Demo: Towards Battery-free Radio Tomographic Imaging

Abdullah Hylamia
KTH Royal Institute of Technology
Stockholm, Sweden
hylamia@kth.se

Ambuj Varshney
Uppsala University
Uppsala, Sweden
ambuj.varshney@it.uu.se

Andreas Soleiman
Uppsala University
Uppsala, Sweden
andreas.soleiman@it.uu.se

Panagiotis Papadimitratos
KTH Royal Institute of Technology
Stockholm, Sweden
papadim@kth.se

Christian Rohner
Uppsala University
Uppsala, Sweden
christian.rohner@it.uu.se

Thiemo Voigt
Uppsala University and RISE SICS
Uppsala and Stockholm, Sweden
thiemo.voigt@ri.se

ABSTRACT

Radio Tomographic Imaging (RTI) enables novel radio frequency (RF) sensing applications such as intrusion detection systems by observing variations in radio links caused by human actions. RTI applications are, however, severely limited by the requirement to retrofit existing infrastructure with energy-expensive sensors. In this demonstration, we present our ongoing efforts to develop the first battery-free RTI system that operates on minuscule amounts of energy harvested from the ambient environment. Our system eliminates the energy-expensive components employed on state-of-the-art RTI systems achieving two orders of magnitude lower power consumption. Battery-free operation enables a sustainable deployment, as RTI sensors could be deployed for long periods of time with little maintenance effort. Our demonstration showcases an intrusion detection scenario enabled by our system.

CCS CONCEPTS

• **Computer systems organization → Sensors and actuators**; • **Hardware → Wireless devices**; • **Security and privacy →** *Intrusion detection systems*;

KEYWORDS

radio-tomographic-imaging, battery-free, backscatter

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1 INTRODUCTION

Recent years have seen significant progress in using radio frequency (RF) to enable novel sensing applications such as device free localization (DFL) [7], human vitals monitoring including breath and heart rate [3], and gesture recognition [1]. These systems are based on the concept that human actions cause variations in the ambient RF signals, which when tracked and processed by an RF receiver enables detection of human activity. This allows for applications such as fall detection for elderly, appliance control through gestures, and intrusion detection systems for surveillance.

Radio Tomographic imaging (RTI) has become a widely used method to enable passive RF sensing applications [3, 7, 8]. RTI builds on the concept that when an object obstructs an RF link in a wireless network, it attenuates the RF signals and thus impacts the link. Hence, by observing and processing the changes in all links across the network, an object can be localized with high accuracy [7]. Further, recent systems demonstrate the use of RTI to detect faint vital signs such as breath [3]. Over the past decade, RTI has enabled novel sensing applications, but has seen limited practical deployments due to a critical constraint; state-of-the-art RTI systems rely on energy-expensive RF sensing mechanisms which in turn requires mains- or battery-powered sensors. Battery-powered sensors negatively impact the sustainability of deployments as they need to be frequently replenished. They also prohibit applications scenarios that require sensors that are embedded in the infrastructure.

State-of-the-art RTI systems consume mWs of power due to the use of energy-expensive radio transceivers to observe attenuation in RF links [3, 7, 8]. Further, sensed changes in the RF signals are locally processed using power-hungry computational blocks such as FPGAs or MCUs [2, 6] before being transferred to more powerful end devices for additional processing. The use of conventional transceivers and computational blocks increases power consumption and forces the sensors to operate on batteries, which consequently induces high maintenance costs for RTI systems.

Contributions. We present a novel battery-free RTI system. Our system can operate on minuscule amounts of energy harvested from

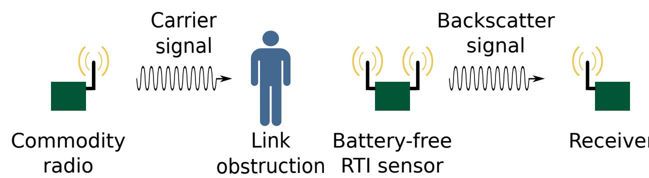

Figure 1: *Radio Tomographic Imaging at μWs of power* We can detect attenuation in radio frequency links due link intrusions and communicate them by reflecting ambient wireless signals at a peak power consumption of 120 μWs.

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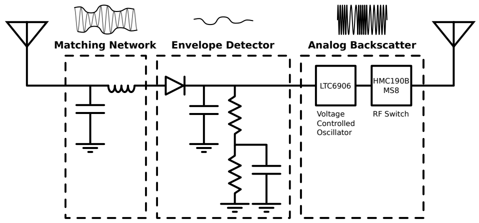

Figure 2: *Battery-free RTI sensor schematic.* Leveraging passive envelope detector and analog backscatter technique enables our battery-free RTI sensor to achieve a peak power consumption of 120 µW.

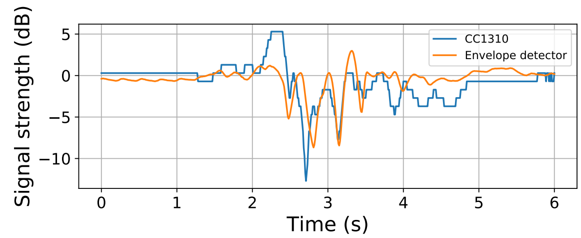

Figure 3: *Applicability of passive receiver for RTI.* A passive receiver detects variations in RF signals due to obstructions similar to an energy-expensive active receiver (CC1310).

ambient sources in the environment. To achieve ultra-low power consumption, we leverage design elements from backscatter communication. We reduce the power consumption required to sense attenuation in RF links by using envelope detectors, commonly used in RFID tags. Envelope detectors are built using passive components and consume no additional energy. Further, we eliminate the computational blocks from sensors [2, 6] to significantly reduce power consumption and support battery-free operation. This leads to the design of the system shown in Figure 1. In this demonstration, we present an intrusion detection scenario enabled by our system. We demonstrate the ability of the battery-free system to detect intrusions with high accuracy while consuming two orders of magnitude less power when compared to the state-of-the-art systems.

2 DESIGN AND IMPLEMENTATION

Our system works as follows: First, we generate a carrier signal using a software-defined radio (SDR). Next, at the battery-free RTI sensor, we use a passive envelope detector to observe changes in the carrier signal caused due to link intrusion. Without performing any local processing, we transmit these sensed changes in the carrier signal using an analog backscatter technique. The analog backscatter technique selectively absorbs or reflects ambient carrier signal encoding the variations observed in the RF links in the reflections while consuming tens of µWs. Finally, a powerful SDR, acting as a receiver, receives, reconstructs and processes the sensor readings to detect link crossing. We next describe the system in detail.

Ultra-low Power Sensing. State-of-the-art RTI systems employ energy-expensive (mWs) radio transceivers to observe attenuation in the RF signals caused by link obstructions [3, 7, 8]. The high power consumption makes the sensors reliant on batteries for their operations. We overcome the high power consumption required for sensing by leveraging passive receivers commonly employed in passive RFID tags or for ultra-low power gesture detection [1]. A passive receiver, as shown in Figure 2, consists of a matching network tuned to the frequency of the signal of interest, and a network composed of passive components, diode, capacitor and resistor to extract the amplitude of the incident signal. The passive receiver similar to energy-expensive receivers employed in state-of-the-art systems demonstrates a large variation in the signal strength when an object obstructs the RF link. The passive receiver does not consume any energy and can, additionally, be used to harvest energy to support the battery-free operation of the tag [4].

Communicating Without Processing. Backscatter by reflecting or absorbing ambient wireless signals enables wireless transmissions at orders of magnitude lower power consumption when compared to conventional radio technologies [5]. On the backscatter sensors, local processing through computational blocks is significantly more energy expensive when compared to wireless communication [9], and acts as a bottleneck to battery-free operations on the harvested energy. In our battery-free RTI sensor, we embrace the emerging research direction that eliminates computational blocks [2, 6], and transmits sensor readings using RF backscatter without performing any local processing. We use a technique we call analog backscatter that introduces changes in the backscatter signal frequency proportional to the amplitude observed at the passive receiver used for sensing in the battery-free RTI sensor.

Analog Backscatter. To enable analog backscatter, we employ a voltage controlled oscillator (VCO). The VCO can map changes in amplitude from the envelope detector to proportional changes in the backscatter frequency. Hence, a receiving device can infer the analog output of the envelope detector by determining the frequency offset between the backscatter signal and the carrier signal, which is equivalent to the output of the VCO. Mathematically, the analog backscatter mechanism can be formalized as follows: The backscatter signal appears at a frequency $f_b(V_i) = f_c \pm \Delta f(V_i)$ at the receiver, where V_i is the input analog voltage to the VCO at an observation i, f_c is the frequency of the carrier signal, and $\Delta f(V_i)$ is the frequency offset of the backscatter signal relative to the carrier signal. Next, the receiver reconstructs the output of the envelope detector by simply calculating the difference in frequency between an observation $i > 0$ and a reference observation $i = 0$, at which $f_b(V_i) - f_b(V_0) \propto V_i - V_0$.

Implementation. The battery-free RTI sensor consists of three modules: sensing, communication and power management. The power management module harvests energy from the incident carrier signal. It consists of a matching network connected to a TI BQ25570 ultra-low-power harvester that stores the harvested energy into a supercapacitor. The sensing module consists of a matching network together with an envelope detector. The matching network consists of an LC circuit together with a charge pump to improve signal voltages. The envelope detector outputs a voltage proportional to the received signal at the antenna. This voltage feeds into the communication module, which consists of the analog backscatter design presented earlier implemented using an LTC6906 low-power VCO. The output of the VCO controls an HMC190BMS8 RF switch that generates the backscatter transmissions.

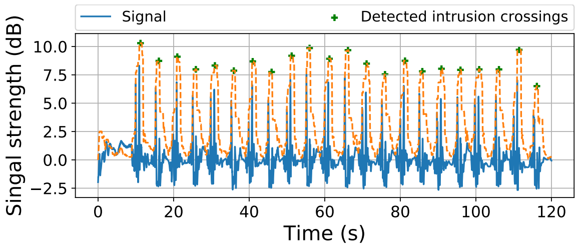

Figure 4: *Intrusion detection scenario* The Battery-free RTI sensor is able to detect all link crossing successfully.

3 EVALUATION

In this section, we first evaluate the suitability of the envelope detector for RTI applications. Next, we present an example scenario of intrusion detection that is enabled by our system.

Experiment Setup. We evaluate our system for the application scenario of intrusion detection. We create the sensing link by placing the battery-free RTI sensor at a distance of 3 m from an SDR. The SDR generates a signal at a frequency of 868 MHz. To receive the backscatter transmissions from the tag, we place another SDR at a distance of 1 m away from the battery-free RTI sensor. We generate a carrier signal of strength 16 dBm. We note that the distances are restricted by the strength of the carrier signal, and we can support larger distances with stronger carrier signal strength [5].

RTI using Passive Receiver. In this experiment, we evaluate the feasibility of the passive receiver for RTI applications. We compare the passive receiver with an active receiver (TI CC1310) to detect attenuation in RF links caused by the obstructions. We set up the two receivers next to each other, and study the signal strength observed by the two receivers. To probe signal strength on the CC1310 receiver, we collect received signal strength indicator (RSSI) samples. To measure the signal strength at the passive receiver, we observe the output voltage using a logic analyzer. We cross the RF link to cause attenuation. Figure 3 shows the result of the experiment. Both receivers demonstrate a large variation in the signal strength caused by the obstruction demonstrating their suitability for RTI. However, the passive receiver consumes three orders of magnitude less power for the operation which helps support battery-free operation.

Intrusion Detection System. Finally, we evaluate the ability of our entire system for intrusion detection. We set up an intrusion detection scenario, and cross the RF link a fixed number of times (22) at normal walking speed. The link crossings are separated by a time interval of 5 seconds. We repeat each experiment three times at different distances to the receiver. Figure 4 demonstrates the result of the experiment. We observe that our system was able to detect all the link crossing successfully.

4 INTRUSION DETECTION DEMONSTRATION

We demonstrate the system's capability to detect link intrusions when operating on harvested energy in the challenging environment of the conference venue. Figure 5 presents a pictorial overview of the system we demonstrate. For this particular scenario, we generate a carrier signal using an SDR to enable RF sensing and to deliver energy to the battery-free RTI sensor. Next, the battery-free RTI sensor harvests energy from the incident carrier signal, and in

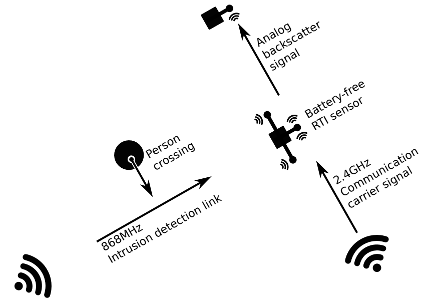

Figure 5: Intrusion detection demonstration scenario for the battery-free RTI system

presence of obstruction detects and transmits these changes to a receiving SDR device located a few meters away from the sensor. The receiver processes the intrusion detection signal and provides the link crossing information.

Participants will be able to move in the vicinity of the sensor and cross the intrusion detection link. When a participant crosses the link, they will be able to observe occurring variations in the received signal and the intrusion detection in real-time.

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