Lighting the Way to Wireless Efficiency

The ubiquity of light makes it an attractive option for both illumination and wireless communication. We explore the future of visible light communication, including next-generation devices, groundbreaking applications, and open challenges.

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When visiting a new location for the first time, we typically whip out our smartphones and check what WiFi networks are available to use. However anyone who has been to a crowded stadium, mall, or coffee shop knows the feeling of connecting to a wireless network congested with hundreds, or even thousands, of other mobile users. Today's standard wireless communication technologies (e.g., WiFi and 4G) are unable to meet the growing number of wireless users while still maintaining acceptable speeds and reliability. Additionally, today's wireless standards are unable to facilitate ultrafast communication for emerging technologies such as virtual reality (VR) and 8K video streaming. As new technologies emerge every day, the world is begging for a paradigm shift

to support gigabit wireless communication in densely populated areas. What futuristic, groundbreaking technology is up to the task? Visible light.

Visible light lies between 430 THz and 770 THz in the electromagnetic spectrum (see Figure 1). Like the radio frequency (RF) spectrum, found between 3 kHz and 300 GHz, the visible light spectrum can be encoded with data to facilitate wireless communication. To encode data into the light, the

intensity of the light can be changed corresponding to the data that's being transmitted. For example, we can wirelessly transmit a binary 1 by turning a light on and a binary 0 by turning a light off. Unlike RF, however, visible light has the added constraint that human eyes will observe these changes to the light's intensity. To overcome this, visible light communication (VLC) changes the intensity of light faster than the sampling rate of human eyes so that we do

not observe any flickering. Photodiodes and image sensors, however, are able to detect these high-frequency changes and convert the varying intensities back into the original data.

BENEFITS OF LIGHT

One of the essential benefits of VLC is the uniting of communication and illumination. Since VLC encodes data into imperceptible changes of light intensity, the existing lighting infra-

structure can be used to transmit data. Because the illumination energy is re-used for communication, the VLC system is inherently energy efficient. This facet becomes even more meaningful when considering recent advancements in energy-efficient lighting solutions. LEDs, for example, can be used to efficiently provide illumination to a room while also providing Mbps wireless throughputs [1, 2]. In addition to the efficiency benefits, the light also has added privacy benefits when compared to RF technologies. Specifically, given that their wavelength is measured in hundreds of nanometers, light is unable to penetrate walls and can, therefore, be confined to specific areas. Traditional security methods, such as locking the door, can physically be implemented to restrict access to VLC networks and prevent potential attacks such as traffic eavesdropping.

Aside from the efficiency and privacy benefits, there are additional ad-

vantages in utilizing light instead of RF to transmit data wirelessly. First, the visible light spectrum has a staggeringly larger bandwidth compared to the RF spectrum—approximately 10,000 times larger than the RF spectrum when considering an RF bandwidth of 30 GHz to 40 GHz. The larger bandwidth can potentially be translated into

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data rates that are orders of magnitude higher, even with the simplest modulation schemes. It can also be utilized to support a large number of users, each communicating on their own separate channel. Second, the directionality of light limits its interference footprint. It is particularly beneficial for supporting dense networks (e.g., crowded conference rooms), where multiple high-speed communication links can operate with minimal cross-link interference. It significantly improves the aggregated network-level throughput.

Existing developments on VLC have been very promising but equally limited. Academic efforts have demonstrated up to 10-Gbps data rates using micro-LEDs [3]. These ultrafast speeds, however, are not supported at room-scale distances in the current research prototypes. In the meantime, commercial VLC products remain largely unavailable and only support data rates in the Mbps range. pureLiFi, the industry leader in VLC

Figure 1. The electromagnetic spectrum, highlighting the visible light portion between 770 THz and 430 THz.

solutions, has recently demonstrated throughputs up to 1 Gbps but only supports throughputs up to 43 Mbps in their commercial products [4]. High-bandwidth technologies that would benefit from mobility, such as VR (requiring at least 5 Gbps throughputs) or 8K streaming (requiring up to approximately 8.5 Gbps throughputs), still remain unreachable given these limitations.

FUTURE VLC DEVICES

These current limitations of VLC can be overcome with advances in both transmitter and receiver devices. The future of VLC-enabled devices begins with the transmitter, i.e., light bulbs. Although existing VLC commonly uses LEDs to provide illumination and communication, LEDs are not designed for communication and impose key limitations preventing VLC from achieving its full potential. The response time of LEDs, which dictates how quickly data can be transmitted in a VLC system, is limited to 10s of nanoseconds. Although micro-LEDs can better approach nanosecond response times, they are unable to provide sufficient levels of illumination because of their small size. Furthermore, single wavelength LEDs have bandwidths spanning 10s of or even 100s nanometers. This wide spectrum footprint limits the number of orthogonal channels and therefore the total aggregate throughput.

We expect future lighting can greatly benefit from the introduction of laser diodes (LDs). To generate white light from narrow-wavelength LDs, red, green, and blue LDs are mixed together and diffused to a fixed an-

gle (see Figure 2). Since LDs have a higher electrical-to-optical efficiency than LEDs at high current densities and can also support higher electrical power/unit area, they are a more efficient illumination solution. More importantly, LDs also provide superior communication performance. With rise times in the picosecond range, LDs can be modulated at GHz speeds. Furthermore, each LD emits light in a very narrow range of wavelengths, e.g., 5–10 nanometers. This results in much more efficient utilization of the visible light spectrum and potentially allows a large number of concurrent optical channels to be multiplexed in the frequency domain. Combining these two facets, robust gigabit communication becomes practical for future VLC devices and has the potential to reach 100 Gbps throughputs [5]. To leverage the fast switching times of LDs, future light bulbs will include embedded microcontrollers to encode data into the light. Algorithms will be designed to choose LD wavelengths and optical output powers that can be effectively mixed to form white light. Furthermore, new materials will be engineered to mix the multiple laser lights into one combined white light and diffuse it for pleasing illumination (that is also safe for human eyes). Finally, a powerline backbone network might be utilized to connect the light bulbs to the internet, while also providing the necessary energy for illumination and communication.

At the receiver side, future devices will have embedded sensors capable of detecting the nanosecond laser pulses generated from the VLC-enabled light

bulbs. Photodiodes capable of GHz speeds will be necessary to detect the ultra-fast laser pulses, and specialty amplifiers will be developed to maintain the required responsivity while providing sufficient gain. To differentiate orthogonal wavelengths, special optical filters will be manufactured, capable of separating the mixed laser light into individual channels (see Figure 3). Furthermore, active optics will need to be developed to reliably focus the received light onto the receiver, regardless of where the user is within the illumination area. Microcontrollers that can sample the photodiode's response fast enough and retain the intensity information will be designed to convert the received light values into the originally transmitted data. Finally, the components will be miniaturized so they can be embedded into VR headsets, smartphones, and other mobile devices.

FUTURE APPLICATIONS

The applications arising from future VLC-enabled devices are manifold. VR headsets, for instance, can be untethered from their wires, allowing users to experience virtual worlds with full mobility. Similarly, high-definition video, such as 8K or more, can be streamed wirelessly from VLC access points (e.g., light bulbs). HDMI connections can be replaced with VLC connections, allowing televisions, computers, and projectors to be placed and used in new environments. Environments where RF waves are precluded, such as hospitals or power stations, can benefit from wireless communication for the first time, opening up the possibilities for new innovations in the health care and utility sectors. Any environment that typically requires ultrafast wired communication can be opened up to the possibilities and innovations arising from mobility.

In addition to supporting wireless communication, the VLC infrastructure can be reused for sensing purposes. For example, an opaque object (e.g., human bodies) can block light rays. By deploying photodiodes in the environment, either on the floor or wall, we can capture and analyze light blockage information caused by users. Since the light blockage information changes as

Figure 2. Laser-based visible light communication light bulb.

Multiple laser diodes are modulated, mixed, and diffused to provide Gbps throughputs and room illumination.

the user moves, we can infer movement and even fine-grained body poses [6]. Such detailed behavioral information can also facilitate health monitoring. Localization and object tracking is another application where photodiodes embedded in the environment or mobile devices can compare the received signal strengths from various transmitters to locate a user or track an object. More importantly, since photodiodes, instead of image sensors, are used to retrieve sensing information, such sensing systems are more privacy-preserving as they capture far less raw sensing data. It also results in more lightweight computations and reduces system energy consumption.

OPEN CHALLENGES

There are numerous challenges toward realizing the future of ubiquitous, VLC-enabled devices. Two major considerations are the costs associated with the VLC infrastructure and mobile device sensors. First, as VLC enters the mainstream, it is reasonable to assume a gradual coexistence of existing lighting infrastructures with communication-enabled transmitters. The entire lighting infrastructure, however, will eventually need to be modified to support VLC enabled light bulbs, requiring a reliable backbone network also capable of Gbps throughputs. Fast-switching lasers have already been proposed to replace wired connections [7]. Similarly, the components required to achieve Gbps throughputs within the light bulbs themselves are more complex and expensive than typical LED-based light bulbs. Innovative manufacturing processes will, therefore, need to be designed to reduce

the overall cost of VLC systems.

Second, the costs associated with miniaturizing the mobile receivers is also a considerable challenge. While VLC is feasible on a large scale, embedding the same functionality into smartphones will necessitate innovations from the physics, engineering, and materials science communities. Furthermore, uplink solutions will need to be considered to fully realize practical, bidirectional VLC. Sufficiently fast components need to be designed and optimized to demodulate the ultrafast laser pulses. Current analog-to-digital converters are expensive and consume watts of power. For VLC to effectively compete with RF, the power consumption needs to be further minimized and the components need to be as inexpensive as possible. Additionally, LDs used for communication and illumination must be made safe for human eyes and also robust enough for highly mobile environments.

CONCLUSION

Light has the potential to change the way users view communication and mobility. High-throughput applications, such as VR or 8K video streaming, are currently limited by wires, reducing the potential for futuristic, groundbreaking technologies. If smartphones, VR headsets, and other mobile devices were VLC-enabled, high-throughput applications would no longer be constrained by mobility restrictions. Furthermore, if high-throughput communication and ubiquitous illumination could be combined into one infrastructure, the world's energy dependency could be cut

Figure 3. Embedded visible light communication receiver capable of focusing, separating, and demodulating the gigabit data.

in half. VLC is the clear path toward a greener, interconnected, and highly mobile future.

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