Enabling the Next Generation of Wireless Sensors

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ABSTRACT

In this early-stage work, we propose various solutions to enable the next generation of wireless sensors. Our vision is to introduce battery-free wireless sensors that can be deployed ubiquitously. Such sensors would have the ability to both infer the physical environment, and communicate the sensed information wirelessly. In particular, we explore the emerging research directions of ambient and analog RF backscatter for communication, and visible light for sensing. We combine these concepts with energy harvesting to achieve self-powered operation. Furthermore, we introduce novel mechanisms that eliminate sensor-local computational blocks, and instead couple sensors directly to ultra-low power communication modules to transmit sensor information. Our initial results show that we are able to achieve operation of both sensing and communication at a few microwatts of power. Moreover, we can maintain a sufficiently high sensing resolution to enable novel battery-free applications such as hand gesture sensing and intrusion detection.

KEYWORDS

Ubiquitous wireless sensors; Battery-free sensing; RF backscatter

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1 INTRODUCTION

As a vast number of wireless sensors are emerging and are being deployed, we find ourselves increasingly surrounded by radio-frequency (RF) signals. Recent work has provided us with a new mechanism for communication, which enables wireless transmissions by reflecting ambient RF signals instead of generating them from on-board active radios [22, 28]. This novel way of communicating is referred to as *backscatter communication*, and enables wireless transmissions at orders of magnitude lower power consumption as compared to conventional radios [8, 13].

Moreover, sensors are being employed in unique ways, taking minimal energy consumption in mind, by mitigating or bypassing the power-hungry computational overhead that is commonly associated with most existing sensing devices. Prior work leverage mechanisms to optimize for energy-efficiency by drastically reducing the computational costs of microcontrollers or FPGAs when performing sensor-local processing tasks [20, 29]. Further, more recent efforts devise novel hardware mechanisms which take advantage of the raw sensing information by encoding them directly on backscatter transmissions, thus avoiding computational blocks entirely [19, 23]. The key idea behind these mechanisms is that, by coupling the sensor directly to the communication mechanism, the power consumption can be significantly reduced to microwatts of power. In turn, the transmitted raw sensor readings can be received by a powerful edge-device which performs all the heavier computational tasks. As an example, the edge-device can process the incoming sensor readings to infer physical activity in the surrounding environment [14]. Figure 1 demonstrates such a scenario.

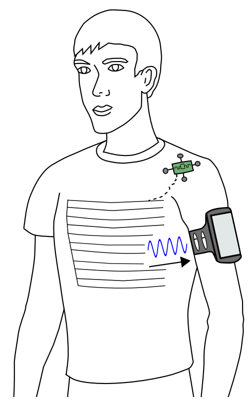

Figure 1: *Next generation wireless sensor.* In this example scenario, a battery-free wireless sensor (green) detects and communicates sensor readings. The raw sensor information is encoded on reflected FM signals (through the antenna embedded in the shirt), and received by a smartphone device which performs heavier processing tasks and employs an algorithm to classify the sensed event.

Furthermore, when coupling ultra-low power wireless sensors with energy-harvesting mechanisms, the potential results are self-powered devices that are able to both sense and communicate without batteries [12, 19]. This allows the devices to live on minuscule energy which is directly harvested from the environment, by using harvested energy to charge small on-board capacitors. These capacitors can then power the devices long enough to achieve the desired functionality, which enables battery-free operation. An advantage of battery-free devices is that they do not require the maintenance and cost overhead that comes from periodically replacing batteries, and allows these devices to be deployed in hard to reach places, such as in concrete or within walls. Thus, by eliminating batteries, it introduces more cost-effective and environmentally sustainable ways to deploy and maintain wireless sensors.

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Research direction. Simple, and inexpensive battery-free sensors that can infer the physical environment and communicate this information wirelessly by reflecting incident ambient signals. These sensors should be self-powered by harvesting energy from the environment. We imagine a future where such sensors are deployed ubiquitously, and can monitor and communicate various properties of the environment, including significant changes in light caused by shadows, temperature, human presence due to changes in RF signals, and so on. Furthermore, they could be designed as flexible and form factor sensors that could be used as part of wearable devices, or attached on surfaces to monitor surrounding properties. Their battery-free operation gives them a potential to operate for decades, and can be embedded in hard to reach places or in common objects such as household utilities or to monitor the quality of food. However, enabling ubiquitous and battery-free wireless sensing requires novel mechanisms that push the limits of performing sensing and communication to microwatts of power. We describe how we can accomplish these feats in the following sections.

2 BACKGROUND AND RELATED WORK

In this section, we explain how we build on recent work in key related areas to realize our vision of enabling the next generation of wireless sensors.

Backscatter communication. Past efforts have demonstrated the potential use of backscatter techniques for deployment in real-world scenarios, by employing mechanisms to reflect incident wireless signals from common technologies, such as FM [24], Bluetooth/Zigbee [5], WiFi [7], and LoRa [22]. However, existing mechanisms backscatter at the same frequency as the incident carrier signal, hence causing self-interference which severely degrades the quality of the communication link [1]. We overcome this issue by employing a mechanism to frequency-shift the backscattered signal away from the incident carrier.

Analog backscatter. Recent advances in backscatter communication leverage *analog backscatter*, which are novel techniques to avoid computational blocks and instead communicate raw sensor information at tens of microwatts of power [4, 14, 20]. The fundamental idea behind this technique is to utilize the analog sensor output as a variable to directly dictate the backscatter transmissions, i.e, by modifying a characteristic of the wireless signal, such as its frequency or the rate of transmissions according to the analog signal from the sensor. We make use of this concept in the design of our sensors to map analog sensor readings to frequency shifted backscatter signals.

Processing overhead. State-of-the-art sensing systems often employ energy-expensive analog-to-digital converters (ADCs) to perform digitization, and power intensive computational blocks such as on-board microcontrollers (MCUs) or FPGAs to perform processing tasks [6, 9, 11]. To overcome the overhead of sensor-local processing, we embrace Zhang et al.'s observation that local processing is significantly more energy-expensive as compared to backscatter communication [29]. Prior work have avoided computational blocks to enable battery-free applications ranging from cellphones [19] to HD cameras [14]. Thus, we argue, that sensor-local processing is a key bottleneck that has to be addressed to achieve ultra-low power consumption at the sensor.

Visible light sensing. One emerging direction that has attracted significant interest in recent years is visible light sensing (VLS). Recent efforts have employed light sensing to enable hand gesture recognition by tracking shadows cast from hand gestures under unmodulated light [11, 12, 23]. We build on such systems to imagine scenarios where users can interact with devices in the environment by casting shadows over light sensors.

However, state-of-the-art light sensing systems employ energy-expensive mechanisms for sensing changes in light levels, which makes it a particular challenge for sustainable deployment. We overcome this issue in the design of our light sensing systems by eliminating the power hungry amplifier components (>mW), such as transimpedance amplifiers (TIAs), which are commonly used with photodiodes in light sensing systems [9, 10]. Furthermore, we can replace conventionally used photodiodes with inexpensive thinfilm solar cells. Solar cells are passive components that are commonly used to harvest energy to power electronic systems. We have previously demonstrated that solar cells can also be used for sensing [23]. Thus, they are well suited to battery-free systems since they can both harvest energy and sense changes in light.

Radio tomographic imaging. Another direction we build on to enable ubiquitous wireless sensing is radio tomographic imaging (RTI). The principle of RTI is to perform localization by observing attenuation in RF signals caused by moving objects that obstruct wireless links. However, state-of-the-art RTI systems rely on energy-expensive radio transceivers for their operation, and are thus forced to operate on batteries or by mains power [15, 26, 27]. We overcome this problems by leveraging passive components to sense variations in RF signals, and analog backscatter to communicate these changes wirelessly. Hence, we enable a battery-free RTI system. This also allows for self-powered operation by harvesting energy from ambient sources.

3 PRIOR CONTRIBUTIONS

In this section, we present an overview of our prior contributions. This section consists of two parts: The first part introduces our technical contributions, which are the mechanisms we have devised to enable battery-free wireless sensing. The second part introduces various applications we can enable using our mechanisms.

3.1 Mechanisms

First, we introduce an ultra-low power mechanism to encode light sensor readings on backscatter transmissions, which we call *Scatterlight*. Next, we introduce our analog backscatter mechanism, which encodes raw sensor information on backscatter transmissions at tens of microwatts of power. Finally, we introduce *Spreadscatter*; an ultra-low power mechanism that improves the reliability of reception by spreading backscatter signals across the spectrum.

Scatterlight. In our prior work, we leverage frequency shifted (FS) backscatter [30] to improve upon existing backscatter mechanisms by avoiding harmful self-interference from incident carrier signals. Figure 2 shows the operation of FS backscatter. In this particular scenario, a carrier signal appears at a frequency f_c incident to the backscatter tag. Next, the tag reflects the incident signal and frequency shifts it by Δf. As a result, the backscattered signal appears at frequency $\Delta f + f_c$. Finally, a receiver tuned to this

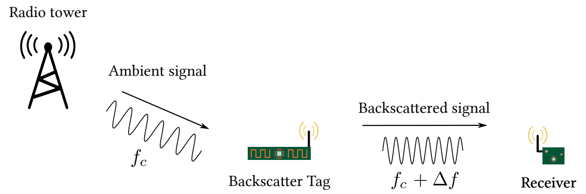


Figure 2: *Ambient FS backscatter.* To avoid self-interference from the carrier, the backscatter tag reflects the incident ambient signal at a frequency shift of Δf.

frequency can observe the backscatter transmissions. Specifically, the process of frequency shifting can be accomplished by using a low-power oscillator to control the switching mechanism of the backscatter antenna. Thus, the oscillator both modulates the carrier and frequency shifts it by taking advantage of the spectral mixing property of backscatter transmissions [22].

We demonstrate the feasibility of FS backscatter for sensing systems by devising a novel light sensing mechanism called *Scatterlight* [23]. The Scatterlight mechanism encodes digitized light sensor information, for instance, from photodiodes or solar cells, on frequency-shifted carriers. The Scatterlight mechanism avoids energy-expensive blocks such as ADCs, and instead employs a *thresholding circuit* to perform digitization of light sensor readings at sub-μW of power. The thresholding circuit consists of a comparator circuit and a low-pass filter to adjust the rate of digitization. We tune the thresholding circuit to detect at a rate of few milliseconds, which is sufficient for sensing shadows from moving objects. Next, we utilize the pulses from digitized sensor readings to modulate FS backscatter transmissions by on-off keying, thus eliminating energy-expensive computational block such as MCUs or FPGAs. Finally, a simple and low-cost receiver can detect the backscatter signals by observing changes in the received signal strength indicator (RSSI). We demonstrate that the Scatterlight mechanism consumes tens of microwatts of power for operation, which is orders of magnitude lower power consumption compared to state-of-the-art light sensing systems and mechanisms [9, 11].

Spreadscatter. One significant problem with FS backscatter is that it is susceptible to reliability issues due to wireless interference from concurrent backscatter transmissions. This effect is particularly severe when taking into consideration a ubiquitous deployment of backscattering devices. Thus, in prior work, we introduce *Spreadscatter*, which improves the reliability of receiving backscatter transmissions by spreading the signals across the spectrum [18]. In our design of the spreadscatter mechanism, we build on the concept of MIMO to improve reliability by receiver diversity [22, 30]. The general idea of Spreadscatter is to vary the frequency of the backscatter transmissions at a much higher rate than the rate at which a receiver samples them. From the receivers perspective, the backscatter signals appear at multiple frequencies simultaneously. This allows for reception of the same backscattered signal using multiple receivers, which improves the reliability.

Analog backscatter. The Scatterlight mechanism is limited to only communicate binary information from light sensor readings, which is insufficient for sensing applications that require a higher granularity, such as light monitoring or fine-grained hand gesture detection. Thus, we present our effort to design a novel mechanism based on analog backscatter to significantly increase the sensing resolution while maintaining ultra-low power consumption for communication to allow for battery-free operation. We achieve ultra-low power consumption by designing our analog backscatter mechanism to avoid local processing and instead and map raw sensor readings onto FS backscatter transmissions. Internally, the mechanism avoids computational blocks by using a voltage controlled oscillator (VCO), which maps raw sensor readings to frequency shifts, i.e., $\Delta f(V)$, of the backscatter signal. Here, V represents the output analog voltage value of a given sensor. Thus, the frequency of the backscattered signal is represented as a function of the input analog signal.

We present our analog backscatter design in Figure 3. This particular design fits well with our vision for ubiquitous and battery-free wireless sensing, as it provides modular capability which allows it to be coupled to diverse types of sensors. For instance, we can design a battery-free light sensor that takes input from a tiny and inexpensive solar cell, which is a device that can serve as both a sensor and as an energy harvesting unit. In addition, we include a simple calibration stage consisting of a voltage divider with two resistor values (R1, R2). By altering these resistor values in the voltage divider, a user can define the frequency range of the VCO and in turn the frequency range of the backscatter transmissions.

However, the downside of our analog backscatter design as compared to the Scatterlight mechanism is that it requires a more complex receiver to perform FFT and decode the FS backscatter transmissions. We have previously demonstrated that we can use a complex receiver such as a software defined radio (SDR) to perform FFT operations and peak detection to extract the exact frequency components of the backscattered signals [16]. The purpose of detecting exact frequencies is that it enables the reconstruction of analog sensor information by finding a function that maps the received backscatter frequencies to the analog sensor readings.

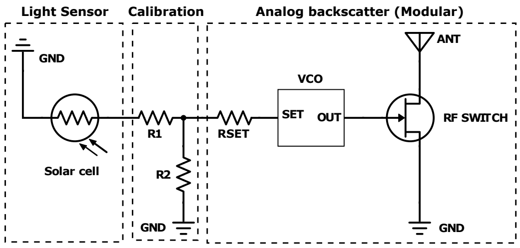
We demonstrate that our analog backscatter system can communicate raw sensor information at an average power level of 60 μW, where the power consumption of the system varies depending on the frequency of the oscillator (between 20 μW to 120 μW). We also demonstrate that we can reconstruct sensor information at the receiving SDR at a resolution of at least 6 bits. This resolution is comparable to a state-of-the-art analog backscatter design which was introduced concurrently with our effort [14].

3.2 Applications

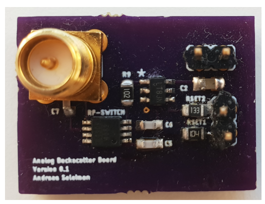
In this section, we present a few of our ongoing efforts to design applications based on our previously mentioned mechanisms.

Hand gesture sensing. We have in our recent efforts demonstrated that we can combine a light sensor in the form of a small and flexible thinfilm solar cell with backscatter communication to enable hand gesture sensing at tens of microwatts of power [23]. We define various hand gestures as unique shadow patterns which emerge in the perceived light sensor readings. For our hand gesture system, we have explored using both our Scatterlight and our analog backscatter designs to communicate hand gesture information.

With Scatterlight, we can achieve binary hand gesture detection, which is restricted to information regarding the duration of the shadow and the time difference between sensor events. With this



(a) Schematic design of battery-free light sensor



(b) Modular prototype

Figure 3: *The analog backscatter design.* It avoids computational blocks by directly mapping raw sensor readings to frequencies of the backscattered signal. Our prototype design (b) is modular in the sense that it can be coupled to an external sensor, such as a thinfilm solar cell to form a battery-free light sensing system, as shown by the schematic (a).

information, we can introduce simple hand gestures such as swiping or tapping motions, which are determined by brief hand movements over the light sensor or longer palm obstructions, respectively. With analog backscatter, we can identify more complex hand gestures (6 bits) such as pushing or pulling motions, which are defined by how the light intensity changes over time. This information can later be received, decoded and processed by more powerful edge-devices that can employ classification to infer the correct hand gesture [16].

Since the power consumption of our system is very low, we can enable battery-free operation even in low indoor lighting conditions (< 500 lx), by using a tiny solar cell to harvest energy and charge an on-board capacitor which can power the system for the duration of a sensing event. In other words, the solar cell serves dual purposes, by both sensing, and by harvesting energy to power the gesture sensing system. Moreover, a significant advantage of solar cells over photodiodes is that they do not require energy-expensive amplifiers such as TIAs, as they are optimized for energy yield in the visible light region. Thus, solar cells consume zero power for sensing.

Polymorphic light sensing. Many state-of-the-art light sensing systems use photodiodes which are sensitive to the main ambient light component (500 - 600 nm) [9, 21, 25]. However, this hinders their capability in scenarios where it is of interest to study individual components of the light spectrum. A polymorphic light sensor is a sensor that can monitor different segments of the light spectrum, such as infrared (IR), ultraviolet (UV), blue, red, green, etc [17]. We propose the design of a battery-free polymorphic light sensor consisting of a series of photodiodes which monitor wavelengths of light that are of particular interest. These photodiodes could be coupled to amplifiers in low-gain settings to achieve a few microwatts of power for operation. Next, and as part of our future work, we will use analog backscatter to communicate each of the raw light sensor readings. Polymorphic light sensors could be useful in health care applications where it is of interest to monitor the combination of effects; blue light to sleep rhythm, ultraviolet to skin cancer, and infrared to eye damage.

Battery-free intrusion detection. Another emerging direction for battery-free wireless sensing is security. In our past work, we explored observing variations in RF signals to perform intrusion detection. We achieve this by observing significant amplitude variations caused in RF signals due to people moving between strategically placed communication links. This form of sensing is commonly referred to as Radio Tomographic Imaging (RTI). The way in which the link is obstructed gives rise to unique variations in ambient RF signals which manifest as a pattern of amplitude values at the receiver. The shape of these amplitude patterns can be extracted using a passive envelope detector [3]. We can use analog backscatter to map variations in sensed RF signals within the communication link to backscatter transmissions. These signals can later be received and decoded at another receiver to extract link obstruction information and perform further processing, for instance, to identify the presence of an intruder. We demonstrate that our RTI system consumes a peak power of 120 µW when combining a passive envelope detector with analog backscatter [4].

Monitoring food quality. Finally, we explore the interesting research direction which is to monitor the state of beverage or food by augmenting utensils with networking capabilities. We imagine the design of a flexible and sticker form factor sensor, which we call *flex sensor*. The flex sensor can be attached to an object to monitor essential properties such as the temperature of a cup [18], which provides information of the current state of a beverage. We can realize the design of a battery-free *flex sensor* by combining our Spreadscatter mechanism with a small and low-cost sensor such as a temperature sensor. Spreadscatter is particularly useful in this scenario, since it is common to find utensils located near each other. As an example, we can imagine an office environment where a multitude of coffee cups are present. The use of Spreadscatter enables all of these cups to be augmented with flex sensors to communicate temperature changes through heat radiated from the cups. Next, the temperature information from each cup can be reliably received by smartphones in the vicinity which notifies users of the current temperature of their respective cups.

Furthermore, we can build on past efforts and leverage changes in backscatter signals to monitor the quality and safety of food or beverage content [2]. We can also imagine that we utilize the present environment as a source for harvesting energy to charge tiny capacitors to power flex sensors. This could be by absorbing energy from changes in temperature, light, or from incident wireless signals, depending on the sensing medium.

Conclusively, we have from our ongoing contributions introduced mechanisms for ultra-low power sensing and communication. We have discussed how we can use our mechanisms to design novel battery-free wireless sensors, which we believe can fit in the vision of enabling the next generation of wireless sensors. Finally, we have introduced various applications that can make use of our proposed sensor designs.

4 FUTURE WORK

Realizing the goal of enabling inexpensive, and battery-free wireless sensors requires addressing several key challenges. Next, we explain a few of these challenges and trade-offs that we can address in our future work.

Improving data encoding. Considering the design choices that are necessary for operating at microwatts of power to enable battery-free operation, it becomes a difficult task to maintain a high resolution at the sensor when sensing events, while keeping minimal power consumption and data loss when transmitting the sensor information. As an example, the received signals from our analog backscatter mechanism can be reconstructed to form a 6-bit representation of the raw sensor information, which is similar to the state-of-the-art [14]. This resolution is sufficient to represent sensor events for many application scenarios, such as the hand gesture sensing scenario mentioned in the previous section. However, this may not be feasible when performing high-precision monitoring tasks which require higher levels of resolution; for instance, monitoring of exact temperature, pressure, or acceleration levels in the surrounding environment. Moreover, the transmitted signals from our analog backscatter mechanism occupy a significant bandwidth (900 kHz), as the range of backscatter signal frequencies is large (100 to 1 MHz), and vary in accord to the the sensor output as a result of frequency mapping through the voltage controlled oscillator. Thus, a direction for future work is to improve the resolution of analog backscatter while aiming to minimize this bandwidth.

One potential approach that we could utilize in future endeavors is to address this issue through a hybrid transmission approach. Specifically, this could work by supporting backscatter transmissions of analog sensor readings that are also mapped in the time-domain, i.e., by altering the rate of reflection of the backscatter antenna. We could achieve this through passive hardware mechanisms that control the switching mechanism, for instance, through a series of flip-flops which can queue bits. However, this would require some form of on-board digitization mechanism. Luckily, there are ways to perform passive digitization at ultra-low power; for instance, by using a network of comparators to digitize analog sensor readings when the sensor output falls below a predefined reference. This reference could be defined as an average of the present environment.

Supporting concurrent transmissions. When imagining a scenario where battery-free sensors are deployed pervasively, an important problem to solve is to support multiple battery-free devices sharing the same wireless spectrum. This becomes increasingly difficult since the sensors have low complexity due to unavailable computational blocks and lack of active components.

However, one method that we can build on to address such a challenge is to introduce a transceiver edge-device that can transmit wake-up calls to multiple devices in a network, in which, sensors are either queued in time or transmit information at different frequencies. Sensor-level hardware mechanisms can be employed to assign unique identifiers that are hard-coded in each device, and can be transmitted by modulating through on-off keying of backscatter transmissions on separate time slots, which is similar to a time-division-multiple-access (TDMA) approach.

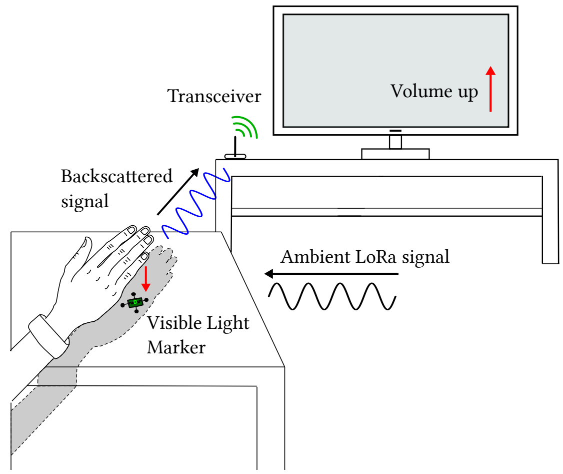


Figure 4: ***Controlling the smart home through hand gestures.*** **The battery-free wireless sensor detects shadows from hand gestures and communicates this information by backscattering ambient LoRa signals.**

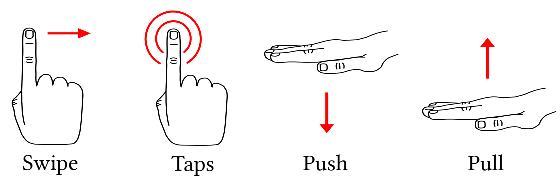


Figure 5: ***Examples of hand gestures that can be supported using our proposed sensor to control devices in a smart home environment.***

Gesture control in smart homes. We imagine an application scenario like in Figure 4, where a user can control devices in smart homes by performing hand gestures over a self-powered wireless light sensor. In this particular scenario, the sensor communicates hand gesture information by backscattering incident LoRa signals. We can also imagine replacing LoRa by other types of ambient RF signals such as FM [24], Bluetooth [5], or WiFi transmissions [7].

The hand gestures could control household appliances in various ways. We could define gestures like in figure 5; a swipe gesture can be used to switch between tasks, taps could be used as ways to play, pause, or repeat tasks. A push could be used to increase the intensity or volume, and a pull could do the reverse.

Other methods of sensing. The vision of enabling ubiquitous battery-free sensing includes many unexplored ways of sensing. We aim to explore various sensing mediums and inexpensive sensors that are feasible for ultra-low power operation. In principle, any mechanism of sensing with analog output such as infrared, piezoelectric (touch), and vibration, can be utilized for sensing applications. For instance, we could explore pressure sensing through low cost piezoelectric sensors. When coupled with mechanisms to backscatter raw temperature readings, it can enable novel applications such as battery-free touch sensing by a network of pressure sensors. One example of such an application is a battery-free wireless touchpad consisting of a network of piezoelectric sensors that can communicate complex gestures information through touch movements. This could be interesting for controlling devices or to enable authentication to unlock devices in smart homes.

5 CONCLUSION

In this paper, we have presented our efforts to realize the vision of enabling the next generation of wireless sensors. We devise novel mechanisms which avoid energy-expensive sensor-local processing blocks, and leverage RF backscatter to achieve battery-free sensing and wireless communication. Specifically, we introduced three ultra-low power mechanisms based on RF backscatter; one to communicate binary sensor information, one to improve the reliability of reception by performing backscatter communication across the wireless spectrum, and an analog backscatter mechanism to communicate raw sensor information. Furthermore, we make use of these mechanisms to introduce designs of various battery-free wireless sensors and their applications. In our future work, we discuss our aim to improve the resolution of analog backscatter by devising a novel data encoding mechanism. We also introduced a mechanism to support concurrent backscatter transmissions by queuing wireless sensors. Lastly, we present a scenario to enable gesture control in smart homes, and we discuss other sensing mechanisms which we can leverage for our future battery-free applications.

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