Poster: Battery-free Visible Light Sensing

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ABSTRACT

We present our efforts to design the first Visible Light Sensing (VLS) system that consumes only tens of µWs of power to sense and communicate. Our system requires no modification to the existing light infrastructure and uses unmodulated ambient light as sensing medium. We achieve this by designing a sensing mechanism that uses solar cells to achieve sub-µWs of power consumption. Further, we devise an ultra-low power backscatter based transmission mechanism we call *Scatterlight* that transmits digital readings without incurring the processing and computation overhead of existing sensors. Based on these principles we build a preliminary prototype. Our initial results demonstrate its ability to sense and communicate three hand gestures at 20 µWs of power.

KEYWORDS

Battery-free; Backscatter; Ultra-low power; Visible light sensing

1 INTRODUCTION

Visible light is a ubiquitous medium that can illuminate spaces or objects through low-cost fluorescent bulbs, light emitting diodes (LEDs) or natural light. Further, visible light can be sensed using simple and low-cost photodiodes or solar cells which requires minimal processing effort at the sensing device. Thus, visible light offers a significant advantage for sensing applications over mediums such as radio frequency (RF) signals which require complex processing and radios operating on licensed spectrum. However, despite the clear advantages there have only been limited deployments of visible light sensing (VLS) systems.

There are two main reasons for the lack of pervasive deployment of VLS systems: First, existing VLS system fail to take advantage of the ubiquitious nature of visible light. These systems combine visible light communication (VLC) together with sensing which requires retrofitting of the luminaries with specialized modulating circuits [3, 4]. This significantly increases the cost and the complexity of deployment. Second, these systems employ conventional light sensing mechanisms to sense changes in ambient light conditions [1, 3, 4]. Such mechanisms employ sensors with components that negatively affect pervasive deployment, as we discuss next.

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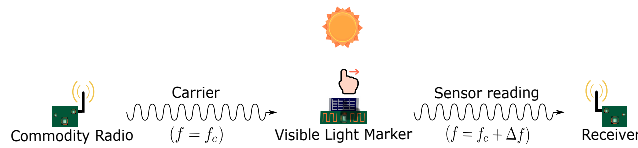

Figure 1: *Shadow sensing at* µW*s of power.* We can detect and communicate shadow events by reflecting RF signals at a peak power consumption of 20 µWs.

Conventional light sensing mechanisms amplify the signals from photodiodes using transimpedance amplifiers (TIA), sample them using analog to digital converters (ADC), and process them using computational blocks involving microcontrollers (MCU) or FPGAs. Further, the sampled values are communicated using traditional RF radios or external cables [3, 4]. This approach suffers from two main problems: *First*, it consumes significant power (mWs) and requires sensors that are battery-powered or powered through other external sources. *Second*, this approach increases the deployment cost due to increased complexity and cost of components.

We present our vision to design simple and ultra-low cost and power light sensors with the ability to sense changes in ambient light. Such sensors can operate on small amounts of energy harvested from ambient light or other harvesting sources, and transform any well-lit surface to a sensing medium. Their low cost enables deployment at a wide scale. Hence, such sensors could make VLS systems pervasive. To enable our vision, we use unmodulated light to sense shadows by building on recent systems [3, 4].

We introduce the first VLS system that can sense changes in unmodulated ambient light by tracking shadows at a power of 0.5 µWs and can communicate these events at peak power of 20 µWs. To achieve this, we make two key contributions over existing state-of-the-art systems [3, 4]: *First*, we design a mechanism that couples solar cells to a thresholding circuit to consume sub-µWs of power to sense shadow events. *Second*, we devise a mechanism we call *Scatterlight* that *offloads processing* from sensors to powerful end-devices using RF backscatter without involving energy-expensive computational blocks. This enables ultra-low power and inexpensive sensors, which we call visible light markers (VLMs).

2 DESIGN AND IMPLEMENTATION

The fundamental operation of our system is to detect and transmit changes in ambient light while consuming µWs in order to identify hand gestures. Towards this end, our system performs a series of steps: We first generate a carrier signal at a frequency of 868 MHz, and of strength 24 dBm using a TI CC1310 transceiver. Next, the VLM senses and backscatters a carrier signal to communicate the shadow events. The VLM leverages a solar cell to harvest

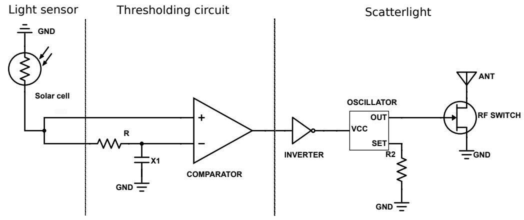

Figure 2: *Visible light marker schematic.* VLM avoids the use of energy expensive parts and local processing. VLM digitise and communicate shadow events at a power of 20 µW.

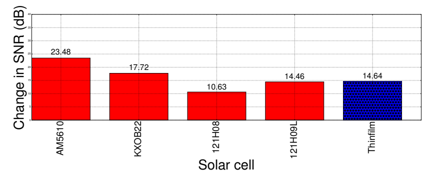

Figure 3: *Sensing using a solar cell.* A shadow cast on a solar cell causes a significant change in the SNR.

energy for its operation and to sense shadow events. The analog changes from the solar cell are digitised by an ultra-low power thresholding circuit, from which the output digital signals are mirrored onto backscattered signals by the *Scatterlight* mechanism. Finally, we receive *Scatterlight* transmissions from the VLM at the end-devices. To receive transmissions, we sample the RSSI at the transmit frequency of the VLM. As an end-device, we leverage a CC1310 transceiver.

2.1 Visible Light Marker

Solar cells as light sensors. Existing VLC-based systems commonly employ photodiodes to sense rapid changes in visible light [3, 4]. The photodiodes are coupled with a TIA to amplify the signal to a level required for further processing. The use of a TIA, however, increases the power consumption to mWs, which makes it difficult to operate on harvested energy.

To decrease the power consumption for visible-light sensing to µWs which is necessary for battery-free operation, we take advantage of solar cells to achieve the necessary amplification without energy-expensive amplifiers. Similar to photodiodes, solar cells transform variations in ambient light caused by, e.g., a shadow to a change in the electrical signal. Solar cells have been recently used to enable high-speed VLC using energy-hungry ADCs [8]. To the best of our knowledge, solar cells have not been explored for VLS.

Selecting solar cell for sensing. We evaluate six different commercial solar cells of different characteristics to select the one that is most responsive to sensing a shadow. We place a solar cell on the floor, and cast a shadow on it. We track its analog output using a logic analyser. We perform the experiment three times for each solar cell. Figure 4 demonstrates that all six solar cells observe a significant change (> 10 dB) in the signal-to-noise ratio (SNR) which confirms that solar cells can be used for passive sensing. Among the best performing solar cells, the thinfilm solar cell offers the highest short-circuit current which improves energy harvesting performance. Thus, we select the thin film (USD 4) solar cell.

Digitising at µWs of power. On existing sensing systems, processing the analog signals and converting them to the digital domain contributes significantly to the high energy consumption. Existing VLS systems use energy expensive ADCs [3, 4] to achieve this. We employ a thresholding circuit in place of commonly employed ADCs to convert changes in analog signals to binary values. A thresholding circuit, as shown in Figure 2 consists of a comparator and a low pass filter (LPF) composed of a resistor (R) and a capacitor (X1). Thresholding circuits are commonly employed in backscatter systems [5]. However, to the best of our knowledge, we are the *first* to use a thresholding circuit with a solar cell to achieve 0.5 µWs of power for VLS systems.

Scatterlight. A key bottleneck on existing sensors is the high energy consumption for the computational blocks involved [6, 9]. For example, existing VLS systems leverage platforms such as an Arduino to preprocess light samples, and transfer these to an end-device such as a workstation [3, 4]. We eliminate this overhead by building on the observation by Zhang et al. [9] that processing is significantly more energy expensive than backscatter transmissions. We devise a mechanism we call *Scatterlight* that causes changes in backscattered signals similar to the digital signals from the sensor without using energy-expensive computational blocks such as FPGAs or MCUs. We face two main challenges to realise this concept: *First*, the carrier adds significant interference to the weak backscatter signals. *Second*, we have to modulate the carrier signal with shadow events without using computational blocks. Next, we describe how we implement the *Scatterlight* mechanism.

We solve the first challenge by building on recent systems [2, 10] that keep the backscattered and the carrier signal at separate frequencies: If the ambient RF signal is present at a center frequency f_c, while the VLM backscatters at a frequency Δf, the backscattered signal appears at an offset Δf away from f_c. This displacement reduces interference from the carrier [2, 7, 10], and allows the receiver to detect backscattered signals. However, a crucial question is the choice of Δf, which is transceiver dependent. In this paper, we employ a transceiver that requires a Δf of 100 kHz.

To overcome the second challenge, we observe that a commodity radio transceiver enables fast RSSI sampling to determine the energy levels, e.g., due to the presence of backscatter transmissions [10]. If we can backscatter for the duration of the shadow event, the receiver by observing backscatter signals in the RSSI samples can detect the presence and the duration of the shadow event. We implement *Scatterlight* and achieve the above capability, by building on the fact that a digital signal from the thresholding circuit can directly control a backscatter switch, thus modulating the carrier with the information of the shadow event without requiring computational blocks. However, the key challenge with such a design is that backscatter signals are at the same frequency as the carrier signal which causes severe self-interference [6]. To overcome these challenges, as we illustrate in Figure 2, we instead control an ultra-low power oscillator (LTC 6906, USD 1.5) through the thresholding circuit. The oscillator controls the backscatter switch (NXP BFT25A, USD 0.2). We configure the oscillator to a frequency larger than Δf required to mitigate self-interference. Hence, when there is a shadow event, the thresholding circuit enables the oscillator to generate a backscatter signal at a frequency Δf from the center frequency f_c of the carrier signal.

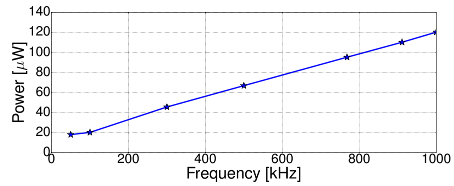

Figure 4: *Power consumption of VLM at* 2 V. At a 100 kHz frequency for transmission, the VLM consumes 20 µWs.

Table 1: Power consumption breakdown of VLM at 2 V

Module	Power consumption
Solar cell	0
Thresholding circuit	0.5 µW
Scatterlight (100 kHz - 1 MHz)	19.5 µW - 120 µW

Scatterlight is similar to battery-free cellphones [6] in that it eliminates computational blocks. *Scatterlight* significantly improves the design presented by Talla et al. [6]. Their battery-free cellphones suffer severe self-interference since they backscatter on the same frequency as the carrier signal which requires extensive processing on expensive SDRs. On the other hand, *Scatterlight* frequency-shifts the backscatter transmissions away without requiring computational blocks which reduces self-interference and enables the use of inexpensive radios to receive the backscattered signals.

3 RESULTS

Experiment setup. We evaluate our system indoors under office lights which were 200 lx; a level much lower than typical indoor illumination. As an energy harvester, we use the TI BQ25570 because it can operate at very low input voltages. We use a capacitor of size 22 µF that is comparable to other energy harvesting platforms such as CRFIDs. We use a thin film solar cell for both sensing and harvesting. At the VLM, we keep track of the analog signal from the solar cell, and the output of the thresholding circuit.

Power consumption. To measure the power consumption, we first connect the VLM in series with a Fluke multimeter, then we vary the oscillator frequency. As the power consumption increases with voltage [10], we keep the voltage to the lowest level required to operate all the modules, which we found to be 2 V.

Table 1 demonstrates the power breakdown of the VLM. The thresholding circuit together with the solar cell consumes 0.5 µW of power to sense and digitise shadow events. In the presence of a shadow, the VLM enables the Scatterlight mechanism to communicate the shadow event, which increases the overall power consumption. Figure 4 shows that Scatterlight, when enabled, consumes power proportional to the backscatter frequency. The power consumption of Scatterlight varies between 19.5 µW to 120 µW when backscattering at frequencies between 100 kHz to 1 MHz. The energy harvested by the solar cell we employ is sufficient to power the VLM, even in darker light conditions (100 lx). Further, at a backscatter frequency of 100 kHz, the ultra-low-power nature of the VLM allows it to be operated on harvested energy from photodiodes [6].

Sensing and communicating gestures. We investigate the ability of our system to detect hand gestures. In this preliminary work, we focus on three gestures: swipe, two taps and four taps, which we illustrate in Figure 5. We perform the experiment indoors, and

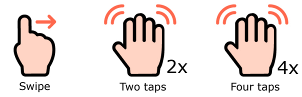

Figure 5: *Supported hand gestures.* We support three hand gestures: Swipe is represented by a single and brief hand movement, Two and four taps are represented by fixed number of slower palm movements.

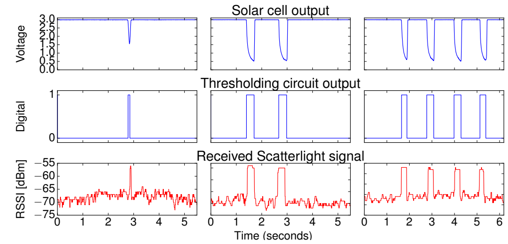

Figure 6: *Sensing hand gestures.* We detect three hand gestures (Swipe, Two taps, Four taps) at 20 µWs of power. The top two rows shows output at the VLM, the bottom row shows received signal at the end-device.

locate the carrier generator approx. 20 m from the VLM. The carrier generator is not in line-of-sight. We place the VLM at a distance of 1 m from the receiver, a typical distance for transmissions from smart clothes to a wearable device.

To conduct the experiment, we perform hand gestures over the VLM's solar cell. We track the digital and analog signal from the VLM, and also sample the RSSI at the RF receiver at an interval of 10 ms. Figure 6 shows the result of the experiment. The figure shows that each gesture causes unique patterns in the ambient light, as also observed by Kaholokula et al. [1]. However, unlike their design we use our energy efficient thresholding circuit to digitise shadow events, and communicate them at µWs of power. Figure 6 shows the distinct patterns caused by the gestures in the received RSSI samples at the CC1310 RF receiver.

4 ACKNOWLEDGEMENTS

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