

Connecting Battery-free IoT Tags Using LED Bulbs

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ABSTRACT

We introduce BackVLC, a system to connect battery-free IoT tags using LED bulbs. We make use of bulbs beyond illumination. We send data to the tags with visible light communication (VLC), and retrofit the bulbs with simple circuitry to enable the uplink channel current VLC systems lack, using Radio Frequency (RF) backscatter communication from the tags. Tags process and send data, harvesting energy from light and radio. We present our system design and implementation, evaluate it in preliminary simulation studies and experiments, and discuss the research challenges to develop a complete network architecture. BackVLC is the first work that combines VLC with RF backscatter.

1 INTRODUCTION

Light Emitting Diodes (LEDs) are taking over the illumination market due to their energy efficiency and lifetime with respect to traditional lighting sources. Industry effort has shown that LED bulbs could embed IoT sensors with the main objective of reducing the carbon footprint of lighting systems and providing the most comfortable light conditions, being managed, configured and controlled remotely [3, 21]. Recent works have challenged the assumption that bulbs are solely an endpoint for IoT connectivity, and may rather communicate wirelessly to *battery-free* IoT devices through LED bulbs. However, they either include an RFID reader in the LED bulb for uplink Radio Frequency (RF) backscatter, which increases the cost and allows only for a short communication range [5], or use uplink Visible Light Communication (VLC) [8, 29], with light sources embedded in IoT tags that disturb the uniform illumination in the environment.

In order to establish battery-free IoT connectivity through bulbs, we present BackVLC, a system where we *retrofit* LED infrastructure for RF backscatter communication. The goal of BackVLC is to take the best of VLC and RF-based technologies for communicating to battery-free IoT devices. First,

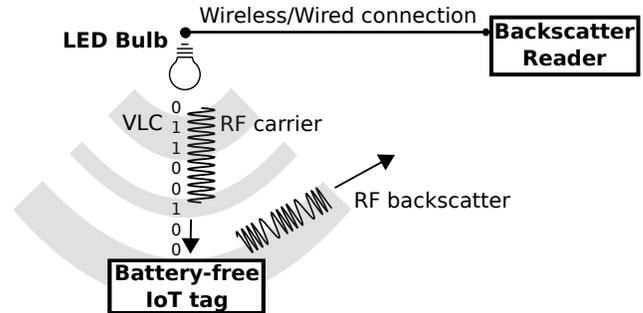


Figure 1: In BackVLC, downlink communication from the LED bulb to the IoT tag occurs with Visible Light Communication (VLC). The bulb provides energy to the battery-free IoT tag and controls the uplink RF backscatter communication with an embedded radio carrier generator. The IoT tag uses a solar cell both for harvesting energy and receiving VLC data. The backscatter signal is sent to the reader, that connects bulbs and IoT tags, and serves as edge controller of BackVLC.

LEDs are pervasively deployed and modulating them allows to send VLC downlink data. Yet, as mentioned above, VLC is undesired for uplink communication. This is a broad problem that affects VLC in general. This is not the case of RF backscatter, used in our design. Second, IoT tags suffer from the low sensitivity of passive RF envelope detectors. In contrast, receiving data from a modulated light source allows to replace the envelope detector with a simple and low-cost VLC receiver based on the direct detection (DD) method. Third, using VLC downlink allows to use the solar cell not only for harvesting energy, as in typical IoT tags employed in RF backscatter [14], but also to receive VLC data. BackVLC is the first work that combines VLC with RF backscatter.

We present a high-level view of our system in Figure 1. Downlink communication from the LED bulb in the ceiling to the IoT tag occurs as in traditional VLC. In this way, the environment is illuminated and the bulb can communicate downlink data to the IoT tags. Communication in the uplink occurs with RF backscatter transmissions. The bulb *controls* the uplink communication, with an embedded radio carrier generator that is used by any IoT tag to enable low-power backscatter transmissions. The bulb provides energy to the battery-free IoT tag through illumination and through the embedded carrier generator. As energy efficiency and cost are essential not only in the tags, but also in the LED bulbs, we decouple the reader from the radio energy source, similarly to the concept of bi-static configuration presented in [27]. The main property of bi-static configurations is that the highest

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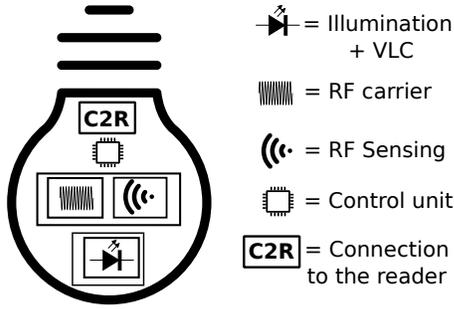


Figure 2: High-level representation of the LED bulb in BackVLC. The bulb is used for illumination, downlink VLC, controlling uplink backscatter communication and providing energy to the battery-free IoT tag. It is also connected to the reader.

signal-to-noise ratio (SNR) at the receiver is achieved when either the tag is close to the source or close to the reader. As we use VLC for downlink, the LED bulb and the tag are confined in the same area (e.g., a room). Therefore, there is a high likelihood that the tag is close to the LED bulb, and, subsequently, of a high SNR at the backscatter reader. The reader is placed in the local or wide area network, depending on the frequency used. It receives the radio backscatter signals from the IoT tag and serves as edge controller of BackVLC. BackVLC can impact several IoT applications. The main requirements are fixed illumination infrastructure, generating (almost) continuous artificial light, and IoT tags that can detect this light. Potential scenarios are smart offices, smart cities, and greenhouses.

The realization of a network architecture that efficiently integrates light and RF for IoT requires the investigation of methods at the intersection of communication, energy and multi-technology integration in software and hardware. The next section introduces our bulb. We then present our battery-free IoT tag design and our backscatter reader. After introducing the principles of the communication protocol, we show preliminary results, including experiments with our customized prototype hardware, and we finally describe the research challenges to realize a full network architecture.

2 LED BULB FOR IOT CONNECTIVITY

We envision to retrofit LED bulbs to connect battery-free IoT tags to the cloud. We use downlink VLC to transmit data to the IoT tags and backscatter communication to support uplink transmissions from the backscatter tag. As shown in Figure 2, the bulb includes five main units we discuss below. The hardware components of the bulb can be affordable for typical form factors. Compared to a design that retrofits bulbs only for VLC [18], ours entails only two additional components that are dedicated to control uplink RF backscatter.

Illumination and Downlink VLC. The LED in the bulb is used for illumination and downlink VLC. A constant bias current flows through the LED to achieve the desired illumination level. A variable current ΔI around the bias is adopted

to send data. Communication causes an additional power consumption at the bulb. Large ΔI increases the received signal strength at the IoT tag, but also consumes more power. The light intensity emitted from the LED is modulated to transmit data using On-Off-Keying (OOK) modulation. We use OOK rather than more complex modulations (like OFDM), as it is the simplest form to send VLC data, with the lowest consumption at the IoT tag for reception.

RF Carrier Generator. We build on LoRea [24] to support ultra-low power backscatter transmissions. BackVLC exploits the following properties of LoRea: i) spatial separation between RF carrier generation and the reception, ii) separation in frequency between carrier and backscattered signals, and iii) narrowband transmissions for sufficient communication range. The RF carrier generator emits the energy required by the IoT tag to transmit RF backscatter signals. Carrier generators are not expensive, with typical prices of a few USD [24]. In this paper, we use commodity wireless chipsets to generate carrier signals. In BackVLC, downlink VLC and RF carrier generation do not occur concurrently. This allows to use a simpler power supply, with lower voltage and current requirements.

RF Sensing. The sensitivity of ambient traffic RF sensing in the IoT tag is low, as it typically uses an envelope detector [16]. In addition, it would increase the energy consumed by the tag. For these reasons, we perform RF sensing in the bulb. This concept is similar to the one in [7], that delegates the power-consuming task of sensing to the power plug device. The module for RF sensing senses both normal WiFi transmissions and other RF carrier generators in the frequency band of operation (e.g. from other bulbs).

Control Unit and Connection to the Reader. The control unit is regulated by a microcontroller. It receives inputs from the reader, and, based on the protocol logic (c.f. Section 5), it decides at run time which operation to perform among illumination, VLC, RF carrier generation and RF sensing. An Ethernet or powerline interface connects the bulb to the reader. The connection to the reader could also be with wireless connectivity.

3 IOT TAG

BackVLC advocates a hybrid RF and VLC design for battery-free IoT tags, as these mediums are complementary. A key challenge in supporting the hybrid design is to support receptions and transmissions within the constraints of the harvested energy. The conventional radio transceivers such as those employed to support WiFi communication are energy expensive [7], which makes it challenging to operate them on harvested energy. Similarly, state-of-the-art VLC receivers often consume significantly higher power than what is available from ambient energy harvesting sources and they target data rates higher than needed by IoT tags (an efficient VLC receiver has recently been proposed with a power consumption of 2.2 mW and a data rate of 24 Mb/s [9]).

We present a high level overview of our tag in Figure 3. The tag operates by harvesting energy from either incident carrier signal (RF) or through visible light using a solar cell. It stores harvested energy in a small capacitor. The harvested energy supplies the processing unit, onboard sensors, and supports communication. To support communication relying only on harvested energy, our tag leverages an ultra-low power VLC receiver for downlink communication as well as RF backscatter for uplink transmission. Our IoT tag supports both uplink and downlink transmissions using only the energy harvested from the credit card-sized solar cell.

Receiver. We implement the receiver on the backscatter tag based on the design of ultra-low power receiver by Varshney et al. [25, 27]. The receiver uses a solar cell to eliminate energy expensive photodiodes and transimpedance amplifier. Further, to reduce the power consumption for digitisation, the receiver uses an energy-efficient thresholding circuit, also widely used in envelope detectors [10, 16]. The receiver allows us to demodulate OOK signals at a peak power consumption of $0.5 \mu\text{Ws}$. The receiver uses a direct detection (DD) method, which only detects the intensity of the optical wave and can be implemented with a few electronic components. This replaces state-of-the-art RF based envelope detectors that are limited by low sensitivity (-68 dBm) [16].

Processing Unit. The processing unit of our IoT tag is responsible for interaction with sensors, performing local processing, controlling the switchover between different energy harvesting sources, and the necessary logic required to support uplink and downlink communication.

We implement the processing unit using a low-power microcontroller - Texas Instruments MSP430 that features low power consumption, and has persistent storage FRAM which enables retention of data even in the case of power failures, a commonly occurring phenomenon on battery-free sensors [11]. Due to its attractive features, the particular microcontroller is also used in other recent systems [10, 24].

Energy Harvesting. Visible light emitted by the bulbs is an obvious source of energy to support the battery-free operation of our tags. In addition, embedding the carrier generator in the bulb opens the possibility of harvesting energy from the RF carrier signal as well. This makes it possible for our tag to function even when the LEDs are turned off.

Our tag can harvest energy from visible light using a credit card-sized solar panel. To harvest from the RF carrier signal, we employ a tuned antenna with a matching network and rectifier similar to the design presented by Talla et al. [20]. The output of the solar cell or RF harvester is fed to an efficient energy harvester Texas instruments BQ25570 that stores the voltage in a small 1 mF capacitor.

4 BACKSCATTER READER

The third component of the system is the reader. Its role is more than the one of traditional backscatter readers. In BackVLC, it serves as edge controller [17], connecting bulbs and IoT devices locally, and managing the data collection and

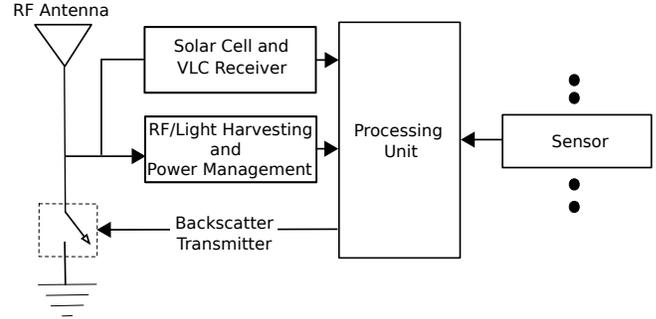


Figure 3: Block diagram representation of the IoT Tag in BackVLC. The tag operates without batteries on energy harvested through incident RF carrier signals, or through visible light. The tag receives data using VLC, and transmits using backscatter communication.

connection to the cloud. For backscatter signals reaching the local area network, we expect the reader to be integrated with the WiFi router, to ease the communication of sensed data to the cloud. The reader is connected to the bulbs with powerline, Ethernet or wireless communication. It is responsible of a few operations, detailed below.

Reception of Backscatter Signal. For receiving backscattered data from the IoT tag, we build on LoRea [24]. We use a commodity CC2500 radio transceiver that is low cost and has a high receiver sensitivity, which allows us to support a sufficient communication range so that a single reader device can cover a typical home or several rooms.

Data Processing and Transmission. The reader performs some data processing. It receives acknowledgements (ACKs) from the IoT tag. Upon failure of ACK reception, it sends a request to the bulb to re-transmit the VLC data. Finally, it forwards requests received from the IoT tag to the bulb. For instance, the IoT tag may request additional energy to transmit its data, and the bulb may subsequently emit the RF carrier. Furthermore, it forwards received IoT data to the cloud.

5 COMMUNICATION PROTOCOL

Based on the system components introduced in the previous sections, we briefly present the communication protocol in BackVLC. We refer to Figure 4. We distinguish four possible main events for the communication:

Case (a). The LED in the bulb is modulated in order to send data to the IoT tag through VLC. The tag receives the information. Subsequently, the bulb starts to emit an RF carrier. The tag acknowledges the reception of VLC data with an ACK message that backscatters the received RF signal. Not shown in the figure, a NACK (Negative ACK) is sent to the reader if the tag does not receive VLC data correctly.

Case (b). The LED is modulated in order to send data to the IoT tag through VLC. The tag receives the information. The RF sensing module in the bulb measures a busy channel and the RF carrier generator is deferred. Once the channel is clear, the tag can acknowledge the reception of VLC data.

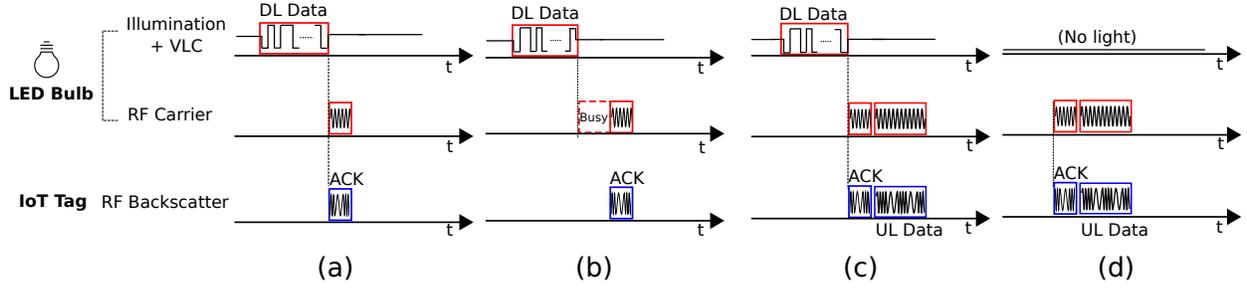


Figure 4: Communication protocol and main events. The wireless communication is controlled by the bulb.

Case (c). The bulb transmits data to the tag as before, and the tag includes a flag in the ACK (or in the NACK) to inform the network that it has data stored in memory to send, and to request the carrier for additional time to transmit this data to the reader. Once the bulb starts emitting the RF carrier, the tag sends its sensed data to the reader.

Case (d). It is possible that no bulb illuminates the environment. No data is sent to the IoT tag under this condition. During light-off period, the bulb can still use its RF carrier to request data from the tag. If the IoT tag has data available, it sends an ACK backscatter signal with a flag to request the carrier source for additional time.

6 FEASIBILITY ANALYSIS

In this section, we present preliminary results that demonstrate the feasibility of our proposed system.

6.1 Communication Range and Transmit Power

Earlier backscatter systems have used carrier generator's with high output power and nevertheless achieved short communication ranges in the order of meters [7]. In this section, we first investigate the required transmission power to cover rooms of different sizes.

We base our analysis on Friis' path loss model. Kellogg et al. have used it to compute the signal strength P_r at the reader [7]:

$$P_r = \underbrace{\frac{P_t G_t}{4\pi d_1^2}}_{\text{Bulb to IoT tag}} \cdot \underbrace{\frac{\lambda^2 G_{passive}^2 |\Delta\Gamma|^2}{4\pi} \alpha}_{\text{Backscatter}} \cdot \underbrace{\frac{1}{4\pi d_2^2} \frac{\lambda^2 G_r}{4\pi}}_{\text{IoT tag to Reader}}$$

The first part of the equation models the signal propagation from the RF generator in the bulb to the IoT tag. P_t denotes the output power of the transmitter, G_t the antenna gain at the transmitter and d_1 the distance between the transmitter and the IoT tag. The second part models the fraction of the signal that is backscattered at the IoT tag. In this part of the equation, λ is the wavelength of the RF signal. For simplicity, we do not model the fact that we shift the wavelength of the incoming signal when backscattering. $G_{passive}$ models the antenna gain of the IoT tag. $|\Delta\Gamma|^2$ is the backscatter coefficient and α models the loss the signal experiences due to synthesis of the backscatter signal. Finally, in the last term, G_r denotes

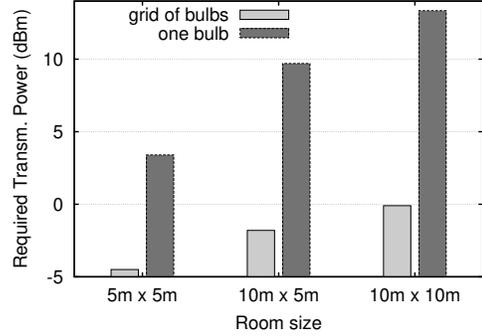


Figure 5: Required transmission power of the RF carrier generator inside the bulb. It is low enough so that standard WiFi modules are sufficient even for larger rooms.

the reader's antenna gain and d_2 the distance between the IoT tag and the reader.

We are interested in the output power P_t required by the RF carrier generator so that the received power at the reader P_r is above its sensitivity threshold. The latter is -110 dBm for state-of-the-art implementations at a frequency of 2.4 GHz (so $\lambda \approx 12.5$ cm) [24]. As both the transmitter and IoT tag are constrained in size, we assume lower antenna gains of 0 dBi and 2 dBi, respectively, whereas for the reader's antenna we assume a gain of 6 dBi. As Kellogg et al., we set $|\Delta\Gamma|^2$ to 1.1 dB and α to -4.4 dB. We believe that our system is more efficient due to the simpler modulation scheme. Hence, using their values is a lower bound for our system.

We assume rooms with a typical height of 3 m and look into three different room sizes: i) 5mx5m; ii) 10mx5m; and iii) 10mx10m. We assume one reader that is placed on the ceiling in the corner of the room. For our analysis, we investigate two different scenarios for the placement of the LED bulbs: First, we assume one LED bulb placed in the center of the room. Since there is only one LED this leads to longer RF communication links. Second, we assume LED bulbs that are placed in a uniform square array of $N \times N$ LED bulbs with a distance of one meter between the bulbs. This setup mimics one with uniform illumination [12].

Our results in Figure 5 show a required transmit power of below 0 dBm with the square array of LEDs, and around 13 dBm when there is only one bulb, even for the largest room size we analyze. Given that modern WiFi chipsets such as the CC3200 have an output power of 18 dBm and 802.15.4 low-power radios such as the CC2420 have a maximum output

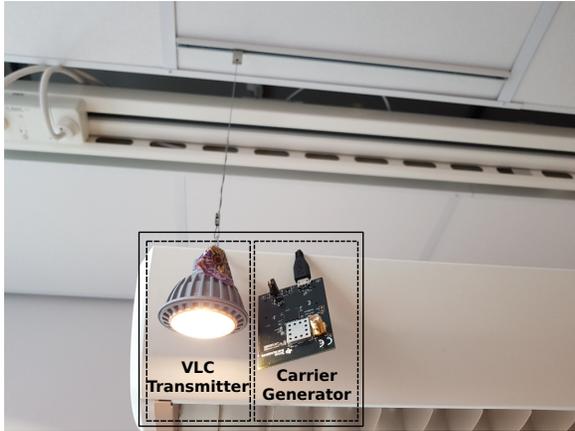


Figure 6: Prototype downlink VLC transmitter and RF carrier generator.

power of 0 dBm, we conclude that off-the-shelf radios can be used as BackVLC carrier generators in larger rooms or even small apartments. This is important to keep the cost of the system low. In addition, the low transmit power required helps the coexistence with other wireless traffic.

6.2 Message Acknowledgement

ACK messages are a vital part of most communication protocols. However, it is challenging to support ACKs on battery-free sensors that employ VLC for downlink communication. This is because commonly used methods for uplink transmission in VLC systems such as infrared or conventional radio transmissions are too energy expensive to operate within the budget of harvested energy. In this experiment, we demonstrate that BackVLC supports this essential functionality.

Setup. We experiment in our lab in light conditions representative for actual deployments: at night with indoor lights, and during the day with natural light. We program a low-cost radio CC2538 transceiver with a CC2592 [6] as a carrier generator. The transceiver can generate an RF carrier at a maximum strength of 22 dBm. We co-locate the RF carrier generator with a 320 lm LED that operates as VLC transmitter, as shown in Figure 6. We experiment with the IoT tag located first on the desk, and then on the floor. The distance from the carrier generator and the light source to the desk is 1.5 m, and 2.2 m to the floor. In the experiment, the tag harvests energy only from the ambient light. We keep track of light levels in the experiment using a light meter. The light levels (including VLC transmitter) on the desk and the floor during daytime are approx. 2200 lx. In the night with office lights, the light levels on the desk and the floor are 840 lx and 440 lx, respectively.

We program the VLC transmitter to beacon every: (0.1, 0.2, 0.5, 1, 2, 10) seconds. The message wakes up the IoT tag that responds with an ACK (3 bytes) that is received by the reader kept in another room about 10 meter away from the IoT tag. The scenario is similar to what we can expect in a typical deployment at home with a WiFi router located several meters away from the IoT tag. This scenario corresponds to the Case (a) of the protocol described in Section 5. We

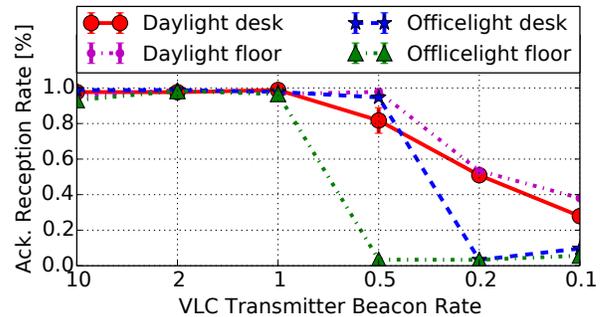


Figure 7: Supporting acknowledgement messages. Bright light conditions provide good energy harvesting conditions that allow high packet reception rate of the ACKs.

perform three iterations of the experiment. As a metric for evaluation, we keep record of ACKs received at the reader.

Result. Figure 7 demonstrates the result of the experiment. At low beacon rates, we are able to receive most of the ACK messages irrespective of the ambient light conditions. However, as we increase the beacon rate, the ACK Reception Rate decreases rapidly. When the ambient light levels are low, the reader receives very few ACK messages. The reason for this behaviour is that the IoT tag must transmit acknowledgement messages more frequently when the VLC beacon rate is high, which increases the overall energy consumption. Further, this also gives the IoT tag less time to harvest and replenish the energy stored in the capacitor. Possible solutions are to improve the rate at which energy is harvested either by employing a larger solar cell, or by harvesting energy from the incident RF carrier signal under low light conditions.

6.3 RF Carrier Generator and WiFi Traffic

The communication range of the IoT tag improves with the strength of the carrier signal [24]. Hence, the RF generators in our bulbs need to generate a reasonably strong carrier signal to achieve sufficient range. In fact, state-of-the-art systems such as PassiveWiFi [7] often generate the carrier signal at highest legally allowed strength for evaluation. However, this occurs in the unlicensed band shared with wireless technologies such as WiFi. The carrier signal could interfere negatively with their communication. In this experiment, we investigate the impact of the carrier signal on the WiFi traffic.

Setup. We set up a WiFi router to generate WiFi traffic in our lab. We use a TP-Link TL-WR1043ND router [4] with DD-WRT firmware [1] and operate it at the maximum transmit power of 20 dBm. We set up the router as an iperf server and a MacBook laptop as an iperf client. The router and the client are at a distance of 6 m. We generate a carrier signal of strength 16 dBm using a USRP B200 software defined radio.

In the experiment, we observe the impact of carrier generation on the WiFi traffic between the router and the client. We set up the carrier generator at a different location away from the setup, and also program it to generate the signal at the centre frequency within and outside the WiFi band.

Result. We observe that when the RF carrier is outside the band of the WiFi traffic, it has little impact on the ongoing

traffic. This is due to the significant adjacent channel rejection of WiFi transceivers. Instead, the presence of the RF carrier within the WiFi band negatively impacts the ongoing WiFi traffic: The presence of the RF carrier defers the ongoing WiFi traffic when the carrier generator is nearby (4 m). As we move the carrier generator at a distance of around 20 m, the WiFi traffic resumes as the RF carrier is too weak to interfere with the WiFi transmissions. We conclude that BackVLC should sense the unlicensed WiFi band and dynamically select a frequency outside the band of most of WiFi traffic.

7 RELATED WORK

In order to provide connectivity to battery-free IoT devices, backscatter communication exploits radio frequency (RF) signals in the environment to harvest energy for computation and passive transmissions [10, 28]. Recent works have also considered applying backscatter to LED bulbs transmitting with visible light communication (VLC), where the receiver replies using an LCD shutter to change the reflected signal in time [8, 29]. However, these works are negatively affected by the visual channel from the IoT tag (undesired for the human eye), and the low data rate of communication.

Gummeson et al. have proposed to add dedicated modules in the bulbs for RF backscatter [5]. Differently from BackVLC, they use the LEDs *only* for illumination, and require an RFID reader in each bulb. Their design is cost prohibitive (about \$300 [5]), and results in a communication range of less than five meters even with a high transmission power of 30 dBm. The RFID reader is the most expensive component of backscatter. In fact, it interferes with its own generated carrier, which hinders the reception of the very weak signals from the IoT tags. Compared to a design that embeds both the RF carrier and an RFID reader in the bulb [5], we achieve a much longer range at much lower cost [27].

An alternative from related work is to sense coarse light variations to modulate the RF backscatter signal [27], but the proposed solution does not allow to send data to the IoT tag. Alternatives for uplink in VLC systems based on infrared transmissions are fragile, because of transmission power regulations for eye safety and narrow their field-of-view [13]. RF uplink can provide wider coverage than infrared link, and protocols with active uplink RF and ACK aggregation have been proposed to alleviate throughput degradation problems for coexistence with WiFi [13]. Yet, active RF for uplink impacts the energy budget of IoT devices and is costly.

8 DISCUSSION

Harvesting RF and light. The amount of harvested energy in each IoT tag from both RF and light can change over time. The IoT tag should optimize its local processing in order to communicate sensed data with the available budget. An efficient hardware design is also needed to reuse electronic components in the RF and light harvesting functionalities.

Multiple LEDs and multiple IoT tags. There is the need of a medium access control to deal with multiple LEDs in the

same area for uniform illumination [15, 23, 30] as well as multiple IoT tags. A medium access protocol may be used so that bulbs do not transmit immediately after a clear RF channel. As RF coverage is likely larger than VLC coverage, only one RF carrier may be generated to cover a given area. The protocol depends also on the type of backscatter signal. For instance, if each IoT tag performs a frequency shift in a dedicated frequency [19, 26], data may be requested simultaneously to more IoT tags without generating RF collisions.

Communicating to IoT tags in absence of light. If the light is off, the bulb may still send some data at very low-dimmed light to the tag. Similar methods such as [22] may be investigated. New designs are needed to solve the low data rate (of about 1.6 kb/s) of previous approaches.

WiFi-friendly architecture. If the reader has a wired connection to the LED bulbs, it may be convenient to reuse the WiFi router [2] as reader and perform some edge computing. LED bulbs at home could be also controlled by the WiFi router. It requires to modify our design, as the IoT tag should perform some processing to generate WiFi compliant codewords [7]. The drawbacks are the additional computational resources in the tag, and the shorter communication range (because of higher loss α in the synthesis of the backscatter signal and lower sensitivity of the reader).

Outdoor deployments. Our architecture can also be used in smart cities as we can embed carrier generators in the street lights and semaphores. These applications require the tags to communicate over longer distances when compared to indoor scenarios. We can support them by operating our architecture in the sub-GHz band, where recent systems have demonstrated the ability to transmit over large distances with a carrier source in proximity [19, 24].

9 CONCLUSION

In this work, we have introduced BackVLC, a new system that addresses a few fundamental problems of current emerging pervasive wireless networks: i) VLC has a long-standing problem with the uplink communication channel and ii) RF backscatter has a long-standing problem with the sensitivity of the RF envelope detector. We have presented the foundation of our system, its components, as well as preliminary results and have discussed key research directions in different layers of the network stack. VLC has not taken off yet. BackVLC can provide the use case it needs, offering better coverage than pure RF solutions for battery-free Internet of Things. As the massive deployments of LEDs and battery-free IoT tags are on their way, they could embrace a joint journey in the next generation of networks.

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