Bracelet+: Harvesting the Leaked RF Energy in VLC with Wearable Bracelet Antenna

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ABSTRACT

Visible Light Communication (VLC) is widely considered a promising technology for the coming 6G networks. Recent studies show that a VLC transmitter not only emits visible light signals but also leaks RF signals during the transmission. In this work, we devote effort to harvesting the free leaked RF energy from VLC transmissions. We observe that the surrounding objects could help a coil antenna harvest significantly more RF energy. Based on this observation, we propose our system *Bracelet+*, which involves the human body in the harvesting system to increase the harvested power. After careful analysis of the influence of the human body on the harvested power, we prototype the coil antenna as a bracelet that achieves both high harvested power and convenience for wearing. The average power of the RF energy harvested by our design is 10× larger than that of the conventional coil antenna, without causing any interference to the communication of VLC systems. The harvested power can reach up to *micro-watts* in our tested scenarios. Such a micro-watt level of harvested energy has the potential to power up ultra-low-power sensors such as temperature sensors and glucose sensors.

CCS CONCEPTS

• **Computer systems organization** → **Embedded hardware**; • **Hardware** → **Power and energy**.

KEYWORDS

Energy harvesting, human body-augmented, RF leakage, side channel, visible light communication

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1 INTRODUCTION

Wireless technologies have changed our world with more and more objects in our physical world connected to the Internet. Globally deployed 5G and actively studied 6G will provide an even higher communication speed and more pervasive coverage. Visible Light Communication (VLC), which achieves a high data rate and causes no interference to the crowded RF spectrum, becomes a promising candidate for the next generation 6G networks [23, 48]. Lots of attention has been paid to increasing the transmission speed [8, 13, 54] and the range [7, 11, 12] of VLC systems.

Recently, researchers find that during the VLC transmission process, the VLC transmitter not only emits visible light signals but also leaks Radio Frequency (RF) signals [17]. This is because VLC adopts intensity modulation to encode data and the signal intensity is controlled by switching ON/OFF the electric current quickly.[1] Fast electric current change induces RF signals according to the Maxwell Equation [17]. Such RF leakage was recently exploited to snoop VLC transmissions through walls [17] and enhance the robustness of VLC against blockage and ambient light interference [18].

In this paper, we look at this RF leakage from a different angle. We view this RF leakage as a form of energy waste. With VLC data rate becoming higher and higher [28], we envision this energy waste will significantly increase. This is because a higher VLC data rate means the LED needs to be turned ON and OFF at a higher frequency and the ON/OFF transitions are the source of the energy waste. In our experiment, when the ON/OFF rate is increased by 10 times, the amount of energy waste is increased by 20×.

To address the above energy waste issue, we ask this question: *could we harvest the RF energy leaked from the process of VLC transmissions?* Existing works have proposed to harvest the energy of light signals emitted from VLC systems [41, 43, 45]. We believe we are the first to harvest energy from the RF leakage of VLC systems. Due to the dramatically different nature (light vs. RF), the existing VLC light energy harvesting method cannot be applied. Besides, the leaked RF signal exhibits a unique pulse-like pattern with changing central frequencies, which is very different from other RF signals we commonly see in commercial wireless charging systems. Thus, it is also inefficient to utilize existing commercial RF harvesters to capture the RF energy leaked from VLC systems.

To efficiently harvest the leaked RF energy, we need to know the signal frequency. As most VLC systems turn ON/OFF the LED at frequencies on the scale of a few Megahertz to tens of Megahertz, the leaked RF signal is a low-frequency RF signal. In communication systems, coil antenna is usually used to receive RF signals in this frequency range [17, 18]. However, while the power level captured by the small-sized coil antenna is enough for communication, there is still a lot of energy wasted in the ambient environment.

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[1]Note that when LED is turned ON and OFF faster than 200 Hz, human eyes cannot perceive the light change.

So the first challenge is *how to harvest more leaked energy?* The straightforward way to harvest more leaked energy at the receiver side is to increase the size of coil antenna (i.e., the cross-sectional area). The larger coil size will allow more magnetic flux to propagate through the coil and thus more energy can be harvested. However, increasing the cross-sectional area also increases the overall physical size of the receiver which hinders the adoption of the design in real-world settings.

In this paper, we propose a new design modality to involve *human body* into the harvesting system to significantly increase the amount of energy harvested. This design is based on one key observation in our experiments: *the harvested energy increases when some specific surrounding object is in touch with the coil antenna*. The reason is that surrounding objects can absorb the leaked RF energy in the ambient environment and help the coil antenna capture more energy. This means that without increasing the physical size of the coil itself, we could still harvest more energy with the help of some proper surrounding objects. Based on this key observation, we conducted experiments with objects of different materials, sizes, and shapes to see the effect of boosting in energy harvesting. We found that as long as the surrounding object is made of permeable material, it can help increase the energy harvested at the coil antenna, and the amount of harvested energy is proportional to the size of the object. To test if commonly seen daily objects in our surrounding environment can help improve energy harvesting, we conducted experiments with walls, tables, electronic devices, etc., as the auxiliary objects. After a thorough study, we identify the most suitable object for our energy harvesting solution – *the human body*, which is permeable and large in size.

To effectively utilize human body to help capture more leaked energy in the ambient environment from VLC transmissions, we need to address the second challenge: *how to utilize the human body to enhance the coil's energy harvesting capability in an effective and convenient way?*

To address this challenge, we conducted experiments to evaluate the effect of coil parameters such as the number of turns, coil size, wire thickness and wire material. Besides the coil design, we also test the effect on energy boosting when the coil antenna touches different positions of the human body including finger, wrist, arm, waist, thigh and ankle. Based on comprehensive benchmark experiments, we propose a bracelet coil design which is convenient and comfortable for the user to wear and at the same time can effectively boost the energy harvesting capability. We believe the antenna+human body design could provide other RF-based energy harvesting systems a new angle to increase the harvested power.

When a user wears a bracelet coil, his/her body and coil together serve as a big antenna (we term it as bracelet+ antenna) to harvest energy from VLC transmissions. When RF energy arrives at the bracelet+ antenna, part of the energy gets absorbed and the other part gets reflected. To increase the harvested power, we want to minimize the amount of energy getting reflected. To achieve this objective, we need to match the frequency of leaked RF signal and the resonate frequency of the energy harvester. However, different from commercial wireless charging systems, in which the frequency of signals is fixed and known priorly, the frequency of the leaked RF signals from the VLC transmitter varies and is unknown. VLC systems vary the transmission rate by adjusting the ON/OFF frequency

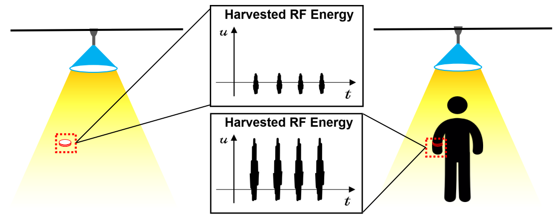


Figure 1: The illustration of harvested RF energy leakage in VLC by bracelet coils without and with human body, where the signal amplitude is largely increased with human body.

and accordingly the frequency of the leaked RF signals also changes. Recent works tried to tune the resonant frequency of the receiver to match the frequency of the leaked signals [17, 18]. However, such a method requires a high sampling rate and heavy computation to perform resource-hungry Fourier transform operation at the receiver side [42], which is impractical for power-restricted energy harvesting system. So the third challenge is *how to match the resonant frequency of the harvester and the frequency of the leaked signal without incurring any resource-hungry operations.*

We find that although the frequency components of the leaked signals change with transmission configurations (e.g., different ON/OFF rates, modulations, and coding schemes), the frequency component which contains the majority energy of the leaked signal does not change for a specific hardware. According to this observation, we only need to tune the resonant frequency of the harvester once based on which VLC system it aims to harvest energy from.

By addressing all these challenges, we successfully prototype *Bracelet+*, the first bracelet antenna design with human body as the key component to boost the energy harvesting capability in capturing the leaked energy from VLC systems as shown in Figure 1. The design is cheap (less than 50 cents) and small. What is more important is that it can be conveniently worn by a user. Bracelet+ could harvest 10× more energy from the VLC system compared with the conventional coil antenna design. The harvested power by Bracelet+ can reach *up to micro-watts*, enough to support many sensors such as on-body health monitoring sensors that only require little power to work owing to their low sampling frequency and long sleep-mode duration [32].

Besides, Bracelet+ is a standalone design which does not affect either the VLC data communication or light illumination. It is also *transparent* to the VLC system, meaning that *we do not require any modifications at the VLC side for our harvester to work.* Compared to near-distance (a few centimeters) power harvester which is widely adopted in wireless charging nowadays, the proposed harvesting system moves one step towards long-distance energy harvesting. Compared to the existing VLC works focusing on data communication, for the first time, we pay attention to the RF energy leakage of VLC systems and propose a novel design to harvest such leaked energy. Our main contributions are summarized as below:

- Without affecting VLC data communication or light illumination, we harvest the leaked RF energy from VLC by introducing the concept of bracelet coil involving human body into the harvesting system to significantly increase the energy harvesting capability.

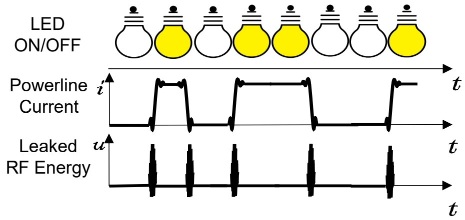


Figure 2: Illustration of the leaked RF energy caused by the power-line current change in VLC. Here we use OOK modulation as the example.

- We design a lightweight resonant frequency matching scheme that can effectively increase the harvested power.
- We prototype a small-size low-cost harvester Bracelet+. Comprehensive experiments in different settings demonstrate that the proposed system is able to increase the amount of harvested energy by 10×, achieving micro-watt level of energy harvesting.

2 BACKGROUND

During the process of VLC transmission, the VLC transmitter not only actively emits out light energy but also passively leaks RF energy into the ambient environment. The reason why there exists this RF energy leakage is mainly due to the intensity modulation scheme adopted by VLC systems. VLC transmitter modulates the intensity of the light signals by changing the current in the power line to represent different data bits (e.g., ON for '1' and OFF for '0' in On-Off Keying (OOK) modulation) and the receiver decodes the information based on the power envelope of the received signals [28]. Due to the extremely high frequency (400–790 THz) and incoherence of light signal emitted, it is impractical to use other modulation schemes such as frequency-based modulations adopted in WiFi for VLC systems [49]. Therefore, when VLC transmitter emits out light signals, the fast current change in the transmitter's power line will create a fast changing magnetic flux and eventually cause RF leakage as shown in Figure 2 according to the well-known Maxwell Equations. This leaked RF energy is what we are going to harvest in this paper.

The physical model of the leaked RF signals has been discussed in recent work [17], including the parameters at both transmitter and receiver sides. As we aim to harvest leaked energy without modifying the VLC transmitter circuit design, we only focus on the parameters at the receiver side:

$$A_r \propto \frac{S \cdot N_{\text{coil}} \cdot G_{\text{res}}}{d^m}\,, \tag{1}$$

where A_r is the voltage of received RF leakage signals; S and N_{coil} are the size of the coil and number of coil turns; G_{res} is the resonance gain, and d is the distance between the transmitter and the receiver. This model only pays attention to the peak voltage of the received signal, which is important for communication. However, such a physical model is not appropriate for energy harvesting since the peak voltage does not present the energy level of the leaked signals.

3 PRELIMINARY EXPERIMENT

In this section, we first conduct experiments to identify the coil parameters that influence the harvested energy level at the receiver side. Then, we investigate the influence of the surrounding objects

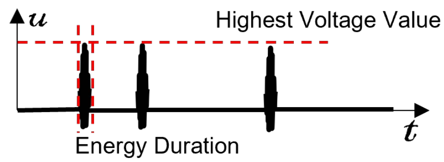
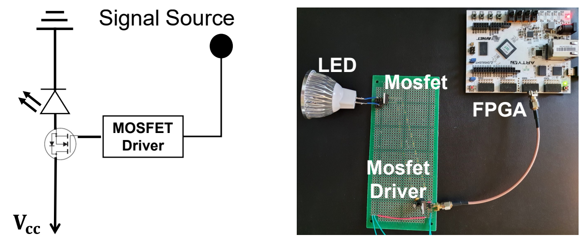


Figure 3: Illustration of the highest voltage value and the energy duration of the leaked RF signal, which both determine the amount of leaked RF energy.



(a) Diagram of VLC transmitter (b) Prototype of VLC transmitter

Figure 4: Diagram and implementation of the VLC transmitter for the preliminary experiment.

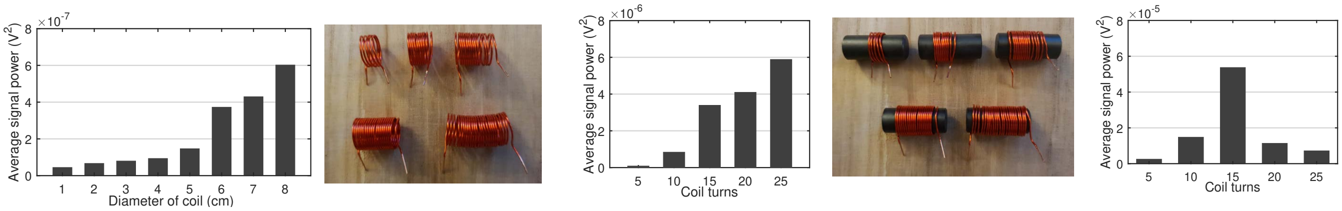
on the harvested energy. Finally, we exploit the daily life objects to increase the harvested power.

3.1 Basic Energy Harvesting Experiment

The existing model for VLC-leaked RF signals takes the highest voltage of the received signal as the final objective parameter [17, 18]. However, the highest voltage cannot precisely quantify the amount of energy harvested due to the pulse-like pattern of the leaked signal. As shown in Figure 3, the pulse voltage can be high; however, if the pulse duration is short, the harvested energy is still limited. Thus, we choose the *average signal power*, the sum of the squares of the time-domain samples divided by the signal length, as the objective parameter to quantify the effect of energy harvesting.

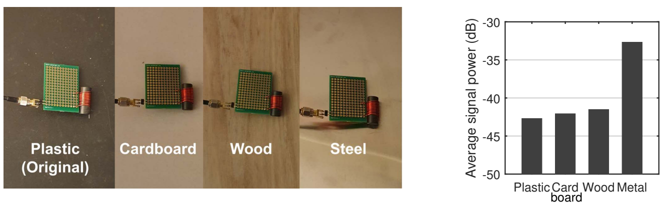
At the receiver side, we connect self-made coils of different parameters to DSOX1102A oscilloscope with a sampling rate of 125 Mbps for capturing and measuring the leaked RF energy from VLC systems. We adopt the basic circuit design for VLC transmitter as shown in Figure 4(a) with one MOSFET to control the ON/OFF of the LED, one MOSFET driver to increase the voltage input of the MOSFET, and one LED to emit light signals. The implemented VLC transmitter is shown in Figure 4(b), consisting of one FQP30N06L MOSFET, one MCP1407-E/AT MOSFET Driver, and one off-the-shelf Kapata 5W LED as the front-end. Besides, Arty A7 FPGA is used as the signal source to drive the MOSFET, enabling LED to transmit alternative ON/OFF light signals at an ON/OFF rate of 1 MHz. The distance between the VLC transmitter and the energy harvesting coil is fixed as one meter. We connect the OpenVLC 1.3 platform's receiver front-end [24] with the oscilloscope to verify that the light channel is operating properly without being affected.

To begin with, we vary the basic parameters of the coil, such as size and number of coil turns to see the effect on the harvested energy. We first use copper wire with a thickness of 22 AWG to



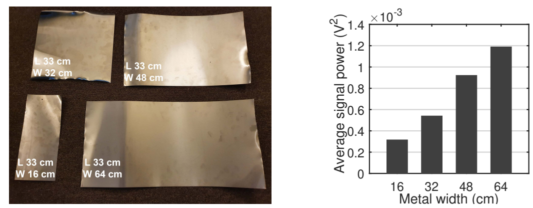
(a) Power vs. coil size (b) Different coil turns (c) Power vs. coil turns (d) Different coil turns with core (e) Power vs. coil turns with core

Figure 5: Energy harvesting model's basic parameters: (a) One-turn coil with diameter starts from 1 cm to 8 cm at a step size of 1 cm; (b–c) 1 cm-diameter coils with turns starting from 5 to 25 at a step size of 5 turns; (d–e) 1 cm-diameter coils, having ferrite cores, with turns starting from 5 to 25 at a step size of 5 turns.



(a) Coils on different materials (b) Power vs. materials

Figure 6: Power vs. surrounding material: (a) Coil on different materials as plastic (original), cardboard, wood, and steel; (b) Average power of the received leaked energy from coils with different surrounding materials.



(a) Different steel sizes (b) Power vs. steel width

Figure 7: Power vs. steel size: (a) Different steel sizes as 32 cm × 16 cm, 32 cm × 32 cm, 32 cm × 48 cm, and 32 cm × 64 cm; (b) Average power of the received leaked energy from coils with different surrounding steel widths (sizes).

create one-turn coils of different diameters starting from one centimeter to 8 centimeters at a step size of one centimeter to capture the leaked RF energy. The result is shown in Figure 5(a), which meets our expectations that a larger-sized coil captures more leaked energy. Then we use the same copper wire to form 1 cm-diameter coils with the number of turns changing from 5 to 25 at a step size of 5 as shown in Figure 5(b). The harvested power from these coils is shown in Figure 5(c). The harvested power increases as the number of coil turns increases.

To further improve the coil's energy harvesting capability, we insert a ferrite core into those coils with different turns as shown in Figure 5(d) and the corresponding result is shown in Figure 5(e). A ferrite core does increase the harvested power for all five tested coils. However, the power does not increase linearly with the number of coil turns due to the resonance effect. When there is no core in the coil, the resonant frequencies of the five coils are far away from the resonant frequency of the leaked RF signals. Thus, the resonance effect does not influence the harvested power. The inserted core changes the resonant frequencies of the coils and the resonant frequency of the coil with 15 turns matches the resonant frequency of the leaked signal. Thus, the harvested power with the 15-turn coil is much larger than that with other coils. Based on the above experiment, we choose the coil with a diameter of 1 cm, 15 turns, and a ferrite core as the default harvesting coil as this configuration achieves the best power harvesting performance so far.

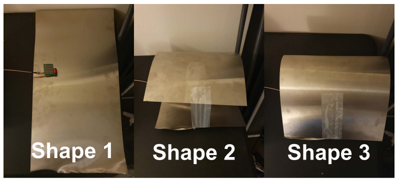
3.2 Influence of Surrounding Objects

Based on the experiments in the previous section, we know that it is impossible to keep increasing harvested energy by just increasing the number of coil turns as shown in Figure 5(e). Making the coil size (diameter) larger is a possible solution, but it is impractical to deploy a huge-sized coil in a lot of real-world settings.

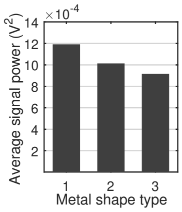
Fortunately, an observation provides us with a new angle to address the problem. We find that when there exist surrounding objects (e.g., an electronic device) touching the coil, the harvested power is larger than that when there is no surrounding object. The reason for this phenomenon is that the surrounding objects can absorb the leaked RF energy in the ambient environment and re-radiate the energy to the coil, enhancing the coil's energy harvesting capability. Based on this key observation, more experiments are conducted to analyze the effect of surrounding objects on the harvested energy.

We first put the coil on an object made of different materials including plastic, cardboard, wood, and steel, as shown in Figure 6(a), to study the effect of object material on energy harvesting enhancement. We can see from Figure 6(b) that although cardboard and wood can improve the performance of energy harvesting, the improvement is much less than that induced by steel. This result indicates that objects with higher permeability can boost the capability of energy harvesting more.

Then we put the coil on the steel of four different sizes: 32 cm × 16 cm, 32 cm × 32 cm, 32 cm × 48 cm, and 32 cm × 64 cm. The amount of harvested RF energy is shown in Figure 7. We can see that the larger the object size, the more energy can be harvested, which is in accordance with our expectations. We further study whether the curvature of an object affects the performance. We place the steel plate with a size of 32 cm × 64 cm as flattened, curved and closed cycle as shown in Figure 8(a). The corresponding harvested power is presented in Figure 8(b), which shows that the curvature of the object also influences the performance. The conclusion is

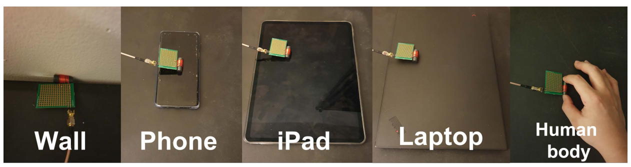


(a) Different steel shapes

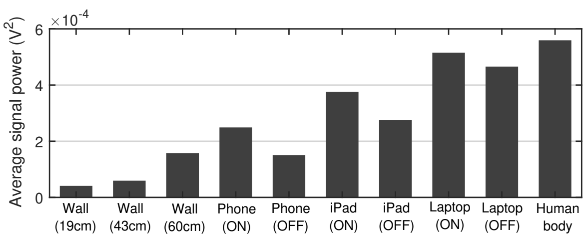


(b) Power vs. steel shapes

Figure 8: Power vs. steel shape: (a) Different steel shapes as: flattened (type 1), curved (type 2) and closed cycle (type 3); (b) Average power of the received leaked energy from coils with different surrounding steel shapes.



(a) Coils on different daily objects



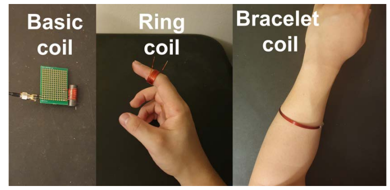
(b) Power vs. daily objects

Figure 9: Power vs. daily object: (a) Coils on different daily objects as walls, phone, iPad, laptop and human body; (b) Average power of the received leaked energy from coils with different daily objects.

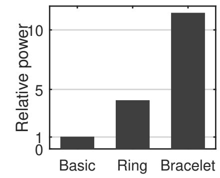
that the larger cross-sectional area towards the leaked energy, the more energy can be harvested.

3.3 Daily Objects for Energy Boosting

According to the experiments in previous sections, the surrounding object which can be used to improve energy harvesting should be made of a material which has relatively high permeability and large physical size. For real-world deployment, what is more important is that this object should be ubiquitous in our daily life. With such requirements, we place the coil on walls, electronic devices (e.g., smartphone and laptop), and human body as shown in Figure 9(a) and the corresponding results are presented in Figure 9(b). Concrete walls of three different thicknesses (19 cm, 43 cm and 60 cm) are evaluated and we find that the thicker the wall is, the larger improvement it provides. The reason lies in the fact that thicker objects can absorb more leaked RF energy [3]. We also find that although the physical size of the wall is huge, the improvement induced by a wall is not large because concrete walls have a small permeability. Compared with concrete walls, the electronic devices such as smartphones, iPad devices, and laptops perform better. In



(a) Different coil designs



(b) Power vs. coil design

Figure 10: Power vs. coil design: (a) Different coil designs: basic coil designs, ring coil, and bracelet coil; (b) Relative average power of the optimal received leaked energy from different coil designs.

addition, we also find that the working status of the electronic devices, i.e., ON/OFF state, also slightly influences the result. Interestingly, we find that the enhancement on energy harvesting is the largest when the coil is touched with a human body as shown in Figure 9(b).

Human body can help increase the harvested energy because a lot of tissues in our body are actually dielectric materials. Note that the maximum instantaneous energy density leaked from VLC is around 0.01 mW/cm^2, far below the maximum power specified in FCC and FDA (i.e., 0.2 mW/cm^2 and 10 mW/cm^2) regulations [1, 2]. Thus, leveraging human body to help harvest the leaked RF energy from VLC systems does not cause any health issues. The coil can be designed as a ring or bracelet so the user can conveniently wear it.

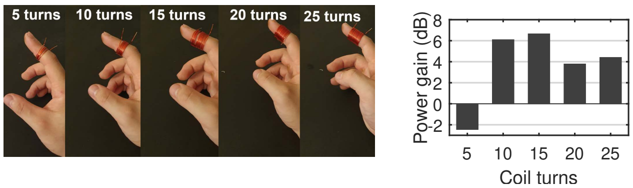
4 SYSTEM DESIGN

In this section, we present the detailed design of our energy harvesting system which utilizes the human body to capture more leaked RF energy from VLC systems. We conduct comprehensive experiments to obtain the proper coil design to work with human body efficiently. To absorb more received RF energy instead of reflecting it back, we propose a method to match the resonant frequencies between the energy harvester and the VLC transmitter.

4.1 Coil Design

Based on preliminary experiments in Section 3, we choose to utilize human body to improve the energy harvesting performance. However, the current design of the coil with a ferrite core is inconvenient for people to wear it. Meanwhile, removing the ferrite core will unavoidably degrade the energy harvesting performance. So the question is: *will the gain brought by human body outperform the gain brought by the ferrite core?* To answer this question, we wind the copper wire around a finger for ten rounds and around an arm for four rounds as shown in Figure 10(a). We measure the harvested RF energy under the above two setups and the corresponding results are shown in Figure 10(b). We can see that the gain induced by the ferrite core is much smaller than that brought by human body. We therefore can remove the ferrite core and design the coil as a ring or a bracelet which is convenient to wear.

We use the ring coil to study the effect of the number of turns as shown in Figure 11. We increase the number of turns from 5 to 25 at a step size of 5 and measure the harvested RF energy from VLC transmissions. The harvested power is presented in Figure 11. It shows that the "best" number of coil turns is 15, which provides

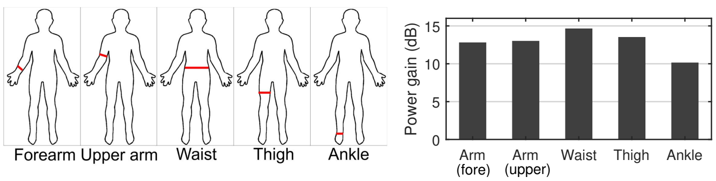


(a) Ring coils with different turns
(b) Power vs. coil turns

Figure 11: Power vs. turns of ring: (a) Ring coils with different numbers of coil turns from 5 to 25 at a step size of 5; (b) Average power of the received leaked energy from ring coils with different turns.

(a) Bracelet coils with different turns
(b) Power vs. coil turns

Figure 12: Power vs. turns of bracelet: (a) Bracelet coils with turns from one to six at a step size of one; (b) Average power of the received leaked energy from bracelet coils with different turns.



(a) Coils on different body parts
(b) Power vs. body parts

Figure 13: Power vs. body part: (a) Diagrams for coils on different human body parts as wrist, arm, waist, thigh, and ankle; (b) Harvested average power from coils with different body parts.

(a) Different coil turns without arm
(b) Power vs. coil turns

Figure 14: Power vs. turns of bracelet without any body part: (a) Coils with turns from one to six; (b) Harvested average power from coils with different turns.

a gain of more than 6 dB compared to the best ferrite core-based coil design. Similarly, we also create six bracelet coils with the number of turns increased from 1 to 6, as shown in Figure 12(a). The corresponding result in Figure 12(b) shows that the three-turn bracelet coil presents a maximum power gain of 13 dB. These results show that the ring/bracelet design is not just more convenient for a user to wear but also presents more power gain than the ferrite core design.

Besides, the above two experiment results imply that a higher number of coil turns does not always present a better harvesting performance due to the resonance effect. In other words, there exists an "optimal" turn number for this coil design with human body which can match the resonant frequencies between the energy harvester and VLC transmitter. We will detail the solution for resonant frequency matching in the next section.

The difference between the largest power gain with ring coil (6.64 dB) and with bracelet coil (12.74 dB) indicates that coils encircling different body parts could induce different amounts of power gain. To verify this assumption, we first wind the copper wires around the upper arm, waist, thigh, and ankle with different numbers of turns to find the optimal turn number for different body parts as shown in Figure 13(a). We find that the optimal designs for different body parts are different: the optimal turn numbers are three for upper arm, one for waist, two for thigh, and four for ankle. In the experiment, the distance between the human body and the VLC transmitter is fixed. The average power of received signals with the coil at different body parts shown in Figure 13(b) demonstrates that different body parts can lead to different energy harvesting performance and the larger cross-sectional area of the coil, the better performance. Although there exist performance differences with coils encircling different body parts, the differences are not big and it is inconvenient for users to wear the coil on the waist or thigh. All in all, we choose the bracelet coil design which balances the energy harvesting performance and convenience.

We evaluated the effect of coil thickness by considering five different thicknesses, i.e., 16 AWG, 18 AWG, 20 AWG, 22 AWG and 24 AWG for copper and aluminum materials. We found that the thickness and material of the coil had little effect on the energy harvesting performance due to the skin effect [56]. Thus, in our design, we choose the common 22 AWG copper wire to make the coil for our energy harvesting system.

4.2 Frequency Matching

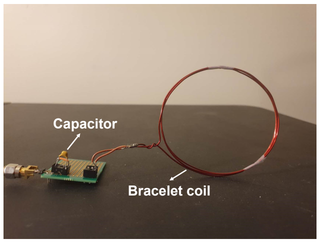
Figure 11 and Figure 12 indicate that resonant frequency matching is essential for energy harvesting. Different from commercial wireless charging systems, in which the frequency of signals sent from the transmitter is fixed and known, the frequency of leaked RF signals emitted from the VLC transmitter varies and is unknown to the energy harvester.

During the VLC transmission, we observe that although the frequency components of the leaked signals change with different transmission configurations (ON/OFF rates, modulations and coding schemes), the frequency component which contains the majority energy of the leaked signals does not change much for a specific hardware as shown in Table 1.[2] In other words, for one VLC transmitter, the resonant frequency of the transmitter is not affected by how it transmits light signals. The reason lies in the fact that the electric components in the VLC transmitter determine the circuit's resistance, inductance and capacitance [31]. For a particular

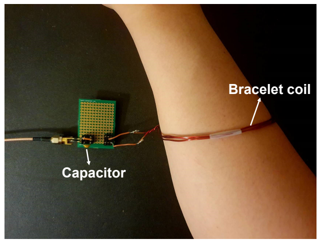
[2]For different modulations and coding, the influence on the leaked RF leakage is the same as the ON/OFF rate since all those parameters only decide how much current change happens in a fixed time window.

Table 1: The major frequencies of leaked RF energy from VLC transmitters with different ON/OFF rates.

ON/OFF rate (MHz)	0.5	1.0	1.5	2	2.5
Major energy Fre (MHz)	23.17	22.68	22.44	21.71	22.07



(a) Implemented energy harvesting antenna of Bracelet+



(b) Implemented energy harvesting antenna worn by human

Figure 15: Implementation of the Bracelet+ front-end, which consists of a frequency-tuning capacitor and a bracelet-like coil antenna.

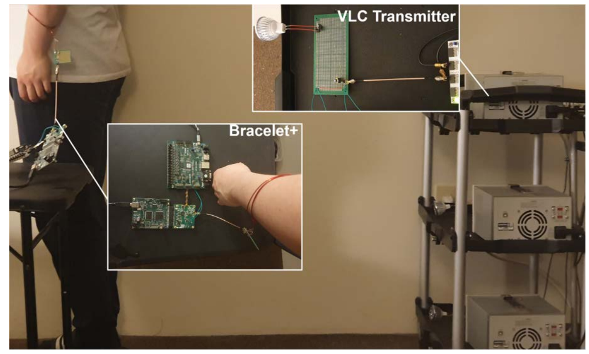


Figure 16: Experiment setup, including the energy harvesting system (bracelet+ front-end and energy measuring ADC circuit) and the VLC transmitters.

VLC transmitter, the resistance, inductance and capacitance of the hardware are fixed, resulting in a stable resonant frequency. Based on this observation, we only need to tune the resonant frequency of the harvester once to match it with the resonant frequency of the VLC system it aims to harvest energy from.

Since human body is utilized to increase the energy harvesting power, to match the resonant frequencies between the harvester and the VLC transmitter, we need to study the human body's impact on the resonant frequency of the harvester. In Section 4.1, a user wore the coil antenna as a bracelet. We now evaluate the harvesting performance when the bracelet coil is not worn by a human. We use coils with a diameter of 7.8 cm and different numbers of turns as shown in Figure 14(a) to harvest energy. The harvested power is shown in Figure 14(b), from which we can see that the three-turn coil achieves the "best" performance. This means that the resonant frequency is not affected much by the human body.

To further investigate human body's impact on the coil's resonant frequency in a fine-grained manner, we fix the number of coil turns as three and fine-tune the frequency of the leaked energy from 10 MHz to 35 MHz at a step size of 0.1 MHz. We utilize the function generator MFG-2260MRA to flexibly control the frequency of the leaked RF signal. The harvested power with and without human body reaches the maximum value at 19.2 MHz and 19.5 MHz, respectively, which implies the resonant frequency of the coil is only slightly affected by human body. This result is consistent with that reported in existing works [34]. We further find that human diversity only slightly influences the coil's resonant frequency. Thus, we can add a fixed-value capacitor or inductor to the coil to tune the harvester's resonant frequency.

5 IMPLEMENTATION

In this section, we present the implementation details of the proposed Bracelet+ energy harvesting system.

Coil prototype. The prototype of the designed Bracelet+ is shown in Figure 15. This system only costs less than 50 cents with three components: copper wires (10 cents), capacitor (10 cents), and SMA connector (30 cents). The design is also very compact; therefore, users can conveniently wear it as shown in Figure 15(b). We build the bracelet coil with three turns using the copper wire of 22 AWG thickness. The coil has a diameter of 7.8 cm. Besides the coil, we implement the resonant matching circuit on a perfboard. We connect a 100 nf HILITCHI ceramic capacitor between the coil and the SMA connector to tune the resonant frequency of the energy harvesting system. Instead of directly connecting a fixed-value capacitor to the board, we choose to connect the capacitor with a socket, which helps the user tune the resonant frequency by using a capacitor of different values. In addition to the bracelet coil design, we also implement a ring coil design for evaluation which will be detailed in Section 6.3.

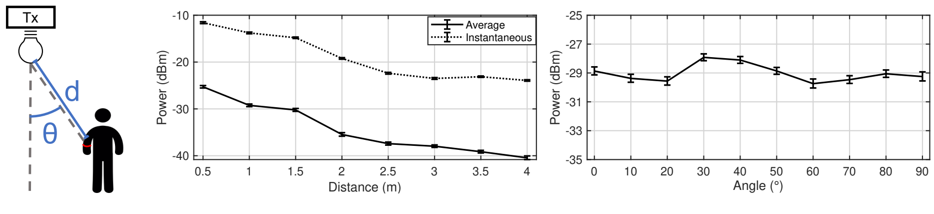
To quantify the harvested energy, we use LINEAR LTC2208 ADC and DC718 CPLD to measure the harvested energy. To study the impact of the proposed energy harvesting system on VLC communication, we employ the widely used OpenVLC 1.3 board [24] to receive the visible light signals.

VLC transmitter. We implement *three* same VLC transmitter front-ends based on the circuit detailed in Figure 4(a). Each transmitter front-end consists of one FQP30N06L Mosfet, one MCP1407-E/AT Mosfet Driver, and one off-the-shelf Kapata 5W LED as shown in Figure 4(b). For signal source, we use Arty A7 FPGA to handle VLC transmissions in terms of coding, modulation, transmitted content, LED's ON/OFF frequency, and to synchronize the three transmitter front-ends when we evaluate the system performance in the Multiple-Input-Multiple-Output (MIMO) scenario.

The effect of power harvesting on user health. We want to point out that the energy harvesting process of Bracelet+ is very safe for human health. Specifically, FCC requires the power density in the low radio frequency band (3 MHz - 30 MHz) to be below 0.2 mW/cm^2 [1] and FDA requires the power density to be below 10 mW/cm^2 [2]. The maximum instantaneous RF power in our experiment is around 0.01 mW/cm^2 which is well below the thresholds. All the experiments conducted in this work were IRB-approved by the host institute.

6 PERFORMANCE EVALUATION

In this section, we evaluate the energy harvesting performance of Bracelet+. The default experiment setup is shown in Figure 16. The



(a) Setup (b) Harvested power vs. distance (c) Harvested power vs. angle

Figure 17: Preliminary evaluation: (a) Experiment setup, where θ and d are the angle and the distance between VLC transmitter and designed energy harvester, respectively; (b) Harvested power vs. distance d; (c) Harvested power vs. angle θ.

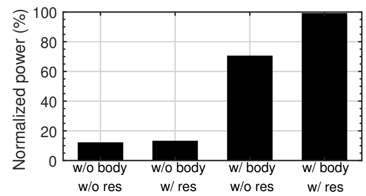


Figure 18: Normalized harvested power with four different harvesting setups.

Figure 19: Average harvested power vs. body postures: stand/walk/bend/sit/lie.

default distance between the harvester and the VLC transmitter is set to one meter. The VLC transmitter repetitively sends '0' and '1' in the visible light channel and the data is modulated with OOK modulation and Manchester coding. The LED's ON/OFF frequency is set to 1.25 MHz. To measure the power level of the harvested energy, we use the following equation:

$$P = \frac{U^2}{R}, \tag{2}$$

where P is the harvested power in Watt, U is the voltage of the sampled signal, and R is the default 50 Ω impedance in the RF circuit. Since the leaked RF signals are pulse signals, we average the harvested signals' power to denote the harvested power level. We use dBm unit for our results, where 0 dBm is one milli-watt and -30 dBm is one micro-watt.

6.1 Preliminary Evaluation

Distance. We first conduct experiments to evaluate the harvesting performance by changing the relative positions of the energy harvester with respect to the VLC transmitter, i.e., the distance d and angle θ, as shown in Figure 17(a). In these experiments, we only use one VLC transmitter front-end to send out the VLC signals. For testing the influence of distance, we fix the angle as 0° and change the distance between the transmitter and energy harvester, starting from half meter to four meters at a step size of half meter. The average harvested power and the instantaneous power at different distances are shown in Figure 17(b). We can see that both the average and the instantaneous harvested energies decrease with the increase of the distance because RF signals' propagation loss increases with distance. We can see that the average harvested power can easily achieve one micro-watt within one and half meters with just a single LED.

Due to the pulse-like pattern of the leaked RF energy from VLC (cf. Figure 2), the instantaneous power is much higher (around 100× larger) than the average power. In the following experiments, we still use the average harvested power instead of the instantaneous harvested power as the metric. However, we want to point out that the much higher instantaneous powers can also benefit a lot of applications detailed in Section 7.

Angle. We then fix the distance as one meter and study the impact of angle between the VLC transmitter and energy harvester on energy harvesting. The corresponding result is shown in Figure 17(c). The harvested power level does not change with angle because the RF energy is leaked in all directions from the VLC transmitter. Although such omnidirectional leakage makes it hard for the energy harvester to receive highly-concentrated energy, it could enable multiple energy harvesters to work simultaneously, which will be detailed in Section 6.3. Unlike VLC signals having a fixed and small illumination angle, our Bracelet+ design can harvest the omnidirectional RF leakage from VLC in a wider area.

Harvester setup. Then we fix the distance as two meters and angle as 0°, and configure energy harvester with different settings including: *without body and without resonant matching; without body and with resonant matching; with body and without resonant matching; with body and with resonant matching.* The harvested power levels of the corresponding setups are shown in Figure 18. We can see that our proposed Bracelet+ (with body and with resonant matching) can harvest power 10× more than the original coil design (without body & with resonant matching).

User posture. We now study if user's posture affects the energy harvesting performance when the user wears the proposed energy harvesting system as a bracelet. We ask a user to wear the bracelet under different body postures: stand, walk, bend over, sit, and lie naturally at a distance of one meter from the VLC transmitter. The measured harvested power is shown in Figure 19. There is almost no difference in the harvested power when the user stands, walks, or lies. However, when the user bends over or sits, the harvested power is 20% and 10% lower, respectively, compared to the case when the user stands. We believe the reason is that sitting and bending decrease the human body's cross section area towards the leaked RF energy from VLC transmitter, similar to the steel shape experiment presented in Figure 8. However, such decrease does not influence the harvested power too much, Bracelet+ can still achieve around one micro-watt power harvesting from just one LED under different body postures.

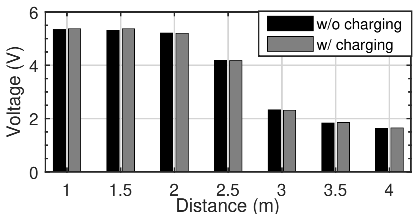


Figure 20: Measured VLC signals' maximum voltages with/without Bracelet+ harvesting energy.

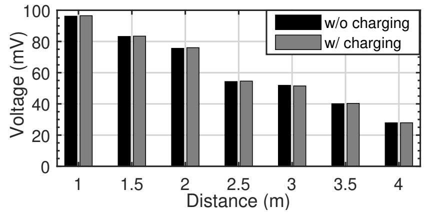


Figure 21: Measured side-channel signals' maximum voltages with/without Bracelet+ harvesting energy.

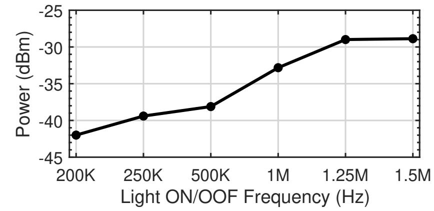


Figure 22: Average harvested power vs. ON/OFF frequency of the LED of the VLC transmitter.

Impact on VLC and side RF channel communication. One advantage of the proposed system is that it only harvests the "wasted free" energy leakage from the VLC transmitter. In other words, the energy harvesting process does not affect the communication on the VLC channel and the side RF channel [18, 19]. We measure the VLC signals and the side-channel RF signals at different communication distances without and with the proposed harvesting energy system Bracelet+ working. The results are shown in Figure 20 and Figure 21, respectively and we can see that Bracelet+ does not influence the performance of existing communication on the VLC channel or its side RF channel.

Blockage. Another advantage of the proposed system is that it can still harvest the leaked RF energy when there is a blockage between the VLC transmitter and the energy harvester. Our system is more resilient against blockages when compared with systems harvesting energy directly from light. We put a piece of thick cloth as a blockage between the VLC transmitter and the energy harvester to block the light signals. We change the distance between the transmitter and the energy harvester, starting from half meter to four meters at a step size of half meter. The average energy and the instantaneous power harvested from the Bracelet+ at different distances are the same as those harvested without the blockage since low-frequency RF signals can easily penetrate through the blockage. Besides, as the Bracelet+ does not influence the light channel, it can be combined with wrist-worn photovoltaic panel for light energy harvesting to improve the overall robustness of energy harvesting.

6.2 Robustness to Various VLC Setups

Bracelet+ harvests the leaked RF energy from VLC and is *transparent* to the VLC system, meaning that *we do not require any modifications at the VLC side for our harvester to work.* Bracelet+ harvests the leaked RF energy from VLC system "passively". As the RF energy is leaked from VLC transmitter and determined by VLC transmitter, we conduct experiments to study the energy harvesting performance of Bracelet+ under various VLC transmission configurations, including ON/OFF frequency, modulation, coding scheme, transmitted data, and LED model.

LED's ON/OFF frequency. We fix the distance between the Bracelet+ and single VLC transmitter as one meter and tune the LED's ON/OFF frequency from 200 kHz to 1.5 MHz. We observe from the experiment that the LED's ON/OFF frequency is very important for energy harvesting, as shown in Figure 22. The harvested power strictly increases with LED's ON/OFF frequency. The power under 1.25 MHz ON/OFF frequency is 20× larger than that under 200 kHz ON/OFF frequency. This is because with a higher ON/OFF frequency, the leaked RF pulse occurs more frequently in a given time window, leading to more energy leakage (cf. Figure 2). Also, as the ON/OFF frequency increases, the ON/OFF transitions period will be smaller. These faster transitions would induce stronger RF signals, further increasing the power leakage for each pulse. We can also notice that the harvested power does not increase when the ON/OFF frequency increases from 1.25 MHz to 1.5 MHz. This is due to the limited bandwidth of commercial LED (around several megahertz), which can not support faster current changes as LED's ON/OFF frequency is approaching 1.5 MHz. The future VLC systems will adopt LED with much higher bandwidth to support higher ON/OFF frequencies and higher communication data rate. We believe our system has the potential to harvest even more RF leakage from future VLC systems.

Modulation & coding schemes. We fix the ON/OFF frequency to 1 MHz and change the VLC modulation and coding schemes. We test three modulation schemes, i.e., OOK, Variable Pulse Position Modulation (VPPM) (25% pulse width), and VPPM (75% pulse width).[3] For coding schemes, we test Manchester coding and 4B6B coding [28]. We configure the VLC transmitter with different combinations of modulation and coding schemes. The experiment results are shown in Figure 23. We can observe that modulation does not influence the performance much because it only determines where the leaked RF pulses occur, instead of how many of them occur. However, the coding method 4B6B induces current changes (symbol '0'→'1', or '1'→'0') less frequently, resulting in less leaked RF pulses and less energy leakage compared with Manchester coding. However, 4B6B coding is usually combined with high ON/OFF frequencies to address the flickering issue [28]. Thus, the minor leakage decrease caused by 4B6B coding could be easily overwhelmed by the leakage increase brought by high ON/OFF frequencies.

Transmitted data. We also study the impact of transmission content on the energy harvesting performance. We transmit other contents in the VLC channel, as listed in Figure 24(a). The result is presented in Figure 24(b), which shows that the transmitted data has an influence on the energy leakage. For example, transmitting "6G technology" leaks around 50% more RF energy compared to "Hello world". The reason lies in the fact that the number of RF pulses differs due to different binary combinations for different

[3]OOK is actually a special form of VPPM modulation with a 50% pulse width.

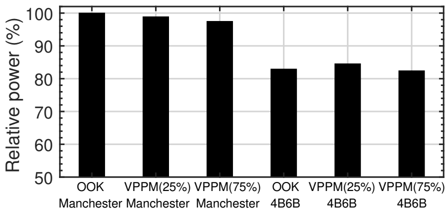
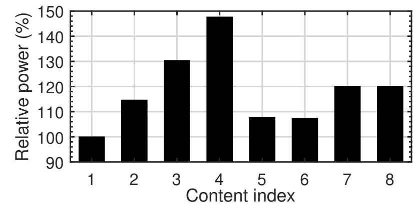


Figure 23: Bracelet+'s energy harvesting performance with different VLC Modulation & coding.

Index	Content	Index	Content
1	Hello world	5	Mobile network
2	Hello SenSys	6	Wireless charging
3	Welcome to CS	7	Energy harvesting
4	6G technology	8	Internet of Things

(a) Different contents

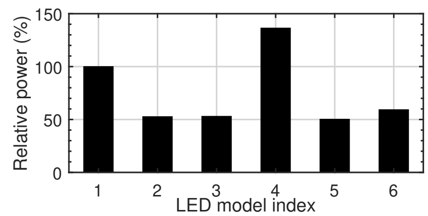


(b) Harvested power vs. Tx data

Figure 24: Bracelet+'s energy harvesting performance with different transmitted data on the VLC channel.

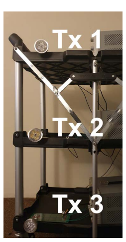
LED index	1	2	3	4	5	6
Brand	JKLcom	Kapata	BAOMING	SIMBA	Boxlood	MLambert
Power cons. (watt)	4	4	5	5	5	5.5
Field of view (°)	30	60	38	38	40	35
Color temperature	2700K	3200K	2700K	2700K	3000K	2700K
Light intensity (lm)	350	300	400	400	450	450

(a) The parameters of tested six commercial LEDs

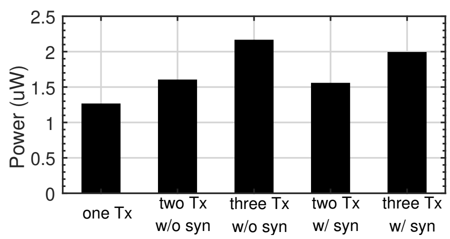


(b) Harvested power vs. LED model

Figure 25: Bracelet+'s energy harvesting performance with various commercial LED models used at the VLC transmitter.



(a) MIMO VLC



(b) Harvested power vs. Tx setup

Figure 26: Average harvested power vs. MIMO VLC setups: two to three asynchronized/synchronized VLC transmitters.

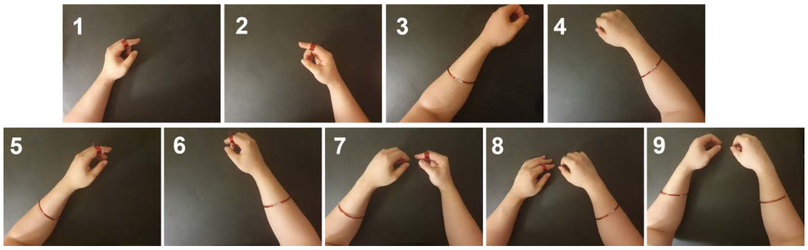
contents. However, regardless of the transmitted contents, each data bit can induce at least one RF pulse for OOK modulation with Manchester coding, causing RF energy leakage.

LED model. We also test different commercial LED models as detailed in Table 25(a). The corresponding harvested energy is presented in Figure 25(b). It is clear that different LED models have different amounts of energy leakage, and the leakage does not change linearly with the power consumption of the LEDs. For example, LED6 has more power consumption than LED4, but LED6 has less RF energy leakage. The reason lies in the fact that the RF energy leakage in VLC is determined by *how fast* the current changes instead of *how much* the current changes. Thus, larger current change (more power consumption) does not mean more energy leakage. On the other hand, all the tested commercial LED models leak RF energy and Bracelet+ can successfully harvest energy from all the commercial LEDs tested.

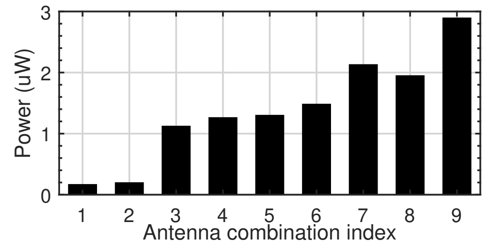
6.3 Multiple Transmitters/Harvesters

Multiple VLC transmitters. MIMO architecture is popular in VLC systems [25, 26, 36]. Thus, we also evaluate the performance of Bracelet+ under multi-transmitter scenarios. We test the system performance with two and three VLC transmitters in both *asynchronized and synchronized* manner as illustrated in Figure 26(a). To be specific, in synchronized scenario, all the working VLC transmitters send out the same information at the same time stamp. Such manner is purposely designed to enhance the communication robustness against the blockage and ambient light interference. In asynchronized manner, different VLC transmitters send out different information at different time stamps. The results are presented in Figure 26(b), where we can observe that more VLC transmitters do leak more RF energy. Besides, we also find that asynchronized transmitters leak slightly more energy than synchronized transmitters. This is because in the synchronized scenario, some of the leaked RF pulses from different transmitters can overlap with each other, cancelling some part of the leaked energy. We can envision that our proposed system can harvest more energy in the future with more LEDs adopted for communication.

Multiple receiver antennas. Due to the high electric resistance of the human body, the harvested energy in different body parts cannot be easily transferred and collected at a single bracelet antenna. Thus, we conduct experiments to study if we can harvest more energy when the user wears more than one coil antenna. Besides the bracelet antenna, we also design a *ring antenna* (cf. Figure 27(a)). We evaluate nine antenna wearing methods: *1)* wearing one ring antenna on left hands' index finger; *2)* wearing one ring antenna on right hands' index finger; *3)* wearing one bracelet antenna on left arm; *4)* wearing one bracelet antenna on right arm; *5)* wearing one ring antenna on left hand's index finger and one bracelet antenna

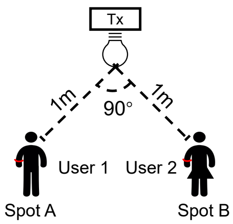


(a) Different antenna wearing methods

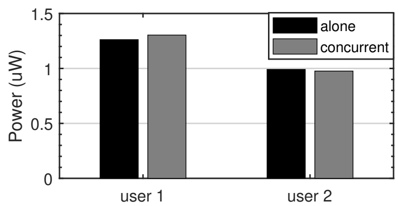


(b) Harvested power vs. wearing methods

Figure 27: Bracelet+'s harvested power vs. antenna wearing method: (a) 1–4: wearing one antenna in four different ways; 5–9: wearing two antennas simultaneously in five different ways; (b) average harvested power vs. antenna wearing methods.



(a) Experimental setup



(b) Harvested power vs. multiple users

Figure 28: Average harvested power for multiple users who stand at different positions.

on left arm; *6)* wearing one ring antenna on right hand's index finger and one bracelet antenna on right arm; *7)* wearing one ring antenna on right hand's index finger and one bracelet antenna on left arm; *8)* wearing one ring antenna on left hand's index finger and one bracelet antenna on right arm and *9)* wearing one bracelet antenna on left arm and one bracelet antenna on right arm.

The results are shown in Figure 27(b). We observe that wearing multiple antennas simultaneously could improve the energy harvesting performance, i.e., more energy is harvested with methods 7–9 than that with 1–4. When the user only wears one antenna, bracelet antenna is always a better choice (methods 3–4 outperform 1–2). When the user wears two antennas, two bracelet antennas outperform the combinations of one bracelet antenna and one ring antenna (method 9 outperforms 5–8). However, when the user wears multiple antennas at one side, i.e., wearing methods 5–6, there is no performance improvement. This is because when multiple antennas are near to each other (methods 5–6), they both harvest the energy absorbed by the same part of human body. In this case, one bracelet-coil (methods 3–4) is enough to harvest energy absorbed by one body part, and thus, there is no much difference when adding another antenna to the same arm.

Multiple users. Last but not least, since the leaked RF energy is emitted from the VLC transmitter in all directions, we also conduct experiments to validate whether Bracelet+ allows multiple users to harvest the leaked RF energy from VLC concurrently. We ask two users 1 and 2 to wear Bracelet+ and stand at Spot A and Spot B to harvest energy simultaneously, as shown in Figure 28(a). Later, we ask each user to stand at their corresponding spot alone and measure the harvested power. The result presented in Figure 28(b) indicates that the two users do not influence each other's energy harvesting, proving that Bracelet+ allows concurrent energy harvesting with multiple users. The reason is that the VLC transmitter leaks the RF energy in all directions. As long as the users do not block each other, they could harvest the leaked energy at different directions without interfering each other. Besides, we also notice that different users have different energy harvesting performance, i.e., user 2 harvests less leaked energy compared to user 1. This is because different users have different muscle and tissue combinations which lead to different dielectric characteristics. Generally, a user with larger weight and height can achieve a better performance.

7 DISCUSSIONS

Potential applications. Bracelet+ can harvest RF energy on the level of micro-watt from a single low-power LED at a distance of one and half meters. This power can be used to support low-power sensors such as temperature sensors [30], electrocardiogram sensors [5], photoplethysmographic sensor [10], glucose sensors [29], and motion sensor [14]. These sensors are designed to conduct measurements at a very low frequency (e.g., once per 10 mins) and transmit data at a low rate. These sensors usually consume power less than several micro-watts and even tens of nano-watts [21]. Besides, due to the pulse-liked pattern of the leaked energy from VLC, the harvested energy has much higher instantaneous power than the average power (cf. Figure 17(b)). Such unique feature can benefit the cold-start stage in which the sensors usually need much higher power to start working [55].

We believe our system can harvest even more energy from future VLC systems, which will adopt higher ON/OFF rate and MIMO architecture. We envision the harvested energy could be used to power up wearable electronic devices such as fitness tracker and smart earring through the body skin as presented in the recent work [39]. Last but not least, the proposed energy harvester can work simultaneously with other energy harvesters harvesting light energy and thermal energy from the VLC system [47]. It is a common approach to harvest different types of energy to guarantee stable power supply under varying situations. We believe the leaked

RF energy from VLC adds another valuable energy harvesting dimension to existing energy harvesting systems.

Different coil designs. Besides wearing the coil as a bracelet or a ring, we also showed that the coil could be encircled other parts of the human body to increase the harvested power in Section 4.1. Thus we could also design necklace/anklet coil for energy harvesting based on application requirements. By leveraging the recent advancement in textile technology [52], we believe our design could also be implemented in cloth as textile antenna to harvest the leaked RF energy from VLC systems.

In addition to human body, we also conducted experiments with other daily objects to see the effect on the harvested power (Section 3.3). Based on the results, we could also deploy the energy harvesting coil on walls to harvest more energy. Although the harvested power is lower than body-based harvester design, it does not involve any human factor into the design. Thus, it can be used in scenarios where people rarely show up. Such deployments could be suitable to charge IoT sensors on the walls.

Future VLC systems. Due to the commercial LEDs' bandwidth limitation, our VLC system currently could only support several Megahertz ON/OFF rate. One factor limiting the LED's ON-OFF rate is material. Phosphor, a solid material, is used in the LED bulb to convert the blue light into white light for illumination. This material has a relatively large relaxation time and therefore the LED's ON-OFF rate is limited [40]. We want to point out that conventional LED is not designed to support communication and therefore the ON-OFF rate is not the key parameter people care about. If communication becomes an important function of future LED design, other material which can support faster ON-OFF rate can be adopted to replace phosphor. Thus, in future high-speed VLC systems, advanced LEDs can be used to support even higher ON/OFF rates and induce faster current change in the circuit [54], which will induce pulse signals more frequently and also stronger pulse signals. In addition to the high-speed VLC systems, more and more VLC systems adopt MIMO architecture to increase the throughput and robustness against the blockage and interference [25, 26, 36], which means a lot of LEDs will work simultaneously and leak out RF signals into the ambient environment. For example, in DenseVLC [6], there exist 36 VLC transmitters in the platform to from the MIMO architecture. Compared with three transmitters in our evaluation, we believe the proposed energy harvester can harvest more energy from VLC systems in the future.

Other energy source. Besides harvesting energy from VLC systems, Bracelet+ has the potential to harvest leaked energy from other devices such as the power grid, computer, microwave oven, and television by properly tuning the coil's parameters.

Leveraging VLC leakage for backscatter communication. In addition to directly harvesting the leaked energy to power up other applications, the VLC leaked RF signals can also be used to facilitate VLC backscatter communication since the power of the leaked signals can reach -40 dBm. Such leaked signal can be leveraged as a carrier signal for backscatter communication [57] without incurring any additional energy consumption. By adding an additional backscatter circuit to Bracelet+, it can harvest the leaked power and backscatter the leaked RF signals for uplink communication.

8 RELATED WORK

VLC's side RF channel. The side RF channel of VLC systems was first found and modeled in the recent work [17] to snoop VLC systems through walls. Besides, the side channel was also exploited to improve the robustness of VLC systems against blockages and ambient light interference [18] and to increase the whole VLC system's data rates [19]. In this work, we consider the side channel of VLC as an energy leakage instead of a communication channel and design coil antennas worn by human body to harvest the leaked energy as much as possible to recycle the wasted energy in VLC.

Human body as an antenna. State-of-the-art research exploited the human body as an antenna to receive RF signals [27, 33, 37, 38]. The authors attached the signal electrode to human body to receive the ambient electromagnetic signals from the power line for energy harvesting [33, 37] and sensing [14, 15]. Users stood on a metal slab to act as a Monopole antenna to receive low-frequency RF signals [27, 38]. Besides, some works took the human body as a power transfer medium to transport electromagnetic energy from one part of the body to other parts [33, 39], and as a communication channel for user authentication [53] and on-body communication [51]. Compared with these works, our work is the first system that designs a bracelet antenna to collect the leaked RF signals from VLC system for energy harvesting with the help of human body.

VLC energy harvesting. As VLC is becoming a potential candidate for future 6G networks, lots of research has already tried to harvest energy from VLC systems [41, 43, 45]. All these works devoted effort to harvesting energy from light signals. There is no study on harvesting energy from the leaked RF signals for VLC systems.

Other energy harvesting systems. Lots of energy sources around us have been exploited for energy harvesting such as ambient lights [20, 35], vibrations [4, 50], thermal radiations [9, 16], and RF signals [22, 46]. Compared with the energy harvesting systems with other energy sources, the key advantage of the proposed harvester is that it is simpler and smaller. It only requires a conductive wire to harvest RF energy with the help of human body. Besides, harvesting energy from multiple energy sources will not only increase the power level but will also improve the robustness. For example, energy harvesting system could rely on RF energy harvesting instead of sunlight energy harvesting on a cloudy day [44]. We believe the proposed new energy harvesting modality can be combined with other modalities to achieve hybrid energy harvesting.

9 CONCLUSION

In this work, we designed a low-cost wearable energy harvester Bracelet+ to harvest, for the first time, the free leaked RF energy from VLC systems. Based on the observation that the surrounding objects can help increase the harvested power, we design a wearable bracelet antenna augmented by the human body to significantly increase the energy harvested. We prototype the harvester Bracelet+ and show that it can harvest 10× more RF energy from VLC systems than conventional coil design, achieving micro-watt power harvesting. We envision the proposed novel body-augmented energy harvesting modality can work independently or together with other energy harvesting modalities to further improve the overall performance.

REFERENCES

[1] 1997. *OET Bulletin No. 65 (August 1997).* https://www.fcc.gov/general/oet-bulletins-line

[2] 2019. *CFR - Code of Federal Regulations Title 21.* https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfcfr/CFRSearch.cfm

[3] Saba Ayub, Beh Hoe Guan, Faiz Ahmad, and et. al. 2021. Graphene and Iron Reinforced Polymer Composite Electromagnetic Shielding Applications: A Review. *Polymers* (2021).

[4] David AW Barton, Stephen G Burrow, and Lindsay R Clare. 2010. Energy harvesting from vibrations with a nonlinear oscillator. *Journal of vibration and acoustics* (2010).

[5] Christopher Beach, Sammy Krachunov, James Pope, Xenofon Fafoutis, Robert J Piechocki, Ian Craddock, and Alexander J Casson. 2018. An ultra low power personalizable wrist worn ECG monitor integrated with IoT infrastructure. *IEEE Access* (2018).

[6] Jona Beysens, Qing Wang, Ander Galisteo, Domenico Giustiniano, and Sofie Pollin. 2020. A Cell-Free Networking System With Visible Light. *IEEE/ACM Transactions on Networking* (2020).

[7] Jona Beysens, Qing Wang, and Sofie Pollin. 2019. Improving Blockage Robustness in VLC Networks. In *Proceedings of COMSNETS.*

[8] Rui Bian, Iman Tavakkolnia, and Harald Haas. 2019. 15.73 Gb/s visible light communication with off-the-shelf LEDs. *Journal of Lightwave Technology* (2019).

[9] Siddharth Buddhiraju, Parthiban Santhanam, and Shanhui Fan. 2018. Thermodynamic limits of energy harvesting from outgoing thermal radiation. *In Proceedings of the National Academy of Sciences* (2018).

[10] Antonino Caizzone, Assim Boukhayma, and Christian Enz. 2019. A 2.6 uW Monolithic CMOS Photoplethysmographic (PPG) Sensor Operating With 2 uW LED Power for Continuous Health Monitoring. *IEEE Transactions on Biomedical Circuits and Systems* (2019).

[11] Nan Cen, Neil Dave, Emrecan Demirors, and et. al. 2019. Libeam: Throughput-optimal cooperative beamforming for indoor visible light networks. In *Proceedings of IEEE INFOCOM.*

[12] Chun-Ling Chan, Hsin-Mu Tsai, and Kate Ching-Ju Lin. 2017. Poli: Long-range visible light communications using polarized light intensity modulation. In *Proceedings of ACM MobiSys.*

[13] Hyunchae Chun, Ariel Gomez, Crisanto Quintana, and et. al. [n.d.]. A Wide-Area Coverage 35 Gb/s Visible Light Communications Link for Indoor Wireless Applications. *Scientific reports* ([n. d.]).

[14] Gabe Cohn, Sidhant Gupta, Tien-Jui Lee, Dan Morris, Joshua R Smith, Matthew S Reynolds, Desney S Tan, and Shwetak N Patel. 2012. An ultra-low-power human body motion sensor using static electric field sensing. In *Proceedings of ACM UbiComp.*

[15] Gabe Cohn, Daniel Morris, Shwetak Patel, and Desney Tan. 2012. Humantenna: using the body as an antenna for real-time whole-body interaction. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems.*

[16] A Cuadras, M Gasulla, and Vittorio Ferrari. 2010. Thermal energy harvesting through pyroelectricity. *Sensors and Actuators A: Physical* (2010).

[17] Minhao Cui, Yuda Feng, Qing Wang, and Jie Xiong. 2020. Sniffing visible light communication through walls. In *Proceedings of ACM MobiCom.*

[18] Minhao Cui, Qing Wang, and Jie Xiong. 2020. Breaking the limitations of visible light communication through its side channel. In *Proceedings of ACM SenSys.*

[19] Minhao Cui, Qing Wang, and Jie Xiong. 2021. RadioInLight: doubling the data rate of VLC systems. In *Proceedings of ACM MobiCom.*

[20] Jasper De Winkel, Vito Kortbeek, Josiah Hester, and et. al. 2020. Battery-free game boy. *In Proceedings of ACM IMWUT* (2020).

[21] Frederick Ojiemhende Ehiagwina, Olufemi Oluseye Kehinde, NA Iromin, Abubakar Siddiq Nafiu, and Deepak Punetha. 2018. Ultra-low power wireless sensor networks: Overview of applications, design requirements and challenges. *ABUAD Journal of Engineering Research and Development* (2018).

[22] Xiaoran Fan, Longfei Shangguan, Richard Howard, and et. al. 2020. Towards flexible wireless charging for medical implants using distributed antenna system. In *Proceedings of ACM MobiCom.*

[23] 6G Flagship. 2019. Key Drivers and Research Challenges for 6G Ubiquitous Wireless Intelligence. (2019).

[24] A Galisteo, D Juara, and D Giustiniano. 2019. Research in Visible Light Communication Systems with OpenVLC1.3. In *Proceedings of WF-IoT.*

[25] Yang Hong, Tesi Wu, and Lian-Kuan Chen. 2016. On the performance of adaptive MIMO-OFDM indoor visible light communications. *IEEE Photonics Technology Letters* (2016).

[26] Chin-Wei Hsu, Chi-Wai Chow, I-Cheng Lu, and et. al. 2016. High speed imaging 3× 3 MIMO phosphor white-light LED based visible light communication system. *IEEE Photonics Journal* (2016).

[27] JH Hwang, CH Hyoung, KH Park, and YT Kim. 2013. Energy harvesting from ambient electromagnetic wave using human body as antenna. *Electronics Letters* (2013).

[28] IEEE. 2018. IEEE Standard for Local and metropolitan area networks–Part 15.7: Short-Range Optical Wireless Communications. (2018).

[29] Cheonhoo Jeon, Jahyun Koo, Kyongsu Lee, Su-Kyoung Kim, Sei Kwang Hahn, Byungsub Kim, Hong-June Park, and Jae-Yoon Sim. 2019. A 143nW glucose-monitoring smart contact lens IC with a dual-mode transmitter for wireless-powered backscattering and RF-radiated transmission using a single loop antenna. In *IEEE Symposium on VLSI Circuits.*

[30] Seokhyeon Jeong, Jae-yoon Sim, David Blaauw, and Dennis Sylvester. 2013. 65nW CMOS temperature sensor for ultra-low power microsystems. In *Proceedings of IEEE Custom Integrated Circuits Conference.*

[31] DH Kwon, SH Yang, and SK Han. 2015. Modulation bandwidth enhancement of white-LED-based visible light communications using electrical equalizations. In *Broadband Access Communication Technologies IX.* SPIE.

[32] Xiaochen Lai, Quanli Liu, Xin Wei, and et. al. 2013. A survey of body sensor networks. *Sensors* (2013).

[33] Jiamin Li, Yilong Dong, Jeong Hoan Park, and et. al. 2021. Body-coupled power transmission and energy harvesting. *Nature Electronics* (2021).

[34] Qiang Li and Hao Liu. 2020. Analysis of Performance Parameters of Wearable Antenna Working near Human Body. In *Proceedings of IEEE ITAIC.*

[35] Yichen Li, Tianxing Li, Ruchir A Patel, and et. al. 2018. Self-powered gesture recognition with ambient light. In *Proceedings of ACM UIST.*

[36] Jie Lian and Maïté Brandt-Pearce. 2017. Multiuser MIMO indoor visible light communication system using spatial multiplexing. *Journal of Lightwave Technology* (2017).

[37] Jingna Mao and Zhiwei Zhang. 2020. Investigation on the Human Body as A Monopole Antenna for Energy Harvesting. In *Proceedings of IEEE EMBC.*

[38] Jingna Mao, Jian Zhao, Huazhong Yang, and et. al. 2017. Using human body as a monopole antenna for energy harvesting from ambient electromagnetic energy. In *Proceedings of IEEE BioCAS.*

[39] Noor Mohammed, Rui Wang, Robert W Jackson, and et. al. 2021. ShaZam: Charge-Free Wearable Devices via Intra-Body Power Transfer from Everyday Objects. *In Proceedings of ACM IMWUT* (2021).

[40] Dominic C O'brien, Lubin Zeng, Hoa Le-Minh, Grahame Faulkner, Joachim W Walewski, and Sebastian Randel. 2008. Visible light communications: Challenges and possibilities. In *Proceedings of the IEEE International Symposium on Personal, Indoor and Mobile Radio Communications.*

[41] Gaofeng Pan, Jia Ye, and Zhiguo Ding. 2017. Secure hybrid VLC-RF systems with light energy harvesting. *IEEE Transactions on Communications* (2017).

[42] Elias Rajaby and Sayed Masoud Sayedi. 2022. A structured review of sparse fast Fourier transform algorithms. *Digital Signal Processing* (2022).

[43] Tamer Rakia, Hong-Chuan Yang, Fayez Gebali, and et. al. 2016. Optimal design of dual-hop VLC/RF communication system with energy harvesting. *IEEE Communications Letters* (2016).

[44] Hanjun Ryu, Hong-Joon Yoon, and Sang-Woo Kim. 2019. Hybrid energy harvesters: toward sustainable energy harvesting. *Advanced Materials* (2019).

[45] Harilaos G Sandalidis, Alexander Vavoulas, Theodoros A Tsiftsis, and et. al. 2017. Illumination, data transmission, and energy harvesting: the threefold advantage of VLC. *Applied Optics* (2017).

[46] Lixin Shi, Zachary Kabelac, Dina Katabi, and et. al. 2015. Wireless power hotspot that charges all of your devices. In *Proceedings of ACM MobiCom.*

[47] Yen Kheng Tan and Sanjib Kumar Panda. 2010. Energy harvesting from hybrid indoor ambient light and thermal energy sources for enhanced performance of wireless sensor nodes. *IEEE Transactions on Industrial Electronics* (2010).

[48] F. Tariq, M. Khandaker, K. Wong, M. Imran, M. Bennis, and et. al. 2020. A Speculative Study on 6G. *IEEE Wireless Communications* (2020).

[49] Dobroslav Tsonev, Stefan Videv, and Harald Haas. 2014. Li-Fi: towards all-optical networking. In *Broadband Access Communication Technologies VIII.* International Society for Optics and Photonics.

[50] Junlei Wang, Linfeng Geng, Lin Ding, and et. al. 2020. The state-of-the-art review on energy harvesting from flow-induced vibrations. *Applied Energy* 267 (2020).

[51] Marc S Wegmüller. 2007. *Intra-body communication for biomedical sensor networks.* Ph.D. Dissertation. ETH Zurich.

[52] Ashok Yadav, Vinod Kumar Singh, Akash Kumar Bhoi, and et. al. 2020. Wireless body area networks: UWB wearable textile antenna for telemedicine and mobile health systems. *Micromachines* (2020).

[53] Zhenyu Yan, Qun Song, Rui Tan, Yang Li, and Adams Wai Kin Kong. 2019. Towards touch-to-access device authentication using induced body electric potentials. In *Proceedings of ACM MobiCom.*

[54] Kou Yoshida, Pavlos P Manousiadis, Rui Bian, and et. al. 2020. 245 MHz bandwidth organic light-emitting diodes used in a gigabit optical wireless data link. *Nature Communications* (2020).

[55] Hengwei Yu, Mingyi Chen, Chundong Wu, and et. al. 2018. A batteryless and single-inductor DC-DC boost converter for thermoelectric energy harvesting application with 190mV cold-start voltage. In *Proceedings of IEEE ISCAS.*

[56] C Patrick Yue and S Simon Wong. 2000. Physical modeling of spiral inductors on silicon. *IEEE Transactions on electron devices* (2000).

[57] Pengyu Zhang, Mohammad Rostami, Pan Hu, and Deepak Ganesan. 2016. Enabling practical backscatter communication for on-body sensors. In *Proceedings of ACM SIGCOMM.*