the availability of multiple channels to propagate data. Future wireless systems have the opportunity to dynamically

exploit the availability of any data channel including multiple RF and optical bands and their replication as small cells. Managing heterogeneous networks with greedy, cognitive, users will be a future requirement. While there has been a lot of recent research in this area [1, 2, 18, 24], we believe that further research into the optimal distribution of traffic related to device characteristics (e.g., device type, use case, mobility, data demand, signal quality, etc.) will ultimately help reach the seamless connectivity goals described above.

(6) *Energy Efficiency and "Lights off" Communications*: As discussed in Section 1, a key factor in the success of VLC networks will be how favorably the energy consumption of the *system* compares with that of an RF network – or, more accurately, how the RF network energy requirements compare with the additional energy required to move from a lighting system to a lighting plus VLC system. The energy consumption and communications capabilities of a lighting system that would otherwise be off is also of particular interest [3]. RF-based systems are devoid of this problem, but if we use lighting as the communications medium, we may incur the full energy overhead of illumination when using VLC unless clever schemes are adopted that provide sufficient signal to achieve target data rates. Streaming movies to multiple users in a dark room is the often-cited challenge. Alternatively, RF-based schemes can augment the capacity in these use cases. Similarly, when lighting control (e.g., dimming) is provided, we will want to sustain data quality and throughput goals.

(7) *Novel Wireless Communications Paradigms*: General wireless access is currently dominated by high speed asymmetric downloads; whereas the use cases and traffic models for future Internet of Things (IoT), virtual/augmented reality (VR/AR), device to device (D2D), and other novel paradigms is relatively unknown. Providing network services that satisfy the diverse requirements (e.g., throughput, latency, energy usage, etc.) of each technology, without compromising others, is an open challenge.

(8) *Integration, Packaging, and Design for Scale*: This challenge is perhaps less of a research problem and more of a challenge in commercialization. Nonetheless, it is of significant importance in the path towards mass adoption of VLC technology. If VLC is to be broadly adopted, it must eventually be packaged and integrated within wireless devices in a way that is invisible to the end user. In other words, devices using VLC should be able to seamlessly access the network without the user needing to purchase additional hardware or even knowing about the VLC connection. If the objective of the end user is to have wireless connectivity, they will not be driven to go out of their way in order to adopt a new technology unless their current wireless connectivity is unsatisfactory – even if the new technology promises “better” performance. The “tipping point” for adoption of RF technologies such as WiFi and Bluetooth came along with integration of the required hardware within laptops, tablets, and smart phones. We believe that a similar integration will be necessary in order for VLC to take off and, accordingly, the packaging and integration of VLC hardware within luminaires and wireless devices is a key challenge that needs to be addressed. In particular, such integration and product readiness will force design decisions that are less expensive, less complex, and more robust – likely at the expense of overall communications performance.

VLC can be a significant contributor in the future wireless ecosystem; especially in addressing aspects that it performs well: high speed downlinks, good signal isolation, and signal placement. While VLC has shown excellent potential as a communications technology, we believe that there are still open problems related to system deployment that must be resolved before the technology become broadly adopted. That being said, we believe that VLC can be successful without solving every problem mentioned; rather it can coexist with RF technologies in order to provide best overall performance.

3 CONCLUSIONS

VLC is a great new technology with unique characteristics that requires revisiting many of the long-standing assumptions about wireless communications. Initially the speed and low cost of LED sources has launched a rush to re-map the communications landscape with new optical links; but the technical and cost-based constraints are rapidly evolving. We continue to believe that VLC will realize its potential as a complementary medium augmenting existing and future RF technologies in a portfolio of media that serve the needs for high aggregate capacity from many diverse and densely distributed end devices. Lastly, we point out that RF-based solutions will be converging on a common set of challenges related to serving the wireless channel – specifically how to service the data ingress/egress from wireless spaces via “backhaul” or access networks; the importance of user locality and traffic in providing contention-free services; and dealing with both heterogeneous networks and heterogeneous devices.

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