Visible Light Communication: Opportunities, Challenges and the Path to Market

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ABSTRACT

Visible light communication is a potentially disruptive form of wireless communication that can supplement radio frequency communication and also uniquely enable novel mobile wireless device use cases. High data rate downlink communication in homes and offices and high accuracy indoor positioning in retail stores are two of the most compelling use cases of this promising new technology. Large-scale commercialization of visible light communication devices will depend on both the development of robust and efficient engineering solutions, and the execution of incremental commercialization strategies.

INTRODUCTION

Visible light communication (VLC) is rapidly emerging as a compelling technology for supplementing traditional radio frequency communication and enabling new wireless device use cases that are uniquely achievable with this technology. The key property of LEDs that enables VLC is their susceptibility to amplitude modulation at frequencies high enough to achieve meaningful data rates while not affecting the LED's primary illumination function. The primary illumination functionality is unaffected because the human eye cannot perceive the amplitude modulation of light as long as the frequency of modulation is above the so-called flicker fusion threshold [1].

We need only glance around to convince ourselves of the ubiquity of LEDs in our every day world. They are used in numerous consumer electronics devices such as television screens, computer monitors, mobile phone displays, advertising billboards, and digital signage displays. In these devices the primary function of the LED is content visualization, and their use has almost completely saturated the market. LEDs are also increasingly being adopted in the general illumination market, in both the commercial and residential segments, because of their advantages over competing lighting technologies in energy efficiency, longevity, color rendering capability, and environmental factors [2]. It is widely expected that LEDs will dominate the general illumination market by the end of the decade [3] and will be particularly prevalent in commercial lighting due to the sensitivity of this market segment to the cost benefits offered by LEDs.

Visible light has certain advantages over traditional radio frequency as a medium for communication. First, the visible light spectrum is unlicensed and currently largely unused for communication. The availability of this free spectrum creates an opportunity for low-cost broadband communication that could alleviate the spectrum congestion currently evident in the 2.4 GHz industrial, scientific, and medical (ISM) band. Second, since visible light does not penetrate through building walls, VLC can exhibit a high degree of spatial reuse: VLC signals in adjacent rooms or apartment units would not interfere with each other, thereby potentially admitting a far higher spatial density of communication rates than is achievable with radio frequencies (RF). The signal isolation property can also be used to enhance communication security by preventing eavesdropping on in-room or in-building communications. Third, due to the fact that VLC with current technology is a non-coherent (relative to the optical carrier) mode of communication, the front-end components of both transmitters and receivers are relatively simple and cheap devices that operate in the baseband and do not require frequency mixers or sophisticated algorithms for the correction of RF impairments such as phase noise and IQ imbalance. Fourth, because the wavelength of light is in the sub-micron range, accurate direction-of-arrival estimation is achievable with photodiode arrays, such as image sensors, which enables accurate indoor positioning of mobile devices.

Visible light communication has, on the other hand, certain shortcomings compared to traditional RF communication. The main downside is that the achievable data rate falls sharply with increasing link distance, which limits the range of high data rate VLC use cases. Since VLC is a non-coherent form of communication, the path

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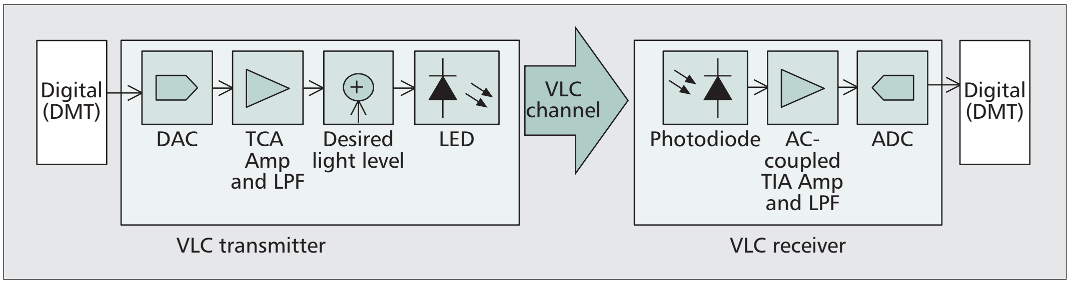

Figure 1. *The VLC radio transmitter and receiver based on intensity modulation/direct detection.*

loss is inversely proportional to the distance raised to the power of four [4], as opposed to the power of two for RF communication. VLC link data rates are degraded by shot noise if the photodiode receiver is exposed to direct sunlight, thus limiting high data rate VLC communication mostly to indoor environments. Another downside of VLC is that the lights have to be powered on in order to transmit data at link rates that approach those of WiFi (for low data rates in the kilobits per second range, however, lights may be dimmed). For these reasons, VLC will not replace high-speed RF communication, which will always be used in situations where long-range non-line-of-sight and/or outdoor links are required. Indeed, VLC and RF communication are complementary technologies that together can offer net gains in wireless network performance.

VLC use cases can be grouped into two categories, to which we refer as high data rate use cases and low data rate use cases. The high data rate use cases require specialized high-speed photodiode receivers, whereas low data rate use cases can be realized using existing hardware available in mobile devices. Downlink communication from a light fixture or lamp used for general illumination to a mobile device, whether in a home, office, or even airplane cabin, is one of the earliest envisioned high data rate VLC use cases [5–7]. Link data rates in the hundreds of megabits per second, rivaling those of Wi-Fi, have already been achieved with commercially available illumination-grade LEDs [8, 9]. Due to a high degree of spatial reuse, however, aggregate system throughput (sum rate) of VLC networks can be far greater than that of WiFi networks in situations where, for example, walls are present to isolate VLC signals from each other. Other high data rate use cases include file transfer between mobile devices and streaming of content from a mobile device to a display. Low data rate use cases include positioning of mobile devices in indoor environments and device pairing. In this article our focus is on mobile-device-centric use cases, although there are other interesting use cases such as vehicle-to-vehicle communication [10].

The remainder of this article is organized as follows. We first focus on high data rate VLC, specifically for the downlink use case and show the radio design, experimental results on LED modulation bandwidth and the achievable data rates. We also discuss issues arising from integration with a backhaul link and look at the problem of uplink design to go with the high data rate VLC downlink. Following that, we shift the focus to low data rate use cases of VLC, such as indoor positioning, that use the camera sensor as the receiver and describe the features of the sensor that should be taken into account when using it in this way. Finally, we discuss some challenges associated with the commercialization of VCL and suggest a path forward.

VLC signals in adjacent rooms or apartment units would not interfere with each other, thereby potentially admitting a far higher spatial density of communication rates than is achievable with radio frequencies.

High Data Rate VLC

The High Data Rate VLC Radio

High data rate VLC is achieved by amplitude modulation of LED sources, and the corresponding communication technique is typically referred to as intensity modulation/direct detection (IM/DD) [4]. At the transmitter, the desired illumination level is maintained by setting the appropriate DC bias of the overall signal fed into the LED. The receiver's "antenna" is a silicon photodiode that converts the received optical power to a current signal that is amplified by a transimpedance amplifier and fed into a digital baseband processor.

The VLC channel exhibits no Doppler spread effects because destructive and constructive interference patterns occur on a micron scale and are effectively averaged by the photodiode receiver whose size is several thousand times greater. This means that sophisticated channel tracking receiver algorithms are not required since the channel is effectively time invariant (shadowing may cause outage, which can be mitigated through automatic repeat request). The frequency response of the LED is not flat, as seen later. Consequently, modulation schemes such as discrete multitone (DMT) are particularly convenient [6, 8, 9], because they decompose the channel into multiple parallel frequency-flat channels. Single-carrier modulation can also be used, along with an appropriate receiver-side channel equalizer.

LED Modulation Characteristics

The data rate of the VLC link is limited by the modulation bandwidth of high brightness LEDs used in light fixtures and lamps. Due to the power-bandwidth trade-off of LEDs and the various parasitic impedances in the LED packaging, signals modulated at high frequencies are strongly attenuated. The frequency response of two LED packages that are typical of those used in current general illumination fixtures and lamps is shown in Fig. 2. From these figures we can see that the signal-to-noise ratio (SNR) can drop by as much as 30 dB over 30 MHz. The SNR reduc-

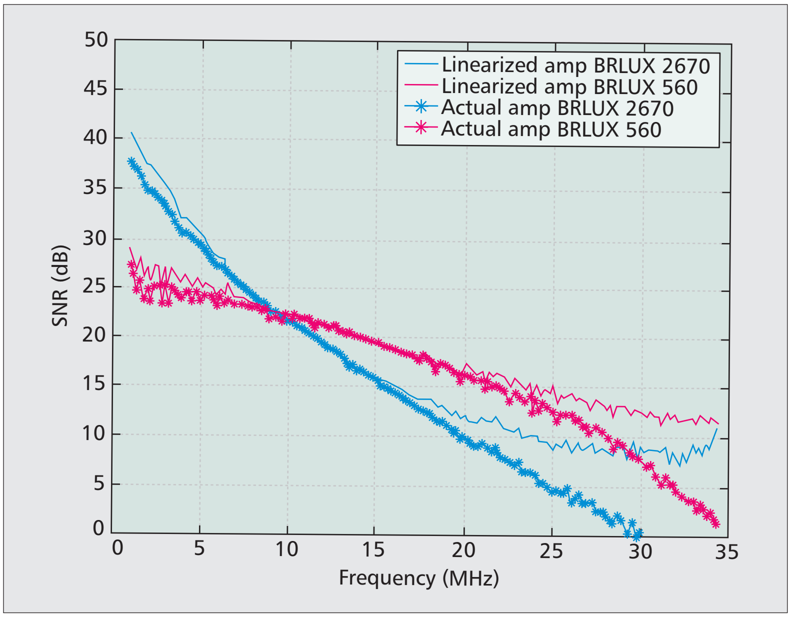

Figure 2. *Example frequency response of a pair of high-powered LEDs used in the general illumination market. The BRLUX 2670 LED package uses 24 Bridgelux LED chips in a 2 × 12 configuration and outputs 2670 lumens (equivalent of a 200 W incandescent bulb). The BRLUX 560 LED package uses 6 Bridgelux LED chips (identical to the BRLUX 2670) and outputs 560 lumens. The parasitic effects create steeper rolloff in the higher powered LED package. The measurement was conducted at a received illuminance of 1000 lux which occurred roughly 1 m away from the BRLUX2670 and 0.5 m away from the BRLUX560.The experiment was conducted by modulating the LEDs with a wideband LTE signal and measuring the error vector magnitude on a per-frequency carrier basis. The curves corresponding to the linearized amplifier were obtained after measuring the frequency response of the amplifiers and applying the inverse filter to correct for their effect in post-processing. The receiver was custom-built and included a Hamamatsu photodiode and amplifier that had bandwidth of over 60 MHz.*

tion over frequency is potentially even greater if the transmitter amplifier exhibits strong nonlinearity (as illustrated by the dotted curves in Fig. 2).

Even with such limited bandwidth, the data rates achievable are high enough to rival those of WiFi. In Fig. 3 we show the link capacities as functions of the received illuminance at the receiver (measured in lumens per square meter or lux) for the two LED packages discussed above. Typical office desk-level lighting is between 400 and 1000 lux. At 600 lux the capacity of the link is around 150 Mb/s.

High data rates over such limited bandwidth can only be achieved by exploiting the high achievable SNRs through the use of high-order constellations. However, such spectrally efficient modulation requires a linear end-to-end signal response. Using linear power amplifiers to achieve this may be counter-productive because these devices are power hungry, and this would undermine one of the main selling points of LED lighting: power efficiency. For example, if class A amplifiers are used, the reduction in overall LED efficacy, in lumens per watt, is 16 and 42 percent, respectively, for the two LEDs whose frequency response is shown in Fig. 2. One way to alleviate this problem is to use more power-efficient amplifier configurations and admit more nonlinearity. Compensation algorithms, such as digital predistortion, would then be needed to mitigate the resulting nonlinearity impairments.

The ultimate solution may come from adopting arrays of smaller, less powerful LEDs as building blocks of illumination devices. Recent work [12, 13] has shown that the modulation bandwidth of micron-scale GaN LEDs can be in excess of 300 MHz, which means that data rates in hundreds of megabits per second could be achieved using simple binary modulation, thereby eliminating the need for inefficient linear amplifiers. The higher bandwidth of these micro LEDs is due to their low internal capacitance and low parasitic impedances when integrated with complementary metal oxide semiconductor (CMOS) drivers. Another method for increasing the data rate is by transmitting independent data streams on different colored LEDs that combine to make white light [9]. Some lighting manufacturers are already incorporating multicolored LEDs to enable warmer color temperatures and color rendering capability in their products.

Integration with Backhaul for the VLC Downlink

In the downlink use case, data must be delivered to the LED fixture or lamp before it can be transmitted as a VLC signal. There are a number of backhaul technologies that can accomplish this. The use of any backhaul technology would require some modifications of the LED lamp or fixture to allow it to receive and potentially process the data coming over the backhaul before creating a current signal with which it can drive the LED.

Given that LED fixtures and lamps are connected to the AC powerline, a natural choice for the backhaul technology is powerline communications (PLC). In this case, the required modifications to the light source for enabling VLC signal transmission take on a particularly simple form [7]. This is because the signals used by PLC modems can also be used to modulate the LED. The PLC modulation is DMT and the bandwidth is up to 30 MHz (for the HomePlug AV1 standard) which ideally matches the envisioned communication scheme for VLC. Even though the lamp or fixture is connected to the AC powerline, PLC signals transmitted on the powerline cannot reach the LED chip inside the lamp without undergoing extreme distortion. Since LEDs need a certain DC voltage to turn on, they cannot run directly off of the 60 Hz power cycle. As a result, most fixture/lamp designs implement some type of bridge-rectifier, or AC-to-DC converter, inside their power supplies that regulate the current supplied to the LED. Since the rectifier completely removes any signal on the powerline, the lamp must be modified to allow the PLC signals to bypass the rectifier. Figure 4 illustrates the required modifications to the LED lamp to allow analog PLC signals to pass through.

The VLC link capacity may be greater than the capacity of the PLC backhaul link based on HomePlug AV1, especially in cases in which multiple mobile devices are being served by fixtures connected to the same PLC network. The new standard HomePlug AV2 alleviates the problem to a large degree by offering data rates in excess of 1 Gb/s. To extract the maximum benefit of VLC, a backhaul technology with throughput greater than PLC may be required. One option is the power over Ethernet (PoE) standard which delivers gigabits per second of data and power to network devices over the same CAT cable. This approach may be particularly suitable for deployments in office buildings in which Ethernet connectivity is ubiquitous.

INTEGRATION WITH THE UPLINK

The downlink use case generally requires an uplink (or reverse link) that the mobile device can use, for example, to send downlink requests and frame/packet acknowledgments. One choice for the uplink technology is WiFi because many mobile devices, such as smartphones and tablets, have a WiFi radio already pre-installed. Furthermore, there are hybrid router/gateway devices on the market that are designed to manage data traffic flows over heterogeneous technologies (one such example is the Qualcomm Atheros Hy-Fi gateway). These devices can be modified to support VLC and also manage the simultaneous operation of the VLC downlink and Wi-Fi uplink for the mobile devices associated with it.

One challenge in using WiFi for sending acknowledgments of VLC frames/packets is that it may create frequent small-packet traffic, which would reduce the throughput of co-located WiFi-only devices. Similarly, the latency and throughput of the VLC link would suffer due to the presence of legacy WiFi devices. Careful management of the WiFi spectrum and quality of service levels must be taken into account when devising a complete system operating on this basis. In addition to traffic management, more robust forward error correction (FEC) techniques could be used to reduce the number of acknowledgments required by the VLC traffic stream.

By feeding back VLC channel SNR information to the Hy-Fi router, a WiFi uplink channel could be used to configure VLC downlink parameters such as rate, channel bandwidth, and power. In the presence of multiple individually addressable VLC-enabled fixtures, this feedback information could also be used to determine with which fixture(s) the mobile device should be associated.

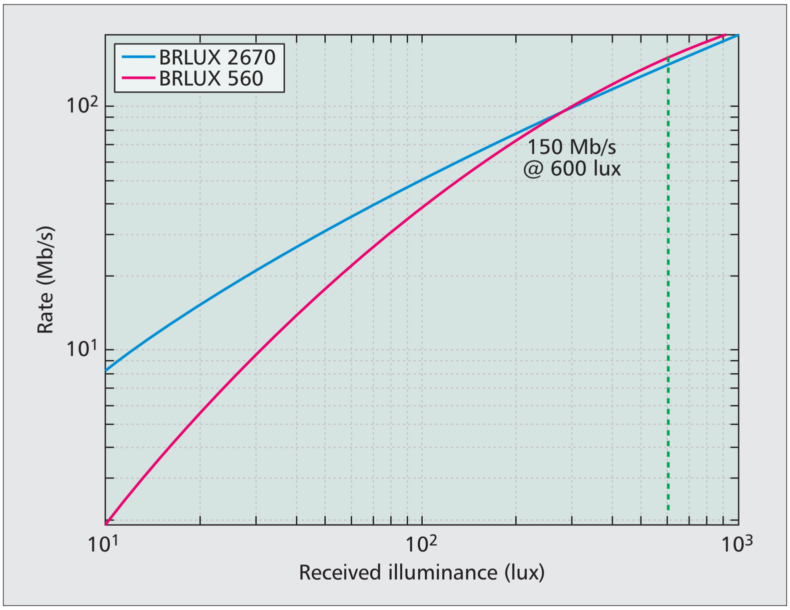

Figure 3. *VLC link capacity as a function of received illuminance in lux. 600 lux is typical office desk-level illumination. The result is obtained by performing a capacity calculation on a polynomial fit of the curves in Fig. 2, up to 35 MHz. The capacity calculation is based on the well-known waterfilling formula [11, Ch. 5].*

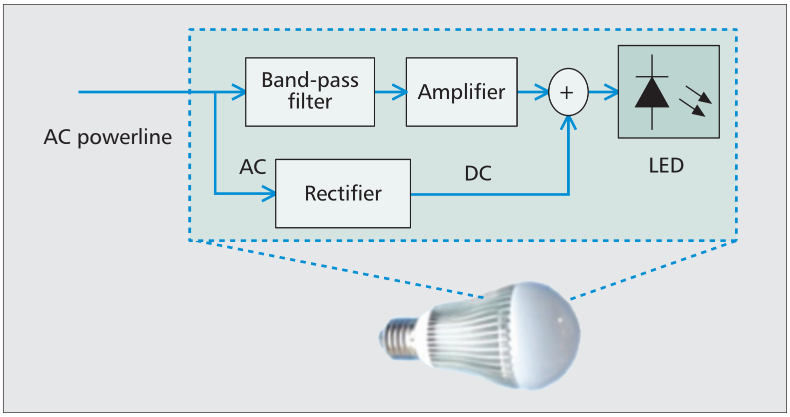

Figure 4. *The modifications to the LED lamp or fixture that are required to enable high data rate VLC signal transmission. The analog PLC signal is isolated and amplified before being forwarded to the LED [7]. An additional regulator may be needed to create a stable DC source.*

LOW DATA RATE VLC

In the category of low data rate VLC we group use cases that can be enabled using hardware already present in mobile devices available on the market today. One key example of such hardware, focused on in this section, is the camera sensor. The camera sensor is essentially a dense two-dimensional array of photodiodes, each photodiode representing a pixel. Peak data rates achievable with camera sensors in today's mobile devices are in the lower kilobits-per-second range. This is, however, sufficient to enable many use cases of interest. (Reference [16] shows one way of using the image sensor as a VLC receiver which can be used when the field of view of the sensor is fully subtended by the VLC source. To achieve decoding at a longer range, an erasure code is required, as mentioned in that reference).

Most smartphones or tablets on the market today have two cameras, one on each side, for photography and video conferencing uses. The front-facing camera of a mobile device is particularly useful for enabling the indoor positioning use case because, while the user is looking at the screen of the mobile device, the camera naturally faces the ceiling lights and hence is able to decode the VLC signals that they transmit. The back-facing camera can be used for decoding signals coming from LED displays in TVs, advertising panels, and mobile devices, to more effectively and unobtrusively support use cases that can currently be partially addressed with

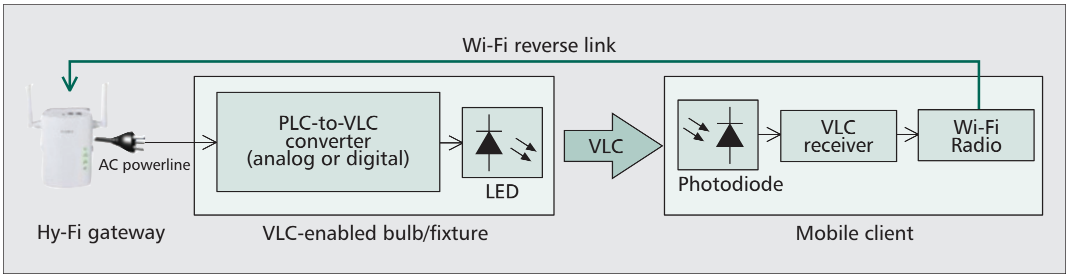

Figure 5. *The uplink can use an out-of-band technology such as WiFi. The Hy-Fi router manages the VLC downlink and WiFi uplink on a per user basis.*

QR codes. The advantages of VLC over QR codes are longer range, greater robustness to illumination, skew and other optical distortion and, of course, the savings of display real estate.

The Need for Indoor Positioning

Accurate indoor positioning is in demand in several markets where LED lighting is currently being adopted, such as the retail store and enterprise markets. Retailers, shopping malls, and supermarkets are interested in positioning technology because it has the potential to vastly increase the revenue of all parties involved in the store's product supply chain. By guiding customers to the precise location in the store of the product on their shopping list, retailers can reduce revenue losses due to unfound items. Targeted product advertising is also a highly lucrative value proposition that can be enabled by accurate indoor positioning: up to 70 percent of sales are made at the aisle level [14]. Overall, the market for mobile indoor positioning in the retail sector is expected to reach $5 billion by 2018 [14]. The lighting manufacturers are very interested in the indoor positioning use case because of the high demand for it from these markets and because of the vast and immediately available consumer base due to the nearly ubiquitous presence of camera-based VLC receivers in mobile devices (Fig. 6).

Achieving Very Accurate Indoor Positioning Using VLC

VLC can achieve centimeter-level accuracy of indoor positioning at low cost. The requirements for modification of lighting infrastructure to support accurate positioning are far simpler and cheaper than those for the high data rate downlink use case. Since low data rates are sufficient for positioning, one can use simple and power-efficient switch-mode amplifiers that are already installed, as part of driver circuitry, in most LED fixtures and lamps. The additional cost would be negligible and would only come from simple programmable logic devices that drive specific relatively low frequency signals into the LED to convey location-related information to mobile devices. On the receiver side, the camera sensor decodes the location information transmitted by the light fixture and also accurately estimates its position relative to that fixture. By nature, the camera sensor is an angle-of-arrival estimator, therefore triangulation algorithms [15] can be used to determine the mobile device's position relative to the light fixtures. If the location of those light fixtures is known relative to objects in the venue, such as products in an aisle, then the mobile device will know its position relative to those objects as well. Moreover, triangulation can determine the device's orientation in space, something that is very hard to achieve with a high degree of accuracy in indoor environments by using, for instance, the mobile device's built-in compass. This feature is important because it would allow the mobile device to determine which aisle the customer is looking at even when they are exactly in-between two aisles.

There are several properties of the camera sensor that must be taken into account when using it as a VLC receiver. The exposure time of the camera must be carefully controlled, or compensated for, in order to maximize the achievable data rate and prevent jitter in the frame rate. The camera sensor also consumes a lot of power (in excess of 100 mW) and would drain the mobile device's battery quickly if it were to be constantly used. Smart algorithms must be used to gate the operation of the camera and/or turn it on only when VLC signals are likely to be present and desired. Finally, the computational resources used for processing of captured camera frames would need to be carefully managed in order to avoid interference with the normal operation of the mobile device.

One of the key challenges in using low-frequency signal modulations, however, is ensuring that perceivable flicker is not being generated by the modulated waveforms. Flicker is avoided by using waveforms whose lowest frequency components are far greater than the flicker fusion threshold of the human eye (which is typically less than 3 kHz). However, high frequency modulation incurs attenuation at the receiver coming from the image sensor's exposure filter. Therefore, exposure control is of paramount importance in the practical feasibility of low data rate applications.

Challenges in Commercialization of VLC

Although the downlink use case has the potential to enhance wireless network performance, there are certain business challenges facing its widespread adoption in the consumer market. One of the main challenges arises from the fact that two different industries must work together in order to bring the downlink use case to mar-

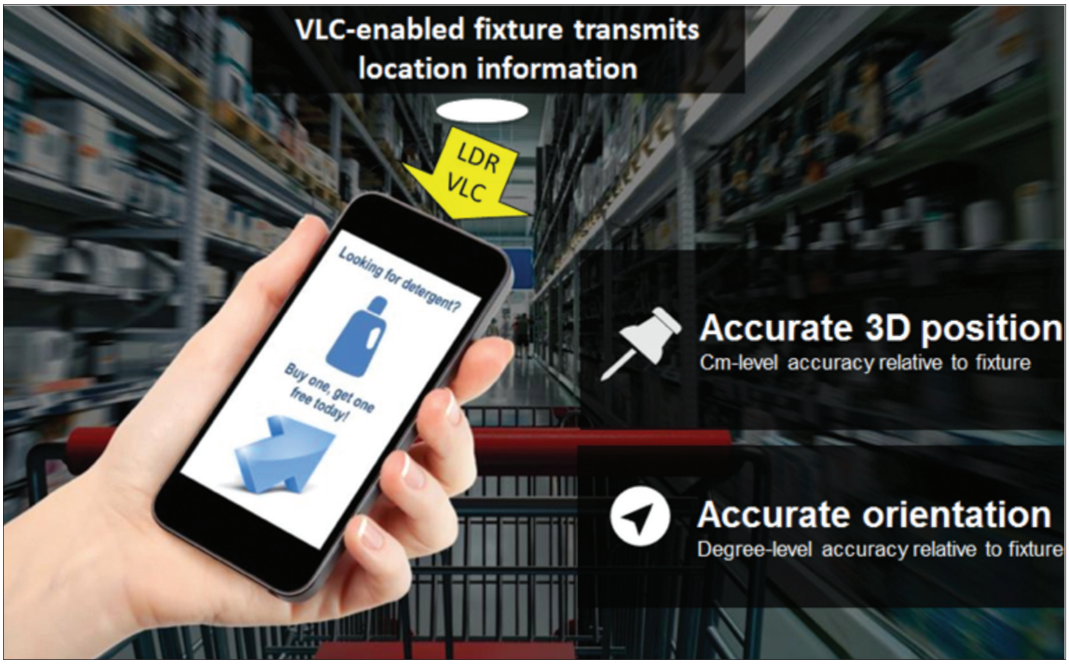

Figure 6. *Low Data Rate (LDR) Visible Light Communication that uses simple, power-efficient ON-OFF signaling can be decoded by the smartphone camera sensor. Combined with triangulation of multiple fixtures, this can enable high accuracy indoor positioning and orientation estimation of mobile devices. This technology is of particular interest to the retail industry as it could enable accurate product search, targeted advertising and customer analytics.*

Since it requires no additional hardware in mobile devices and achieves a functionality that is in high demand by retailers, the indoor positioning use case is the most promising first step in the commercialization of VLC.

ket. On one hand, the lighting original equipment manufacturers (OEMs) need to make certain modifications to their lamp and/or fixture designs, and on the other hand, mobile device manufacturers need to install high-speed photodiode receivers in their devices.

There are compelling reasons why both parties should seriously consider VLC. From the perspective of lighting manufacturers, the relatively extreme longevity of LEDs (50,000 hours or more) compared to older lighting technologies is a double-edged sword: it drives LED sales in the near term, but leads to "socket saturation" in the long term. VLC could provide lighting OEMs with a new source of revenue by incentivizing their customers to upgrade to VLC-enabled lamps and fixtures after they have made the initial upgrade to LED lighting. Even before socket saturation occurs, VLC could play an important role in providing differentiation to lighting products, which will be increasingly important in an LED market that is becoming commoditized. Mobile device OEMs would also benefit from equipping their devices with VLC receivers because this would give them a competitive edge in the market and justify higher average sale prices.

Commercialization of VLC is likely going to come by way of an incremental strategy that first brings to market certain use cases of VLC that are not afflicted by the "chicken and egg" problem confronting the high-speed downlink use case. These use cases can be grouped into two categories: those that do not require additional hardware in the mobile device and those that mobile device manufacturers can unilaterally bring to market. High-accuracy indoor positioning is an example of a use case that requires no additional hardware in the mobile device and, as discussed earlier, there is already great interest in this use case from the lighting manufacturers and their customers. Bringing such use cases to the consumer first may create a positive feedback effect on the general demand for VLC, which will lead to the accelerated adoption of other use cases, eventually including the downlink use case.

Regarding the use cases that mobile device manufacturers can unilaterally bring to market, device-to-device pairing, file transfer, and wireless docking are the most promising. In wireless docking a mobile device streams the output of its screen to another device such as a display. Device-to-device file transfer and wireless docking applications would use the same high data rate VLC technology that can be used for the downlink use case (i.e., high speed photodiode-based receivers in addition to LED transmitters). If device manufacturers begin installing such hardware in mobile devices, the lighting OEMs would have an immediate incentive to create high-data-rate VLC-enabled LED fixtures and lamps.

Conclusion

Visible light communication can supplement radio frequency communication and improve wireless network performance wherever short-range links are used, such as in a home or office for downlink Internet access or for device-to-device file transfers and video streaming. VLC can also uniquely enable highly accurate indoor positioning of mobile devices. Since it requires no additional hardware in mobile devices and achieves a functionality that is in high demand by retailers, this use case is the most promising first step in the commercialization of VLC.

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