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LocalVLC: Augmenting Smart IoT Services with Practical Visible Light Communication

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***Abstract*—Visible Light Communication (VLC) emerges as a communication technology for Internet of Things (IoT) services with appealing benefits not present in existing radio-based communication. However, current VLC designs commonly require dedicated LED lights to emit modulated light beams which entail high energy overhead and unpleasant visual experiences due to the perceptible light blinking effects for end users. This greatly limits the deployment and applicable scenarios of VLC. In this paper, we design and develop LocalVLC, a practical and low-cost VLC system that can be used as a standard light source to augment smart IoT services. LocalVLC introduces a novel Morse-code inspired modulation scheme that can operate on off-the-shelf LEDs with low energy overhead. It can effectively overcome the light flickering by encoding data into high frequency light pulses without requiring extra processing hardware such as FPGA or micro-controller. We have implemented and evaluated a full-fledged system prototype based on LocalVLC design. Under practical settings, our LocalVLC prototype can support up to 10 meters of range, and attain reasonable throughput (up to 1.4 Kbps) with low error rate and energy consumption. Comparing with the widely adopted Manchester encoding, LocalVLC yields 8x improvement on both throughput and energy consumption. In addition, we demonstrate the practicality of LocalVLC through two IoT use cases where we developed two lightweight LocalVLC-based solutions using low-cost off-the-shelf hardware to exemplify the usage of LocalVLC for indoor service discovery and smart home key management.**

I. Introduction

The motivation behind visible light communication (VLC) is to reuse the ubiquitous light sources around us for data communication. For instance, the widely used Light-Emitting Diode (LED) lamps in residential and office settings can be used to add data communication as an additional functionality of the lighting infrastructure (e.g., by installing low-cost modulation unit to existing LED lights) [1], [2]. This is an appealing benefit of VLC since it introduces minimal deployment overhead in terms of hardware replacement. VLC also offers security and privacy benefits by confining its communication range within a boundary (e.g., office room) because the light signals cannot penetrate concrete walls. In addition, VLC can effectively ward off the interference with existing radio-based communications (Bluetooth and Wi-Fi), on which many IoT services depend. Besides that, VLC can serve as a feedback channel for users, e.g., as in our use case for smart homes changing the light color to indicate a successful user authorization.

However, in spite of those distinct advantages, many VLC designs focus mainly on the communication performance and novel functionality [3]–[10]. This results in a dilemma for deploying VLC in practice because existing solutions either entail high energy overhead or exhibit unpleasant visual experiences due to the perceptible light flickering effects for end users [11]. The light flickering effect greatly limits the deployment and applicable scenarios of VLC (e.g., to be used as a regular light source for indoor). In light of this challenge, the DarkLight design [11] tackles the problem sphere by emitting extremely-low luminance of light pulses, which makes the lighting device appear as a unnoticeable "dark" bulb. Although DarkLight addressed the flickering issue through an unconventional design, their solution provides a shorter communication range (1.3 m) and cannot replace existing regular light sources compared to our custom light bulb. Specifically, a dedicated DarkLight bulb should be installed besides normal LED lamps where DarkLight services are needed which causes light pollution by overlapping light signals for illumination and communication.

This leads to the fundamental question of adopting VLC: **how to achieve a practically deployable VLC with low cost and power footprint?** Given that common VLC modulation schemes can hardly keep light pulses imperceptible and hence causing light flickering effects [11], we tackle the usability challenge for VLC by proposing a holistic system solution named LocalVLC. In its core, LocalVLC introduces a Morse-code inspired modulation scheme that can operate on off-the-shelf LEDs with low energy overhead. We have implemented and evaluated a full-fledged system prototype based on LocalVLC design. In practical settings, our LocalVLC prototype can support up to 10 meters of range and attain reasonable throughput (up to 1.4 Kbps) with low error rate and energy consumption. Compared to the widely adopted Manchester encoding, LocalVLC yields 8x improvement on both throughput and energy consumption. Our design can effectively overcome the light flickering effect by encoding data into high frequency light pulses but does not require extra processing hardware such as FPGA or micro-controller. As inspired by but different from DarkLight, LocalVLC can be deployed as standard light source to overcome the light pollution problem by replacing existing lighting. The unique features of VLC can benefit many

IoT scenarios as we demonstrate by means of two exemplary use cases based on LocalVLC: indoor service discovery and smart home key management.

In a nut shell, our work makes the following contributions:

- We design and develop LocalVLC, a ready-to-deploy system solution to address the crucial challenge faced by conventional VLC designs: usability in practical deployment. LocalVLC strikes a balance between cost and complexity to eliminate the light flickering effect, making it feasible to be embedded as a regular light source into the infrastructure.
- We introduce a dedicated modulation scheme for VLC as inspired by Morse coding. The LocalVLC modulation enables off-the-shelf hardware to operate at high frequency and sustain low power footprint. Based on the testbed evaluation, our LocalVLC prototype can support up to 10 meters of range and attain reasonable throughput with low error rate and energy consumption. Comparing with the open-source solution with widely used Manchester encoding, LocalVLC yields 8x improvement on both throughput and energy consumption.
- We further demonstrate the practicality of our proposal by developing lightweight LocalVLC-based solutions for two exemplary scenarios: proximity based service discovery and automation of key management for smart homes. Those solutions shed light on how we can harness VLC to augment future IoT services.

II. LocalVLC Platform

LocalVLC aims to provide a communication platform with several wireless communication channels to enable practical user services. We realize a custom light bulb prototype as shown in Fig. 1 to combine mid-range radio-based communication such as Wi-Fi or Bluetooth with VLC. We benefit from the naturally limited VLC communication range for use cases such as indoor service discovery and key management for smart homes presented in Section III. For our VLC transmissions we seek for a robust and yet simple encoding scheme for creating a low-rate signaling channel. On this basis, we propose Morse encoding as lightweight data encoding for VLC to achieve a broadcast with low processing overhead. Our custom light bulb allows replacing existing illumination infrastructure and avoid light pollution, at which different visible lights are overlapping for illumination and communication. We are able to overcome this problem by simultaneously using visible light for illumination and communication.

A. Hardware Platform for LocalVLC

The LocalVLC hardware platform consists of a power supply for the BeagleBone Black. During normal operation the battery is loaded and provides the power for the BeagleBone Black. The battery improves the service availability of LocalVLC and maintains the lighting in case of a power blackout. The BeagleBone Black offers an API for VLC and controls the LED transmitter and wireless modules such as Wi-Fi and Bluetooth.

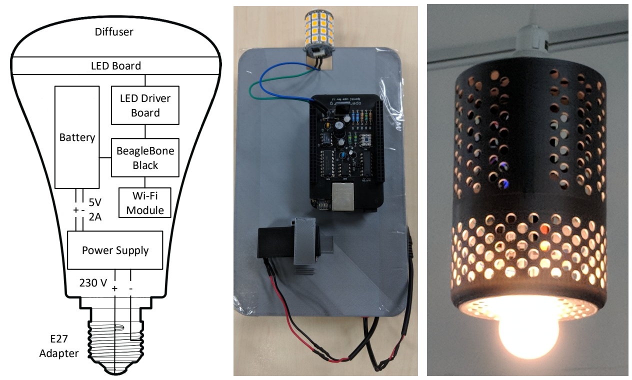


Fig. 1: LocalVLC hardware architecture; installed light bulb components; our deployed 3D-printed LocalVLC light bulb.

Our LocalVLC platform follows two principles to enable practical services:

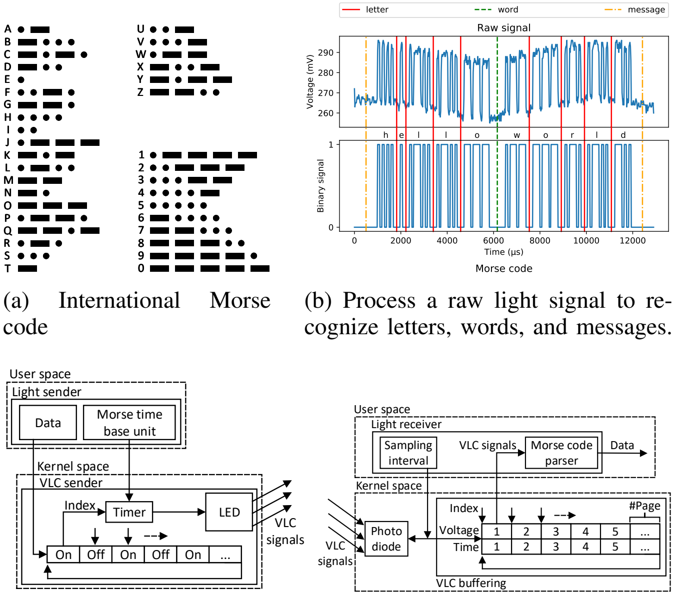
1) **Deployable at low-cost** by using off-the-shelf components. LocalVLC requires only basic programmable boards (in our case BeagleBone Black at $60) with general-purpose input/output (GPIO) support. Due to the low processing overhead, it is possible to run LocalVLC on micro-controllers. The light-emitting diodes (LED) used by LocalVLC are low-cost.
2) **Practical platform** that imposes as little constraints as possible on typical indoor IoT usage. This implies a practical working range in normal indoor situations, flexible orientation, easy portability on devices with ambient light sensors, and an open-box design with adaptive APIs for developer.

B. Morse Code Definition for VLC Signaling

To enable robust and efficient VLC signaling, we use the Morse code defined by the International Telecommunication Union [12] for data encoding. In general, the Morse code is based on two signs, a *dot* as the smallest, time base unit, and a *dash* is about three time units. Fig. 2(a) presents the ISO basic Latin alphabet and Arabic numerals encoded in Morse code. For instance, the letter "B" consists of one dash followed by three dots. We transmit data as a series of light on and off periods, each light on phase is followed by a light off phase. To detect letters, words and messages, we use timely different light off phases. The space between parts of the same letter is one time unit, the space between letters is three time units, the space between words is seven time units, and the space between messages is ten time units.

C. LocalVLC Modulation

How does the LocalVLC Morse encoding works based on a practical example? We illustrate the processing of a raw light signal, i.e., "hello world", in Fig. 2(b). LocalVLC uses Algorithm 1 for signal decoding. In specific, we quantize the raw voltage signal with a mean threshold to get a binary sequence of light on and off phases (lines: 1-4). In the next step, we detect the change points from light on and off phases



(a) International Morse code

(b) Process a raw light signal to recognize letters, words, and messages.

(c) Processing chain for VLC sender

(d) Processing chain for VLC receiver

Fig. 2: LocalVLC Morse encoding

and calculate the duration of each phase (lines: 5-11). To improve the robustness, the letter threshold is dynamically computed by the mean over all light off phases (lines: 12-14). As predefined by Morse code, the duration thresholds for words and messages are the multiply product of the letter threshold (line: 15). Subsequently, we categorize all light on phases into dot or dash signals based on the corresponding duration (lines: 16-23). This signal series of letters is split into single letters and decoded via a dictionary (lines: 26-28). Finally, we recognize word or message stops to add the correct formatting sign, either a white space or line break (lines: 29-34).

How do the LocalVLC sender and receiver work? We implemented two Linux kernel modules to send and receive data encoded in Morse code. For the VLC sender in Fig. 2(c) the most important parameter is the Morse time base unit which specifies the period for a dot, the smallest time unit for Morse encoding. On this time basis, all signs [a-z, 0-9] can be encoded into different light on and off phases which trigger two real-time kernel timers to switch the LED between on and off state. The VLC sender periodically transmits the same information, e.g., service identifier or password token, for a limited period of time. On the receiving side in Fig. 2(d), we implemented another Linux kernel module which samples the raw light signal via the photodiode. We receive the voltage in mV from the photodiode, where a higher voltage value indicates a light on phase and a lower voltage value indicates a light off phase. We have tested different sampling intervals, i.e., how often voltage values are sampled. This affects the VLC buffering to store and access light signals from the kernel module. Our buffering of light signals dynamically adapts

Algorithm 1: Morse Code Processing of LocalVLC

input : voltage $\leftarrow (v_1, v_2, ..., v_n)$, t $\leftarrow (t_1, t_2, ..., t_n)$,
morse-code-dict

output: message

Step 1: preprocessing

1 $\overline{v} \leftarrow \frac{1}{n}\left(\sum_{i=0}^{n} \text{voltage}_i\right)$
2 **for** $i \leftarrow 0$ **to** n **do**
3   voltage-on-off [i] $\leftarrow \begin{cases} 1, & \text{if } v_i > \overline{v} \\ 0, & \text{otherwise} \end{cases}$
4 **end**
5 **for** $i \leftarrow 0$ **to** n **do**
6   changepoint [i] $\leftarrow$ voltage-on-off [i+1] - voltage-on-off [i]
7 **end**
8 changepoint-pos $\leftarrow$ `seek` (changepoint = 1 or = -1)
9 **for** $i \leftarrow 0$ **to** n **do**
10   duration [i] $\leftarrow$ t[changepoint-pos [i+1]] - t[changepoint-pos [i]]
11 **end**

Step 2: parsing

12 voltage-on-off $\leftarrow$ voltage-on-off [changepoint-pos]
13 voltage-off-pos $\leftarrow$ `seek` (voltage-on-off == 0)
14 $\theta_{\text{letter}} \leftarrow \frac{1}{n}\left(\sum_{i=0}^{n} \text{duration}[\text{voltage-off-pos}_i]\right)$
15 $\theta_{\text{word}} \leftarrow 2.5 \cdot \theta_{\text{letter}}, \quad \theta_{\text{msg}} \leftarrow 4.5 \cdot \theta_{\text{letter}}$
16 voltage-on-pos $\leftarrow$ `seek` (voltage-on-off == 1)
17 duration-on $\leftarrow$ duration [voltage-on-pos]
18 $\theta_{\text{dash}} \leftarrow \frac{1}{n}\left(\sum_{i=0}^{n} \text{duration-on}_i\right)$
19 dash-pos $\leftarrow$ `seek` (voltage-on-off == 1 and duration $> \theta_{\text{dash}}$)
20 voltage-on-off [dash-pos] = dash
21 letter-pos $\leftarrow$ `seek` (voltage-on-off == 0 and duration $> \theta_{\text{letter}}$)
22 letters $\leftarrow$ `split` (voltage-on-off, letter-pos)
23 duration-off $\leftarrow$ duration [letter-pos]

Step 3: translation

24 message $\leftarrow \emptyset$
25 **for** $i \leftarrow 0$ **to** n **do**
26   letter-on-pos $\leftarrow$ `seek` (letters$_i$ == 1 or == 3)
27   letter-pattern $\leftarrow$ letters$_i$ [letter-on-pos]
28   message $\leftarrow$ `append` (morse-code-dict [letter-pattern])
29   **if** duration-off$_i$ $> \theta_{msg}$ **then**
30   message $\leftarrow$ `append` ("\n")
31   **end**
32   **else if** duration-off$_i$ $> \theta_{word}$ **then**
33   message $\leftarrow$ `append` (" ")
34   **end**
35 **end**

to the available system's memory, to meet different memory constraints ranging from IoT boards to micro-controllers. We save voltages and the relative time chunked into pages. We control the maximum page size and number of pages based on available memory and sampling interval to provide sufficient information for Morse code parsing in terms of throughput and response time. After parsing the VLC signals, we apply error correction based on a majority rule, i.e., the VLC receiver selects the most frequently received information via a sliding time window of a few milliseconds.

III. Use Cases of LocalVLC

To apply LocalVLC, our demo [13] has covered the indoor wireless (Wi-Fi) authentication scenario to avoid manual distribution and tedious input of passwords for user login. In this section, we further illustrate two IoT oriented use cases

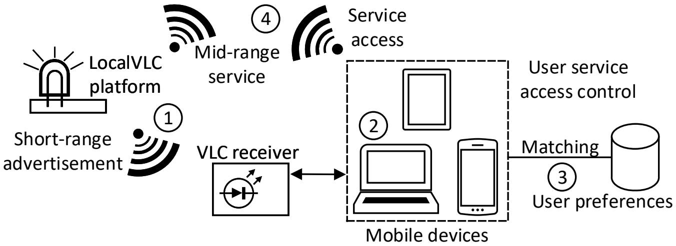


Fig. 3: Indoor service discovery using LocalVLC

to demonstrate how we can practically benefit from the VLC communication capabilities.

A. Indoor Service Discovery

LocalVLC enables proximity-based indoor service discovery without revealing users' private information (e.g., location tags, wireless interface meta data). Our lightweight solution as illustrated in Fig. 3 aims to refine the range of service discovery and improve users' privacy by transforming conventional service advertisements into LocalVLC based signaling. In this setup, users will remain passive (no need of GPS, Wi-Fi or Bluetooth Low Energy (BLE) discovery beacons), collecting advertisements via VLC signaling when approaching the service area, without any need to associate with service hubs. For instance, in a shopping mall with a dense distribution of shops, it is challenging to realize spatially fine-grained service advertisement for commercial coupons (e.g., nowadays manually distributed at the shopfront). Comparing with service announcements over Wi-Fi or Bluetooth, LocalVLC can flexibly reduce the "visibility" of service advertisements only to what is immediately relevant in the vicinity.

By default Morse code lacks support for binary data. Therefore, we apply Base16 encoding to transmit non-alphabetical data such as encrypted service advertisements. The work flow of our solution is illustrated in Fig. 3. The principle is to use short-range VLC advertisements ① dedicated for proximity and location oriented services. The service advertisement is encrypted and includes a location identifier, the password to access the service and a description for the user interface. The VLC receiver obtains and processes the VLC transmitted data. The service advertisements are accumulated over time and shown to users according to pre-defined preferences ②. From a management perspective, users can define preferred services through LocalVLC for specific times and locations. On this basis, the user preferences are matched with the collected service advertisements ③ for carrying out operations (e.g., turning on wireless interfaces or GPS to access certain services). If the user allows the advertised service, the device can access the service flexibly through, for instance, a standard mid-range radio-based communication like Wi-Fi or BLE ④.

B. Key Management for Remote Control of Smart Homes

A smart home incorporates a communication network that connects the key electrical appliances and services, and allows to be remotely controlled, monitored or accessed. Via

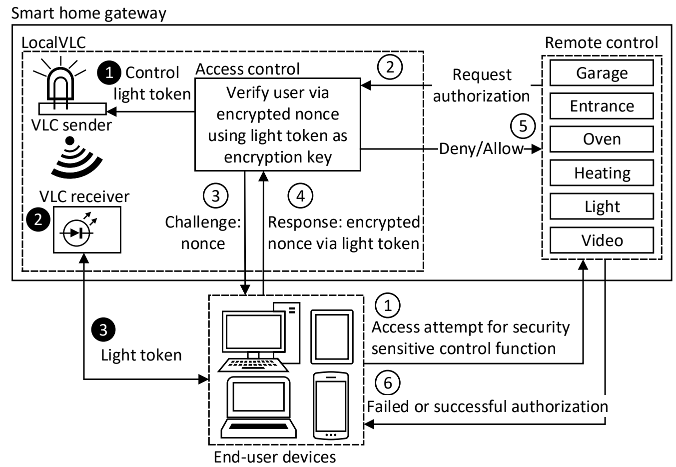


Fig. 4: Key management for smart homes using LocalVLC

LocalVLC we fully automate the key management for remote control of smart homes to improve the usability of system's security. To secure remote control of smart homes, existing systems typically use one authentication factor, user name and password, while more secure home controls utilize two-factor authentication. For example, the second authentication step could be a time-based one-time password (TOTP) scheme. A user will generate a random secret key and share the secret key and the validity period with the home control. On this basis, the user generates a new TOTP and enters it at the home control. The drawback of this standard TOTP scheme is the ongoing manual interaction between user and home control. The secret key has to be exchanged, e.g., via a QR code and the user has to manually generate new passwords for each authorization attempt.

To avoid time-consuming user interactions, we integrate LocalVLC into a smart home gateway to realize an automated key management for the remote control of smart homes. We categorize the functionality of the home control into sensitive (e.g., open the entrance door) and standard control functions such as light on and off. The standard control functions can be used remotely and at home. The sensitive control functions can only be used at home via an automated authorization scheme to enhance usability of system's security. Our adapted authorization scheme uses VLC as an out-of-band channel to exchange secret keys and integrates a challenge-response mechanism for on-demand access requests. In this way, we fully automate the user authorization to avoid manual interactions and enabling continuous re-authorization in the background and automatic key revocation based on physical proximity.

Fig. 4 shows our approach to achieve an automated key management for the remote control of smart homes. The home control gateway consists of two independent action flows, distribution of light tokens via LocalVLC and the user authorization at the remote control of the smart home. As basis for user authorization, the access control of LocalVLC generates encryption keys using TOTP and broadcasts it via the VLC sender ❶. The VLC receiver ❷ continuously obtains the light signals and selects the up-to-date encryption key based on a majority rule. The user's device is cable-bound to the light receiver ❸ and receives light tokens. On this basis, the user can attempt to access a sensitive home control function via our Android app for smart homes ①. That triggers the remote control of the smart home to request an authorization from the access control of LocalVLC ②. The access control sends a nonce to the end user device ③, the Android app for smart homes increments the received nonce and encrypts it via the Speck cipher [14] using the out-of-band light token as encryption key ④. The access control of LocalVLC performs the same action and compares the encrypted nonce from the end user device with the own nonce. In case the encrypted nonces are equal ⑤, LocalVLC grants access, otherwise denies it. Finally, the Android app for smart home control ⑥ displays the authorization result to the end user. Moreover, we benefit from the visible light as feedback channel for users, i.e., change the color of the light bulb to indicate a successful user authorization or a failed user authorization. The lightweight Speck block cipher is designated for performance limited IoT devices.

IV. Evaluation

The evaluation of LocalVLC is divided into three parts. First, we analyze the LocalVLC system's performance in terms of throughput, latency, error rate, communication field of view (FoV), transmission distance, and impact of ambient light. Second, we compare our LocalVLC data encoding based on Morse code with Manchester encoding regarding throughput and energy consumption. Finally, we evaluate our key management for smart homes based on LocalVLC with regard to latency of light tokens, authorization success rate, and the duration of successful and failed user authorization.

Test Environment: For the evaluation, we use the VLC platform in Fig. 5 from the openVLC project [6] with two different LED types as transmitter and a photodiode as VLC receiver because it is widely deployed on mobile devices, e.g., as ambient light sensor. In all evaluation runs, except for range evaluation, our testbed consists of a sender and receiver in a distance of 50 cm. The sender continuously transmits a test string: "abcdefghijklmnopqrstuvwxyz1234567890". The evaluation encompasses 100 rounds, at which the receiver collects the VLC transmitted data for a duration of ten seconds to compute throughput, error rate, and energy consumption.

A. Micro-benchmarks of LocalVLC System Performance

What are the best operational parameters for LocalVLC encoding based on Morse code? We determine the best VLC parameters in terms of throughput and error rate during VLC transmissions using two different LED types as VLC transmitter: directional and omnidirectional LED. The evaluation includes two test parameters, the sampling interval at the receiver and the Morse time base unit at the sender, both of which affect the throughput and error rate. In detail, at the receiver we use a sampling interval (µs) in the range of [5, 10, 15, 20, 25, 30, 50, 100, 150], which determines how often the

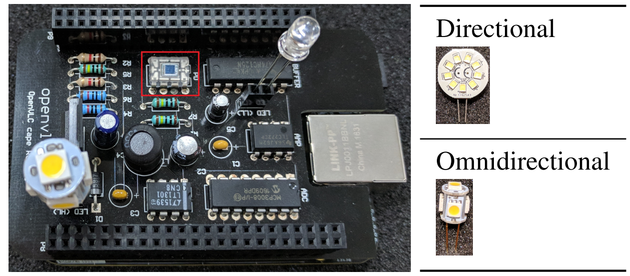


Fig. 5: Evaluation platform with two LED types as transmitters. The photodiode acts as a receiver (highlighted red).

photodiode is sampled to receive voltage values and thereby data. At the sender side, we analyze the Morse time base unit which means the time period of one dot, in other words the smallest time base unit to encode the to be transmitted data. Due to different ignition times of the omnidirectional and directional LEDs, we use a different set of time periods for the Morse time base unit (µs): [5, 10, 20, 50, 100, 150] for the omnidirectional and [100, 110, 120, 130, 140, 150] for the directional LED. In case of the omnidirectional LED, Fig. 6 shows the throughput and error rate for different sampling intervals and Morse time base units. On this basis, the best working VLC parameters are a sampling interval of 30 µs and a Morse time base unit of 50 µs. With these parameters we achieve a throughput of 1423.35 Bytes/s without errors. Using the directional LED, Fig. 7 presents the results for throughput and error rate. In this case the best working VLC parameters are a sampling interval of 50 µs and a Morse time base unit of 130 µs resulting in a throughput of 517.68 Bytes/s without errors. The hardware limitations of the directional LED cause a lower sampling interval and a decreased throughput. Regarding a flickering effect at the VLC sender, we transmitted shorter (10 signs) and longer (254 signs) messages and determined a recognizable LED flickering with a Morse time base unit of 150 µs ~6.66 kHz. The frequency range of our VLC sender is above this range using the directional or omnidirectional LED.

Besides the sampling interval and Morse time base unit from the previous section, the page size, how many light signals are buffered, also influences the LocalVLC system performance in terms of throughput and response time until the VLC data is available. **What is the best page size to buffer light signals with regard to a quick response and a high throughput?** Our signal buffering as described in Fig. 2(d) uses a ring buffer and the number of pages scale with the total memory size and page size. The page size of the buffer determines how long it takes until one page is filled with light signals and influences the throughput and user experience in terms of how quick the data is available. Our results in Fig. 8 show the throughput for different page sizes. With a larger page size the throughput increases due to a smaller processing overhead. However, as shown in Table I the response time until the VLC data is available also increases. A fast response time is important for a good user experience, hence we choose a page size of 10k values for the buffering of VLC signals and

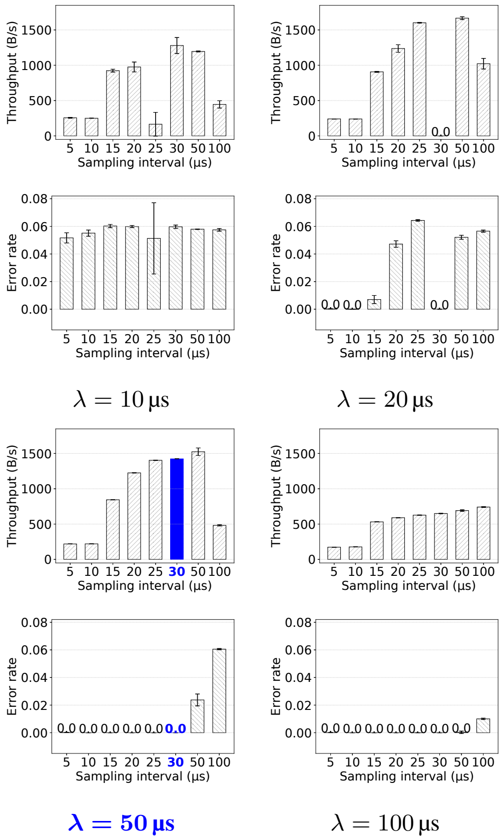


Fig. 6: Evaluation of VLC parameters for LocalVLC encoding using *omnidirectional LED*. We have identified the best working parameters (highlighted blue): sampling interval of 30 μs and Morse time base unit of 50 μs (λ) ~20 kHz.

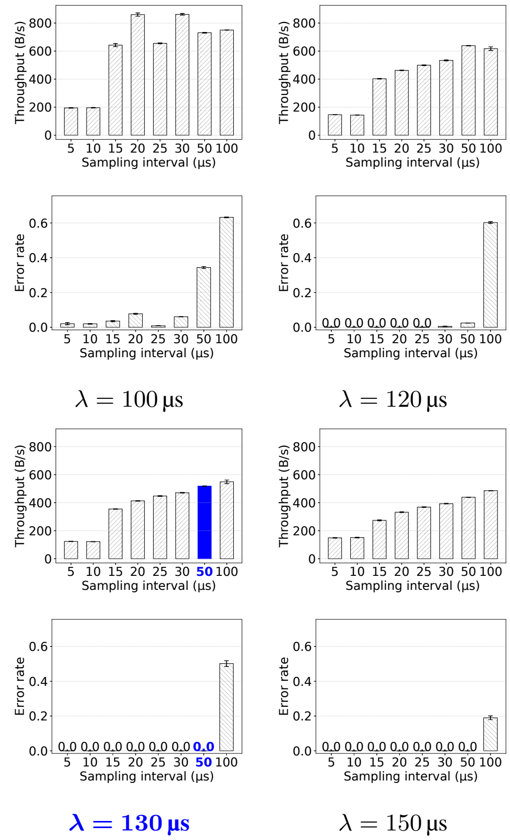


Fig. 7: Evaluation of VLC parameters for LocalVLC encoding using *directional LED*. We have identified the best working parameters (highlighted blue): sampling interval of 50 μs and Morse time base unit of 130 μs (λ) ~7.69 kHz.

accept the slightly decreased throughput by 5.35 % resulting in 1500.81 B/s compared to a page size of 30k values with a higher throughput of 1585.57 B/s but a three times greater response time.

What are the VLC communication characteristics regarding maximum range, field of view (FoV), latency, and impact of ambient light? Fig. 9 shows the maximum achievable transmission range with regard to the error rate. The directional LED reaches a maximum distance of 10 m, the omnidirectional LED is able to cover a distance of 3 m. With a larger distance between sender and receiver the error rate increases to a level at which the communication is no longer usable. The throughput only counts the received number of characters within a time frame regardless of whether the data is correct, which is shown by the error rate. We measure the FoV in Fig. 10, the omnidirectional LED obtains a range of 165°–50° and the directional LED achieves a FoV of 175°–5°. In practice, we can utilize mirrors to steer the light signal to dynamically adapt the communication distance and FoV at the given situation. To illustrate the overhead of LocalVLC, the latency using the directional LED results in 0.58 s ± 0.01 s which increases by 25 % (0.77 s ± 0.01 s) if using the omnidirectional LED.

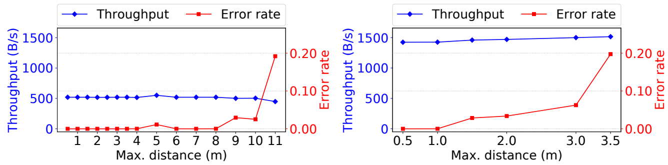
Fig. 8: Throughput (B/s) vs. page size

Page size	Response time
10k	0.3 s
20k	0.6 s
30k	0.9 s

TABLE I: Response time (s) vs. page size

Evaluation of VLC buffer

Besides that, we analyze the effect of ambient light at the omnidirectional LED with a weak light signal and the directional LED with a strong, beaming light signal. Our expectation is that, the stronger the ambient light, the higher the error rate and the lower the throughput. The results in Table II highlight that the directional LED with a throughput between 517 to 654 B/s is less influenced by the ambient light compared to the omnidirectional LED. Nevertheless, with a stronger ambient light the error rate increases significantly limiting a reasonable communication performance using the directional LED. In contrast, the omnidirectional LED only works reliably



(a) Directional LED (b) Omnidirectional LED

Fig. 9: Maximum range of VLC communication with different LED transmitters regarding throughput (B/s) and error rate

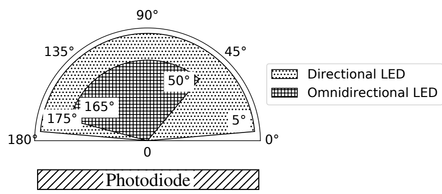
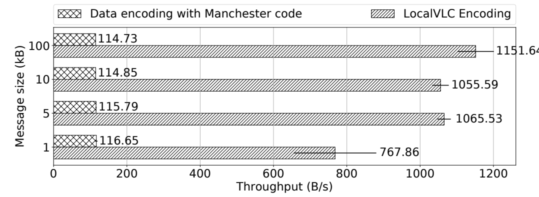
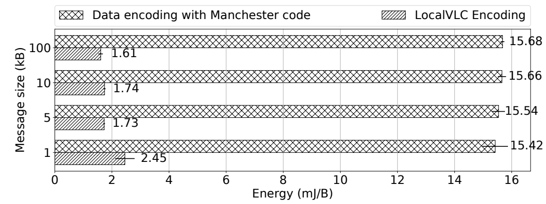


Fig. 10: VLC communication angle: opening and closing field of view at the photodiode (receiver)



(a) Throughput (B/s)



(b) Energy consumption (mJ/B)

Fig. 11: Performance comparison between LocalVLC encoding and Manchester encoding

at a low ambient light intensity. With a slight increase of the ambient light, the throughput drops below 25 B/s and the error rate makes it impossible to successfully transmit data. We encounter an unforeseen effect at the omnidirectional LED, with the highest ambient light intensity, the throughput slightly increases and the error rate drops by 50 % compared to the medium intensity of ambient light.

B. Comparison of LocalVLC Encoding with Manchester Code

To highlight performance differences with regard to throughput and energy consumption, we compare our LocalVLC encoding based on Morse code with a baseline using On-Off keying modulation with Manchester code and Reed-Solomon error correction code. In the following, we describe the testbed for the performance measurements. We only use the omnidirectional LED due to missing hardware support by Manchester encoding for the directional LED. As previously determined our LocalVLC encoding works best with a sampling frequency of 20 kHz and Morse time base unit of 50 µs. The data encoding with Manchester code utilizes a 50 kHz sampling frequency. To measure the energy consumption, we use the high voltage Monsoon power device by powering our hardware platform (BeagleBone Black) with 5 V. During the data transmission, we measure the current (mA) and voltage (V) to compute the required energy in Joule per Byte. We measure the energy consumption only at the receiver because the energy consumption at the sender is mainly influenced by the LED power and the data encoding scheme has minor influence on the system's energy. Fig. 11(a) shows in average a 8.75 times higher throughput of LocalVLC encoding with 1010.16 B/s compared to Manchester encoding achieving 115.51 B/s. We obtain a similar result for the energy consumption as shown in Fig. 11(b) because the energy $E = U \cdot I \cdot t$ is mainly dependent on the transmission time. LocalVLC encoding consumes 8.27 times less energy as Manchester encoding, in total numbers 1.88 mJ/B compared to 15.58 mJ/B. Based on these results, our LocalVLC encoding achieves a several orders of magnitude better performance regarding throughput and energy consumption as the usual Manchester encoding. The superior performance of LocalVLC is mainly based on a more efficient Morse encoding compared to Manchester code. Since Morse code takes advantage of encoding pulses and pauses with different length and pauses are more frequent, while the Manchester code requires a high and a low pulse for sending each bit. Furthermore, our error correction, selecting the most frequently received information over a time window, does not decrease the possible payload and is computation-wise faster compared to the Reed-Solomon error correction code.

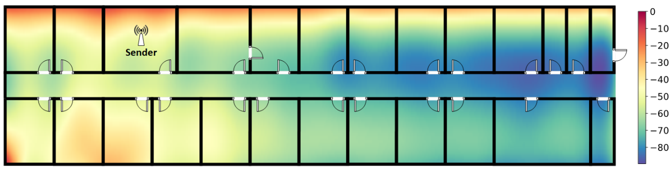
C. Evaluation of Key Management for Smart Homes

We evaluate our key management for smart homes based on out-of-band LocalVLC transmission and automated user authorization scheme. For this environment our testbed experiment in Fig. 12 reveals the competitive advantage of VLC where the coverage of the VLC signals is naturally limited by spatial barriers like walls and doors whereas mid-range radio-based communication covers the entire space. This causes new threats such as localization attacks [15] whereat the adversary track individuals in their home from outside walls by analyzing reflections of ambient Wi-Fi transmissions.

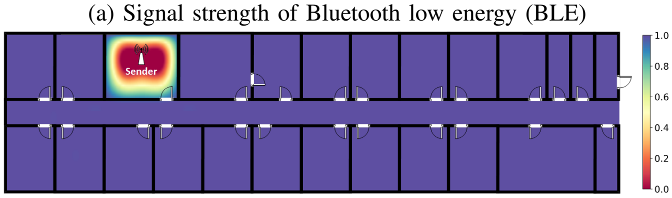
Test setting: Our home control testbed consists of two BeagleBone boards, one acts as home control gateway with integrated LocalVLC for automated key management via VLC transmitted password tokens referred as light tokens. The home control continuously broadcasts light tokens with a predefined refresh period at which the light token randomly changes. The second BeagleBone acts as VLC receiver and selects the light token from the most frequently received messages via a sliding time window. The users' smartphone and the BeagleBone receiver are treated as one device. To perform the automated key management for user authorization at the

TABLE II: Impact of ambient light at VLC with regard to throughput (B/s) and error rate

Indoor ambient light		Directional LED		Omnidirectional LED	
Level	Intensity (lx)	Throughput (B/s)	Error rate	Throughput (B/s)	Error rate
Low	6.34 ± 0.2	517.08 ± 1.84	0.0 ± 0.0	1423.25 ± 1.84	0.0 ± 0.0
Mid	18.73 ± 0.22	575.22 ± 8.44	0.17 ± 0.01	1.79 ± 0.52	0.71 ± 0.08
High	39.53 ± 0.28	654.09 ± 20.27	0.38 ± 0.04	22.66 ± 1.52	0.35 ± 0.01



(a) Signal strength of Bluetooth low energy (BLE)



(b) Error rate during visible light communication

Fig. 12: Comparison of signal propagation

smart home control, the users' smartphone connects to the access point of the home control and tries to access a sensitive home control function, e.g., open the entrance door, which automatically triggers a challenge-response request from the home control gateway to the users' smartphone. Due to space limits we only show the evaluation results for the directional LED as the omnidirectional LED achieves similar results.

How robust is the automated key management? We measure the success rate of user authorizations with a varying token refresh period ranging from 5 s to 60 s. The token period defines the duration at which the home control generates and broadcasts new light tokens. Table III shows the success rate of 5,000 user authorizations. The larger the token refresh period, the fewer failed authorization attempts due to reducing the change frequency of light tokens. The success rate of user authorizations ranges from lowest 84 % to 99 % in case of a token refresh period of 60 s. Due to the latency to receive a light token, each time we change the light token, for a short period of time the users' client has not the up-to-date valid light token and hence the authorization fails. As a result, the less frequently we change the broadcast light token, the more successful are the user authorizations. For a satisfying user experience, a practical system design should allow users to use sensitive home control functions for some limited time (e.g., VLC latency) after initial successful user authorization.

How efficient is the automated key management? In case of a successful user authorization, the users' client has the up-to-date light token, Table III presents the duration ranging from 0.15 s to 0.2 s until the home control functionality is

TABLE III: Evaluation of key management for smart homes

	Token period			
Result	5 s	10 s	30 s	60 s
Success rate	86.68 %	93.3 %	97.62 %	98.84 %
Duration success	0.17 s	0.15	0.18 s	0.2 s
Duration fail	0.72 s	0.73 s	0.76 s	0.75 s

available for the user. In contrast, the user authorization fails, if the users' client does not have the currently valid light token. Using a directional LED and a token refresh period of 30 s, the consecutively failed user authorization attempts took in average 0.76 s. We identify the latency as major influence factor for a successful authorization, if we consider, that the directional LED has a latency to distribute light tokens of 0.6 s ± 0.16 s. Hence, the larger the token refresh period, the better the success rate of the user authorization.

V. Related Work

Regarding VLC transmissions, previous VLC systems [6] utilize Manchester encoding for data transmission causing annoying light blinking. Another work [11] takes advantage of short periods of light signals to overcome the unpleasant visual experience of VLC but requires additional transmission hardware besides the existing illumination infrastructure and increases the light pollution, overlapping illumination and VLC signals working at the same visible light spectrum. LocalVLC improves the usability of VLC by overcoming the LED flickering effect and enables easy VLC deployments based on our 3D printed custom light bulb to replace existing light infrastructure. Thereby, we avoid light pollution by providing illumination together with communication capabilities via VLC.

VLC use cases include LED lights integrated in the ceiling, for indoor localization [16], human identification [17], occupancy detection [18], gesture recognition [11], and activity detection [19]. Another approach [20] utilizes passive light communication at which the environment modulates ambient light signals for data transmission. The reflections caused by the object's surface are received via a photodiode and decoded to read passive information. Our use case with seamless key management for smart homes enables automatic key revocation by fully automating user authorization based on the distance-limited nature of VLC transmissions. Other works for contextual co-presence enforce proximity by comparing ambient information, e.g., sound [21], acceleration [22], temperature [23], Wi-Fi, LTE, BLE signals [24], [25], or audio signals [26].

VI. Conclusion

LocalVLC is a ready-to-deploy system solution to address the crucial challenge faced by conventional VLC designs: usability in practical deployments. LocalVLC provides a pleasant visual experience by avoiding noticeable flickering effect based on our modulation scheme. Moreover, we are able to equip the existing lighting infrastructure with LocalVLC through a custom light bulb. Some assumptions made in LocalVLC include the repeating transmission of a limited amount of signaling data, e.g., a few bytes, instead of bulb transmission, and a customized error correction by selecting the most frequently transmitted data over a time sliding window. LocalVLC supports transmissions of up to 10 m with a single light source and a throughput ranging from 517.68 B/s to 1423.35 B/s depending on the LED transmitter. Our evaluation reveals that the encoding scheme adopted by LocalVLC provides 8.75 times higher throughput and 8.27 times power saving compared to existing Manchester encoding. Regarding our use cases, LocalVLC can enable seamless key management for smart homes by means of robust and fast user authorization with 99 % success rate and a duration of 0.2 s.

For future work, we aim to improve the general end-device support for VLC. Most user devices and IoT environments do not have sufficient hardware capabilities for real-time processing of VLC signals and require add-on hardware. Our goal is to shrink the VLC receiver to an appropriate (e.g., coin sized) volume for everyday usage towards ubiquitous VLC. The intended VLC sticker shall be easily attached to different devices for VLC transmissions and supply itself with energy from the light source.

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