Lighting Up the Internet of Things with DarkVLC

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ABSTRACT

Visible Light Communication (VLC) holds a great potential to solve the spectrum crunch problem and to provide scalable connectivity to zillions of mobile and IoT devices. However, VLC commonly requires LED lights to be on, which fundamentally limits the applicable scenarios of VLC and makes VLC less attractive to mobile and IoT devices with tight energy budget. We present *DarkVLC*, a new VLC primitive that allows the VLC link to be sustained even when the LED lights appear dark or off. The key idea is to encode data into ultra-short light pulses imperceptible to human eyes yet detectable by devices equipped with photodiodes. Realizing DarkVLC faces several challenges to generate and deal with the ultra-short light pulses reliably. We describe our preliminary efforts to tackle these challenges and build a DarkVLC prototype using off-the-shelf LEDs and low-cost photodiodes. DarkVLC fundamentally broadens the application scenarios of VLC and provides a new ultra-low power, always-on connectivity affordable for mobile and IoT devices.

CCS Concepts

•Networks → Wireless access networks;

Keywords

Visible light communication; Energy efficiency; Internet of Things

1. INTRODUCTION

Scaling out zillions of mobile devices and Internet of Things (IoT) encounters a critical roadblock: the radio spectrum crunch and the energy cost of communicating with a large number of embedded devices and sensors. Going beyond the radio spectrum frequency, Visible Light Communication (VLC) [7] holds a great potential to mitigate the radio spectrum crisis. It offers the following benefits: orders of magnitude (10^4) higher bandwidth than the radio spectrum, reusing existing lighting infrastructure, simple modulation and demodulation without complex signal processing (suitable for IoT devices with limited capability), being free of electromagnetic interference, and finally better security and privacy since light cannot penetrate walls.

When bringing VLC to the world of mobile and IoT devices, however, we face a fundamental constraint – VLC commonly requires the light to be on during communication. This constraint leads to two key problems. *First*, communication stops when lights are off (e.g., inside a dark car, during night when we are in sleep), which severely limits the applicable scenarios of VLC. Consider the use of VLC-enabled ceiling lights to provide network connectivity to the mobile devices or smart sensors in the environment (e.g., a home, office, car). The connectivity is lost once the ceiling lights are off, which can hinder a wide range of monitoring applications. *Second*, for mobile devices to transmit data using VLC, they have to emit visible light beams. Emitting visible light beams not only consumes a high power (∼900 mW [1]) quickly draining the device battery, but also creates unpleasant visual experiences to mobile users who are potentially carrying or wearing these devices. A recent design [15] encodes data into reflected light to eliminate the need of actively emitting light rays. However, it still requires ceiling lights to be on and the reflected light beams remain visually unpleasant for mobile users.

In this paper we propose *DarkVLC*, a new VLC primitive that allows a VLC link to be sustained even when the LED light appears dark or off. The key idea is to reduce the LED's duty cycle to an extremely-low level and encode data into ultra-short light pulses. The light pulses are imperceptible to human eyes, but light sensors (photodiodes) can detect these light pulses and decode data. By removing the constraint of requiring perceptible light beams, DarkVLC fundamentally broadens the applicable scenarios of VLC. It can be integrated with VLC in its normal mode (i.e., when lights are visually on), so that ceiling lights can transition from the normal mode with lights on to its dark mode when lights are off, allowing communication to be 24/7. DarkVLC also provides a new ultra-low power, always-on connectivity affordable for mobile and IoT devices to communicate with either the ceiling light in the uplink, or other mobile devices in a peer-to-peer manner.

The design and development of DarkVLC entail several challenges. *First*, it is non-trivial to emit and detect ultra-short light pulses using off-the-shelf LEDs and photodiode sensors. We need to switch the LEDs on and off at a ultra-high speed, requiring the LED/photodiode driver circuit, the wiring, and the micro-controllers attached to LEDs and photodiodes to react very fast with minimal delay (within tens of nanoseconds). *Second*, the ultra-low duty cycle imposes challenges on the design of modulation schemes. Common VLC modulation schemes either modify the LED duty cycle and thus cannot keep the light pulses imperceptible, or achieve very low data rates because of DarkVLC's ultra-low duty cycle, or require special hardware support. *Third*, the DarkVLC link can be

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fragile in practice, as ambient light, transmission distance and angle can all affect the detection of the ultra-short light pulses and lead to decoding errors.

This paper describes our preliminary efforts on tackling the above challenges. We judiciously design the driver circuit of both the transmitter and the receiver to generate and detect the ultra-short light pulses. To encode data, we explore the use of pulse position modulation (PPM), which can efficiently represent multiple bits as the occurrence of a single light pulse in the time domain. To diminish the interference of ambient light, we decode data by locating the rising edge of the encoded light pulse, which is more rapid than ambient light fluctuation. We have built a prototype of DarkVLC using a commercial LED and a low-cost photodiode. Our current prototype supports 1.77 Kbps data rate, generating 0.09 lx of luminance and consuming only 46.8 μW of transmit power. We conclude the paper by discussing remaining challenges and potential applications built atop DarkVLC.

2. DarkVLC DESIGN

We first describe the key concept of DarkVLC, i.e., adapting the LED's duty cycle to generate ultra-short, imperceptible light pulses. We then present our preliminary design to encode and decode data into patterns of light pulses. A prior study [3] has discussed the standard for lights to appear off and simulated resulting data rates. Our work goes beyond the analytical results and simulations. We tackle the practical challenges to realize DarkVLC.

Concept. In practice, an LED emits light rays by periodically transitioning between ON and OFF states. The resulting luminance is determined by both the peak light intensity and its duty cycle d (i.e., the percentage of the ON duration t_{ON} in a period t_{period}, $d = t_{\text{ON}}/t_{\text{period}}$). Thus, to reduce LED's luminance to an extremely-low level, we can reduce its peak light intensity and lower its duty cycle. Reducing the peak light intensity, however, results into lower light pulses and curtails the communication distance as light luminance degrades over the square of the distance [8]. To eliminate this undesired side effect, we keep the peak light intensity high and only reduce the duty cycle.

To reduce the duty cycle, we should narrow t_{ON} and widen t_{period}. The configuration of these two parameters is subject to the capacity of the electrical components and human eyes' perception (e.g., flickering effect). The minimal t_{ON} is determined by the response time of the LED, the rise- and fall-time of the switching circuitry [5], and the response time of the photodiode. Our experiments show that $t_{\text{ON}} = 100$ ns is feasible for off-the-shelf LED and low-cost photodiodes (§ 3). Configuring t_{period}, however, faces a tradeoff. On one hand, a larger t_{period} means a smaller duty cycle and thus lower luminance, better maintaining DarkVLC imperceptible. On the other hand, a larger t_{period} also lowers the switching frequency ($f = 1/t_{\text{period}}$) and possibly causes the flickering effect. Prior studies [16] show that human eyes can perceive light flashes if f is below 120 Hz or 160 Hz [16]. A lower switching frequency also constrains the link data rate. Therefore, we need to carefully configure t_{period} to achieve the best tradeoff between user perception and link data rate. In our current hardware setup (§ 3), we observe that $t_{\text{period}} = 5.2$ ms performs the best.

Modulation. Encoding data into the ultra-short light pulses is challenging because the light pulses have to be short (e.g, 100 ns) and sparsely spread in the time domain to keep the LED's duty cycle ultra-low (0.0019% in our experiment). Common VLC modulation schemes, however, either involve modifying the pulse duration (e.g., PWM [7]), or lead to much lower data rate. As examples, On-Off Keying (OOK) encodes only a single bit over a light pulse, while Frequency-Shift Keying (FSK) requires multiple light pulses to transmit a single bit. To achieve efficient encoding and boost the data rate, we choose Pulse Position Modulation (PPM) [7] to encode data. The key idea is to encode bits into the exact position of a light pulse in the time domain. More specifically, PPM divides time into symbols with equal length, where only a single light pulse occurs per symbol. Each symbol is further divided into 2^N time slots, and thus the exact time slot where the light pulse occurs represents N bits. Figure 1 shows an example where each symbol is divided into 1024 time slots and thus 10 bits are transmitted per symbol. While rich literature [19, 22, 23] has studied advanced forms of PPM to boost its data rate, these PPM variants are inherently unable to maintain a constant ultra-low duty cycle, a key requirement to realize DarkVLC. Thus, we use the basic PPM in our current design. We leave detailed discussions on these PPM variants to § 7.

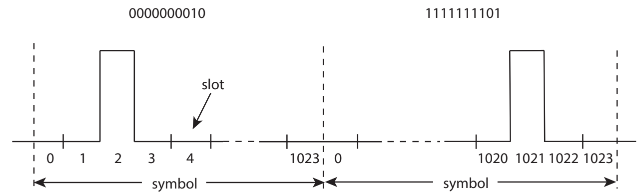
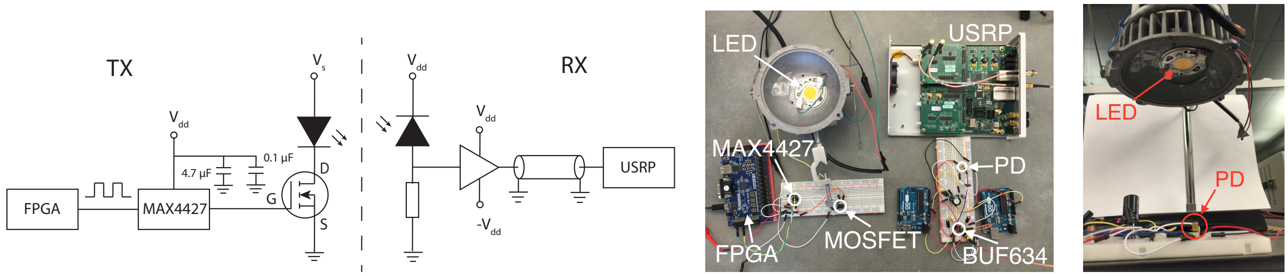


Figure 1: Pulse Position Modulation (PPM). A light pulse occurs only once per symbol. Each symbol is divided into 1024 time slots, thus the time slot where the light pulse resides represents 10-bit information.

Demodulation. The receiver decodes data by continuously sensing the incoming light intensity. To detect the occurrences of light pulses, a simple method is to collect the light intensity values within a symbol, average the observed light intensity values of each time slot, identify the time slot with the highest mean intensity value, and treat this slot as the light pulse position to decode bits. However, because of the ultra-short duration of the light pulse, ambient light fluctuation can mislead the receiver and cause errors in pulse detection. To diminish the interference of ambient light, we apply an edge-detection method to detect pulses. The key idea is to distinguish the ambient light fluctuation from the encoded light pulse based on the speed of the light intensity change. Our experiments show that the light intensity of an encoded light pulse rises much more rapidly than the ambient light fluctuation. Therefore, we first compute the first-order derivatives of the light intensity values. We then identify the local maximum to locate the edge of the encoded light pulse.

Accurate pulse detection also requires tight synchronization between the transmitter and the receiver. To help the receiver detect the beginning of a packet and align the slots, we design a preamble of pattern 11010101 using OOK and pulses are located at predefined slots. Since the receiver's ADC can occasionally lose sample points, we realign the slots once a rise edge is detected. The reason is as follows. When the ADC misses sample points, the rise edge is assumed to appear earlier than its actual occurrence. Given that we obtain only five samples for each pulse, losing even a single sample causes a significant misalignment of the slots. Losing the first sample does not immediately affect the decoding of the next pulse because we round it to the closest slot. However, errors can accumulate and lead to incorrect decoding in later slots. Therefore, to address the problem, each time we detect a rise edge, we determine the slot it belongs to, realign the slot to the rise edge, and shift the subsequent samples correspondingly.



(a) Circuit design (b) Hardware (c) Testbed setting

Figure 2: DarkVLC implementation. The LED is driven by a Xilinx Artix-7 FPGA through a MOSFET (STF5N52U) and a gate driver (MAX4427). The photocurrent generated by the photodiode is converted to the voltage signal by a resistor. The voltage signal is sampled by a USRP with an LFRX daughterboard. The voltage follower (BUF634) between the resistor and the USRP is for impedance matching.

3. DarkVLC PROTOTYPE

We build a proof-of-concept prototype for a DarkVLC link. The fast switching speed of the transmitter and receiver circuits is the key to realize DarkVLC. Next we briefly overview our implementation of the transmitter and the receiver. Figure 2 shows our circuit design and the prototype hardware.

Transmitter. We use CREE CXA2520 as the LED driven by an FPGA board. We choose an FPGA board as our micro-controller, because it offers the clock-level (10 ns) control granularity and can generate light pulses as short as 40 ns (limited by its I/O capacity 24 MHz [6]). In comparison, common micro-controllers (e.g., Arduino UNO) cannot provide clock-level control. To further boost the switching speed of the LED, we insert a dedicated gate driver between the micro-controller and the MOSFET. The gate driver can supply a burst current to switch the MOSFET. It also acts as a voltage amplifier if the output voltage of the micro-controller cannot reach the threshold voltage of the MOSFET.

We notice that wiring also affects the circuit switching speed. Long wires introduce the so-called transmission line [9], where signal reflection occurs, resulting into oscillating signals. This effect is non-negligible for our circuit with high frequency. We reduce the effect by minimizing the wire length. It will be less of an issue once we integrate these electrical components into a printed-circuit board (PCB) in the future.

Receiver. Our receiver photodiode is Honeywell SD5421 connected to a USRP radio. We choose USRP because it offers sufficiently high ADC sampling rate (100 MS/s). We equip the USRP with an LFRX daughter-board with a 50-Ω input impedance. We connect the photodiode to a 100-kΩ resistor. We use a unity gain voltage amplifier to transform the impedance so that the USRP does not load the signal source. Because of the bandwidth of our low-cost photodiode, our current prototype supports 100-ns light pulses. We plan to examine high-end photodiodes in our future work to further reduce the pulse duration.

Our current prototype uses customized hardware to demonstrate the concept and feasibility of DarkVLC. Moving forward, we plan to examine the prospect of implementing DarkVLC on existing mobile devices (e.g., smartphones). We will discuss associated challenges and research plan in § 5.

4. PRELIMINARY RESULTS

Using the DarkVLC prototype, we examine user's perception of DarkVLC and its practical performance under different link distance, viewing angle, ambient light condition.

Experimental Setup. We conduct experiments in a typical office environment, where sunlight and fluorescent light are present. We fix the LED on a stand with adjustable height. The LED is not covered by any lampshade (Figure 2(c)). By default, we place the photodiode right below the LED. We configure $t_{\text{ON}} = 100$ ns and $t_{\text{period}} = 5.24$ ms. All experiments are repeated 10 rounds.

4.1 User Perception

We start with examining the luminance level of DarkVLC, aiming to examine whether users can perceive DarkVLC's luminance under different ambient light conditions. We conduct the study with five participants (23 – 28 years old) in both day and night. We consider two viewing scenarios: (a) *Indirect viewing*, where we place a white paper below the LED, and ask the participant to look at the paper and report whether the LED is switched off. It tests whether the participant can perceive LED's luminance in the environment, which is also how we typically perceive light; and (b) *Direct viewing*, where the participant stares directly into the LED and reports if the LED is off. In each viewing scenario, we conduct 10 tests. In five of them we set the LED to the DarkVLC mode and in the other half we switch LED off. We mix them in a random order. The participant is unaware of the actual state of the LED.

Table 1 lists the percentage of times participants reporting lights to be off when the LED is actually off or in the DarkVLC mode, respectively. We observe that participants cannot differentiate DarkVLC and the light-off mode when they do not directly stare at the LED chip. This demonstrates that our LED duty cycle configuration is sufficient to keep light pulses imperceptible. Participants can identify the DarkVLC mode when they stare closely into the LED chip in a low ambient light condition (0.6 lx). This is only to test DarkVLC in an extreme case, since the LED chip is not covered by any lampshade and the participant is only 30 cm away from the LED chip.

We further systematically measure the luminance of DarkVLC with different duty cycles. We fix the light pulse duration to 100 ns and vary the period (t_{period}) from 0.04 ms to 5.24 ms. We place the light meter (Extech 401036) 15 cm away from the LED to measure the illuminance. We also plot the ambient light level I_0. We observe that the illuminance gradually drops to I_0 as t_{period} increases. In our default setting (t_{period} = 5.24 ms), the illuminance shift of the LED is only 0.09 lx. For reference, the full moon on a clear night produces about 3 lx of illuminance outside [3]. The same experiment conducted in the day shows that the variation of the ambient illuminance (60–110 lx) caused by cloud movements already exceeds the illuminance of the LED. Hence the luminance of DarkVLC is imperceptible in the day.

Table 1: **User perception of DarkVLC, where the percentage measures the likelihood of users perceiving the light to be off.**

Viewing	Ambient Light	Light-off	DarkVLC
Indirect	Day (385 lx)	92%	96%
	Night (0.6 lx)	100%	100%
Direct	Day (385 lx)	92%	88%
	Night (0.6 lx)	100%	12%

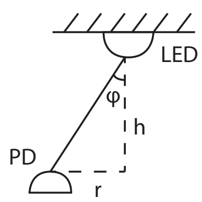


Figure 3: Experiment setup. By default $\varphi = 0$.

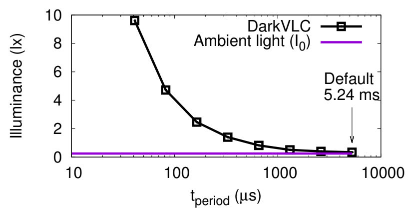


Figure 4: DarkVLC luminance w/ varying t_{period}.

4.2 System Performance

We now measure the throughput and accuracy of DarkVLC, examining how the channel parameters and environment affect its performance (Figure 5(a)-(b)). In each experiment, the transmitter sends 2040 random bits of payload (one packet) in 1.152 s including overheads. The throughput is the number of bits (only payload) correctly received per second and the accuracy is the ratio of correctly received bits over all transmitted bits. We repeat each experiment 10 times and compute the average throughput and accuracy.

Overall, we observe that DarkVLC achieves 1.77 Kbps throughput with BER around 0.01%. The throughput is very stable with standard error below 1 bps. This aligns with the prior study [28] that verifies the stability and predictability of the optical channel.

Supporting Distance. To examine DarkVLC's supporting distance, we change the LED height while keeping the viewing angle φ as 0°. Figure 5(a) shows the throughput and accuracy as the distance varies from 5 cm to 15 cm. We observe that our current prototype supports up to 10 cm distance. As long as the distance is within the communication range, the throughput is stable. Once the distance exceeds 10 cm, the throughput drops dramatically to 0. This is because the received pulse height is comparable to the noise (mainly circuit noise) and the receiver cannot decode any bits.

The limited supporting distance is due to the ultra-short pulse modulation, which prevents the light pulse from ascending to its normal peak intensity before it starts to fall. In our current prototype, the rise time of the LED is approximately 1 μs. Since we set the pulse width as 100 ns, the peak light intensity of the current DarkVLC is far below LED's peak intensity in its normal mode. Therefore, for a given noise level, the communication distance is largely affected. In comparison, using the same LED with pulse width longer than 5 μs, the supporting distance can be extended to 2 m. We will discuss our research plan to boost the transmission distance in § 5.

Viewing Angle. To examine the viewing angle of DarkVLC and the impact of the receiver misalignment, we horizontally move the photodiode away from the LED with the photodiode facing upright (Figure 3). We also vary the LED height h and repeat the experiments. Figure 5(b) plots the throughput and accuracy as the irradiance angle (φ) increases from 0° to 30°. We observe that each height is associated with a corresponding maximum viewing angle. With the increase of distance, the support viewing angle decreases. At a height of 5 cm, the view angle is around 50° (±25°).

Sensitivity to Ambient Light. We also evaluate DarkVLC under different ambient light conditions, including: (a) Daytime with other lights on; (b) Daytime with all lights off; (c) Night with other lights on; (d) Night with all lights off. Figure 5(a) indicates that ambient light does not influence the throughput and accuracy of DarkVLC. The reason is two-fold. *First*, the modulated light pulses change much more rapidly than the ambient light – let it be the natural (sunlight) or artificial (fluorescent or LED lamp) light. The sunlight is almost a DC signal, while the flashing frequency of a commercial LED lamp (Cree A19) is only 120 Hz (8 ms period). Our modulated light pulse rises and falls within μs. Thus our edge detection-based demodulation can effectively decode bits even with ambient light interference. The major noise that affects the SNR is from the circuit. *Second*, most photodiodes have a limited field of view (FoV), resembling a directional antenna. The receiver gain of signal with an incidence angle exceeding half of the FoV is very small. For SD5421, at 20° incidence angle, the received signal strength is only 10% of that at 0°. Thus the possible ambient light perceived by the photodiode has been largely attenuated. In summary, our current design is robust against ambient light interference, demonstrating the efficacy of our pulse detection scheme.

4.3 Power Consumption

Finally, we measure the power consumption of DarkVLC and compare it to VLC in the normal mode with LED on. The experiment setting is the same as Figure 4. Figure 5(c) shows how the power of the LED changes with different duty cycle (fixed t_{ON}). We measure the average LED forward current with a multimeter and calculate the power by $P = V_s I$. The power of the LED used in common mode is 19.8 W, while the power of DarkVLC is as low as 46.8 μW. With fixed pulse width, the power of the LED is directly proportional to the duty cycle.

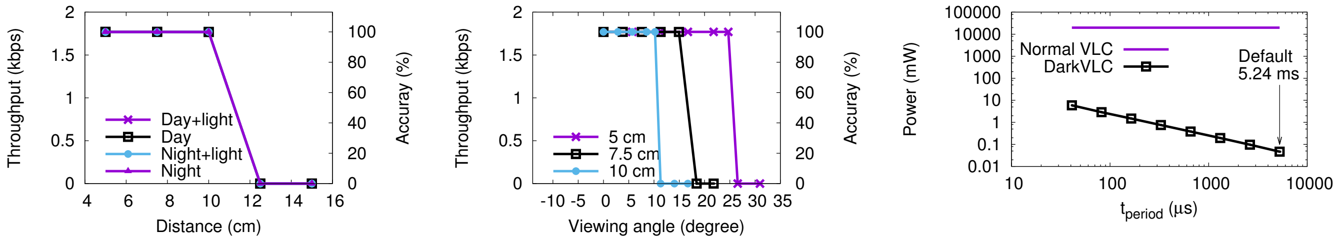
Our current demodulation requires the USRP radio as its ADC provides sufficiently high sampling rate (1 MS/s), which can be power-consuming for wireless devices. However, since IoT devices typically upload sensor data more frequently than receiving commands, the power consumed by receiving data can be insignificant. In addition, we plan to examine the following two methods to reduce the power consumption of data reception. First, we can add an analog circuit component that prolongs the pulses before the ADC such that the sampling rate can be reduced at the cost of lower data rate. Second, we can potentially replace USRP with low-power FPGAs (e.g., [25]). The embedded ADC of these FPGAs can support 1 MS/s sampling rate, yet consuming much lower power.

5. REMAINING CHALLENGES

Initial experimental results demonstrate the feasibility of DarkVLC. We also recognize the limitations of our current study and plan to address following remaining challenges.

DarkVLC Networking. We plan to study a network of DarkVLC links and seek efficient medium access control (MAC) protocols to maximize network throughput. Since light pulses are ultra-short and sparsely spread out (0.0019% of duty cycle), two uncoordinated DarkVLC links are very unlikely to collide. However, the resulting multiple light pulses in a symbol make the receiver unable to detect the source (i.e., transmitter) of each light pulse. Inspired by a recent study [10] on RF backscatter, we will examine physical-layer features of each transmitter to separate light pulses from different links. Another solution is for each DarkVLC transmitter to emit light pulses in a different color (i.e., frequency), which separates links in the frequency domain.

Boosting Link Distance. The supporting distance of our current



(a) Supporting distance (b) Viewing angle (c) Power consumption

Figure 5: DarkVLC's performance at different distances and viewing angles (a)(b). Its throughput is very stable with a standard error $<$ 1 bps. (a) shows DarkVLC with varying distance in four ambient light settings: Day + light (385 lx), Day (149 lx), Night + light (105 lx), and Night (0.6 lx). (b) shows DarkVLC with varying viewing angle under three distances. (c) shows DarkVLC's power consumption with varying t_{period}. The transmit power of DarkVLC is 46.8 μW, multiple orders of magnitude lower than that of VLC in normal mode (19.8 W).

prototype is still very limited – only 10 cm. It is not a concern for short-range, device-to-device communication, yet is unable to support the communication between ceiling lights and IoT devices in the environment, which can be 1 – 3 m away. To significantly boost the transmission distance, we will examine LED chips with shorter rise time and optimize the LED driver so that the light intensity can rise to a higher peak within a short duration. We will refine the circuit design, especially the receiver circuit, to reduce the circuit noise and increase the photodiode's sensitivity. We will also consider signal processing techniques to minimize the impact of the hardware noise.

Adapting LED Duty Cycle. Our current design uses a fixed LED duty cycle to generate imperceptible light pulses. The ultra-low duty cycle limits the link distance and data rate. We plan to slightly relax the constraint and adapt the duty cycle based on the ambient light. As shown by our experiments and prior studies [20], our eyes are less sensitive to flashes in brighter environments. Thus when ambient light is brighter, we can slightly increase the LED's duty cycle by reducing the OFF duration (t_{OFF}) while still keeping light pulses imperceptible. A larger duty cycle leads to a shorter period (t_{period}) and thus higher link rate. As an example, doubling the duty cycle (0.0019%) used in the current DarkVLC prototype results into an illuminance level of only 0.09 lx, which is still imperceptible under a bright ambient light condition, yet the resulting data rate increases nearly twice using PPM. To enable such adaptation, we can consider LED itself as a sensor that senses the ambient light condition, which has been shown feasible in prior work [21], without embedding additional photodiodes.

DarkVLC on Mobile Devices. We will also explore the implementation of DarkVLC on off-the-shelf mobile devices such as smartphones, which are often equipped with LED and photodiode sensors. We face two key challenges. First, existing smartphones cannot support the LED switching speed required by DarkVLC to generate ultra-short flashes. Our initial experiments with Nexus 5 show that the the shortest flash the phone can generate is 32.86 ms on average, far too long for DarkVLC. Furthermore, the flash duration is unstable with a standard deviation of 2.36 ms. Second, restricted by the OS scheduling, current phones support only up to 100 S/s sampling rate [16] of the light sensor data. We will need solutions to gain finer-grained and more precise control of the flash duration, and speed up the sampling of the light sensor data.

6. DarkVLC APPLICATIONS

IoT Networking. DarkVLC can enable a new IoT network architecture built atop VLC. We can turn existing lighting infrastructure into a backbone of the IoT network. The ceiling LED lights are connected to the Internet using power line communication (PLC) technology. The ceiling lights smoothly transition between the VLC's normal mode (when lights are on) to DarkVLC when lights are off (e.g., night). Shining a light onto IoT devices provides them with always-on connectivity and makes them searchable as part of the open web of things [2, 24]. IoT devices not only decode data from the ceiling light, but also emit or reflect [15] modulated lights using DarkVLC to sprinkle their collected data, or to send out periodic beacons (e.g., UriBeacons [24]) to facilitate device discovery and interaction.

Wireless Authentication. As mobile payment becomes increasingly popular, DarkVLC can serve as a new means for wireless authentication. DarkVLC reuses the LEDs and light sensors that existing mobile devices (e.g., smartphones, smart watches) are already equipped with. DarkVLC leverages imperceptible, directional light beams[1]. It is secure because light signal strength decreases dramatically with the increase in distance or viewing angle. Light can be easily blocked and its multi-path effect is minimal, preventing attackers from eavesdropping the authentication traffic.

Visible Light Sensing. DarkVLC also broadens the use case of visible light-based sensing. Recent works have proposed the use of visible light to track whole-body postures [17] or 2D finger movements [27]. These sensing systems do not require the VLC channel to deliver a high data rate, yet always-on connectivity is crucial to sustain light sensing. Therefore, DarkVLC is a very suitable candidate. By integrating DarkVLC into these sensing systems, we can achieve always-on behavioral monitoring even when lights are off (e.g., night), and realize unobtrusive near-field finger tracking without having LED lights visibly on.

7. RELATED WORK

VLC Modulation. We divide VLC modulation schemes into two categories: 1) Basic single-carrier pulse modulation schemes [7, 8] encode bits in the pulse presence, pulse width, pulse position, pulse amplitude, or the light polarization [26]. Specifically on pulse position-based modulation (PPM), rich literature have studied its variants to increase the data encoding efficiency and boost the data rate. As examples, MPPM (Multipulse PPM) [23] allows multiple pulses in a symbol and uses combinatorial pulse patterns to increase data rate greatly; DPPM (Differential PPM) [22] encodes bits in the number of empty slots between adjacent pulses, thus elimi-

[1] Infrared is also unobtrusive, but not all smart devices are equipped with infrared emitters.

nating the slots after each pulse in the basic PPM; EPPM (Expurgated PPM) [19] selects a subset of symbol patterns of MPPM and uses the bandwidth more efficiently than PPM; 2) Advanced multi-carrier modulation schemes (e.g., OFDM) provide higher data rates using more complicated hardware [7]. DarkVLC's modulation design is inspired by these prior schemes. It faces a new constraint of keeping light pulses imperceptible, which makes some prior design either not applicable or inefficient in data encoding. We focus on single-carrier pulse modulation schemes for hardware simplicity.

VLC Applications. Recent research has studied VLC applications that go beyond communication. Examples include indoor localization and sensing. VLC-based localization employs LEDs as anchors, which broadcast beacons containing light IDs and locations [13, 16]. A recent design [26] further allows any illumination light sources to be used for indoor localization. The idea of visible light sensing is to collect the light intensity values from photodiodes to track bodies [17] or finger movements [27]. All these current designs, however, require lights to be visibly on. They can leverage DarkVLC to broaden the sensing scenarios.

Infrared Communication. Another line of related research is on infrared communication, which is also imperceptible to human eyes and operates on optical wireless channels. Prior works [12, 4, 11] have extensively studied its modulation schemes and channel characteristics. However, since these modulation schemes are designed for infrared light that is intrinsically imperceptible to human eyes, when being applied in the DarkVLC link, most of them cannot keep the visible light pulses imperceptible. Compared to infrared communication, DarkVLC brings two unique benefits. First, DarkVLC reuses existing LED lights to enable imperceptible communication while infrared links require extra infrared emitters dedicated to communication. Second, operating on higher frequency, visible light is securer than infrared and is harder to be eavesdropped, since its reflectivity is lower than that of the infrared band [14].

Low-Power Communication for IoT devices. Active research focuses on low-power communication technologies for IoT devices. One representative example is RF backscatter, where the transmitter reflects incoming RF signals to encode data [18] and harvests energy from ambient RF signals. Backscatter often uses lightweight modulation (e.g. OOK) schemes and MAC protocols [10], as it demands simple circuit with low energy. DarkVLC is orthogonal to these designs and exhibits similar properties. It differs in that it operates on the visible light spectrum, offering one more option to achieve ultra-low power connectivity. A recent work [15] applies backscatter in VLC to design low-power uplink for IoT devices. DarkVLC can be integrated with this design to enable VLC backscatter when lights appear off.

8. CONCLUSION

We presented DarkVLC, a new communication primitive that encodes data into imperceptible, ultra-short light pulses, allowing a VLC link to be sustained even when the light appears dark or off. We demonstrated its feasibility by building a prototype using off-the-shelf LEDs and low-cost photodiodes. DarkVLC broadens the applicable scenario of VLC and significantly drives down the power consumption of a VLC transmitter. It provides a new ultra-low power, always-on connectivity affordable for mobile and IoT devices.

9. REFERENCES

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