Enabling L3: Low Cost, Low Complexity and Low Power Radio Frequency Sensing using Tunnel Diodes

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ABSTRACT

The past decade has seen a great interest in developing radio frequency sensing technology and its applications. At a basic level, these systems operate by tracking changes in the wireless signal reflected from a physical object. These reflections contain a wealth of information about the object, such as its motion and material. However, existing radio frequency sensing solutions are constrained by the complexity of the deployment and their high power consumption. This is because these systems extract weak reflections in presence of a strong incident signal. This paper introduces a new radio frequency sensing modality that allows tracking of the incident signal and not reflections from the object. This allows us to simplify the receiver and algorithm design significantly. We design the system using tunnel diode oscillators to generate a high-frequency carrier signal at only tens of microwatts of power consumption. The critical contribution that we make is to show that the frequency of the tunnel diode oscillator is sensitive to the physical environment. As an example, we demonstrate that performing simple hand gestures near the tunnel diode oscillator causes notable changes to its frequency. Thus, the receiver tracks the frequency of the carrier signal generated by the tunnel diode oscillator, and not reflections from physical objects. It enables inferring of sensing information using a commodity receiver costing only a few USD. Our system enables radio frequency sensing at low cost, complexity and power.

CCS CONCEPTS

• **Hardware** → **Sensors and actuators**; **Wireless devices**; • **Human-centered computing** → *Systems and tools for interaction design*;

KEYWORDS

Wireless, Contact-free Sensing, Gesture Sensing, Internet of Things, Tunnel diodes

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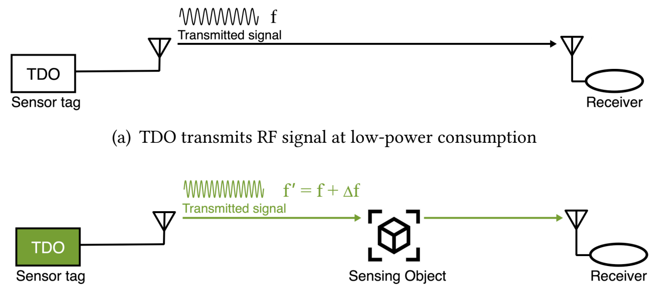

(a) TDO transmits RF signal at low-power consumption

(b) Physical objects causes changes the TDO resonant frequency

Figure 1: *Overview.* A tunnel diode oscillator generates a high-frequency carrier signal. Physical objects in the environment reflect this carrier signal. Next, the reflected signal reaches back to the tunnel diode oscillator, alters the resonant circuit, and changes the tunnel diode oscillator's frequency. An off-the-shelf radio receiver tracks the frequency of the carrier signal. These changes in the frequency of the carrier signal convey information about the physical object.

1 INTRODUCTION

Radio frequency (RF) technologies are ubiquitous in our lives and primarily used for communication. However, recent years have also seen a significant interest in using RF for sensing the ambient environment. As an example, RF sensing is used for applications ranging from sensing material of an object [3], human gesture and activity recognition [1, 4, 8] to vital sign monitoring [2]. These systems use similar principles as radar and sonar, relying on characteristics of the signal reflected by the physical object to determine properties such as motion, material and location. The object is therefore not instrumented, making it possible to perform contact-free sensing.

Despite the significant promise of RF sensing technologies and decades of research efforts, they have seen only limited traction. This constraint largely results from the high complexity and the cost of RF sensing systems. On the transmitter side, typically, they require a powerful RF transmitter, such as Wi-Fi devices [3, 8], sophisticated SDR platform [1, 2, 4], or other such specialized transmitters. Off-the-shelf Wi-Fi chipsets are designed for wireless communication, not sensing applications; re-purposing them adds significant complexity to the system. Moreover, software defined radios are specialized devices, that are both expensive and complex. They also consume a significant power (in the order of tens of milliwatts). As a result, continuous and long-term sensing is difficult, and these systems cannot be deployed for long periods.

On the receiver side, RF sensing systems are highly sophisticated. They employ a software-defined radio to track the signal reflected from a physical object. The receiver extracts and exploits different properties of the reflected signal, such as signal strength and phase [3], channel state information [8], and frequency doppler shifts [4]. The extraction of various signal properties also requires complex algorithms and mechanisms. As the reflected signal is significantly weaker than the incident signal, the receiver has to

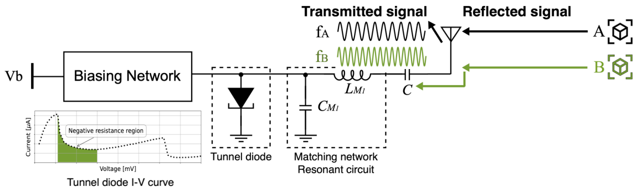

Figure 2: ***Schematic of the tunnel diode oscillator.*** **Coupling a tunnel diode with a resonant circuit allows the generation of a high-frequency carrier signal. The circuit consumes only tens of µWs of power consumption for the carrier signal generation. It is highly susceptible to the changes in the physical environment that affect the tunnel diode oscillator's resonant frequency.**

employ complex self-interference cancellation hardware. Due to the high complexity of transmitters and receivers and their high power consumption, RF sensing systems are not widely deployed.

We present a low cost, low power and low complexity RF sensing mechanism based on tunnel diodes. The proposed RF sensing system can sense minor changes in the physical environment while only consuming only tens of µW of power consumption for transmissions. Furthermore, it employs low-cost, commodity receivers for tracking the wireless signal. In designing this system, we make two contributions: *First*, we introduce a RF sensing mechanism based on a free-running tunnel diode oscillator (TDO). It allows us to generate a high frequency, RF carrier signal while consuming only tens of µWs of power consumption. Thus, we avoid the complex and power-consuming transmitters employed in existing RF sensing systems. *Second*, we avoid complex receiver designs and algorithms, as a TDO allows us to avoid measuring the properties of a reflected signal. Instead, the physical environment impacts the transmitted signal's frequency from the TDO. Thus, the receiver consists of a commodity radio receiver that only has to track the frequency of the incident signal from the TDO. We show a high-level diagram of the system in Figure 1. It consists of a tunnel diode-based tag and a commodity radio receiver to detect the frequency of the incident signal. This paper presents preliminary results demonstrating that the system can detect hand gestures.

2 DESIGN

2.1 Overview

The system has two primary components: a TDO and a receiver. We show the design of the system in Figure 1. This system works as follows: A weak single-tone carrier signal is emitted by the TDO, which is reflected by a physical object. Reflected signals then travel back to the TDO and alter its frequency. Finally, the receiver tracks the TDO's frequency, processes the drift in its frequency, and captures the sensing information. We next describe the system.

2.2 Tunnel Diode Oscillator as a Sensor

We design the TDO by building on Varshney et al. [5–7]. An overview of the circuit is presented in Figure 2. This circuit consists of a tunnel diode coupled to a resonant circuit. Tunnel diode and resonant circuit properties jointly determine oscillation frequency. Specifically, we use a tunnel diode (GE 3712) in the circuit. This tunnel diode demonstrates negative resistance characteristics at low voltages and currents [5], also shown in Figure 2. We tune the TDO's resonant circuit to generate a carrier signal in the 868 MHz frequency band. More importantly, benefiting from the low-power

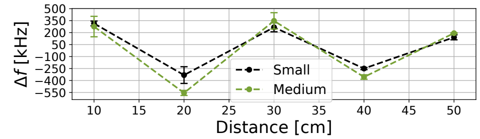

Figure 3: ***Impact of size of an object.*** **An object is placed at varying distances (10 cm to 50 cm) from the TDO. The frequency shifts are more pronounced when a larger object is closer to the tunnel diode oscillator. This is because of the larger magnitude of the reflected signal traversing back to the TDO.**

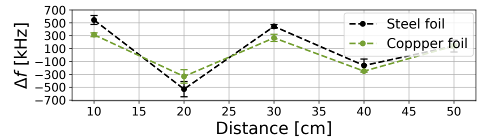

Figure 4: ***Impact of material.*** **The choice of material for physical object influences frequency drifts. This is because of the different permittivity of the material, thus resulting in different strengths of the reflected signal.**

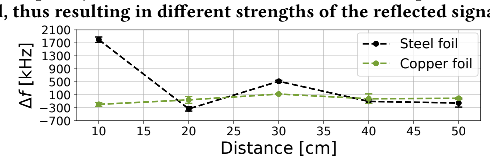

Figure 5: ***Indoor environment.*** **We vary the distance between the object and the TDO. We observe drifts in TDO frequency are smaller, as the sensing object is at greater distance from the TDO. It causes weaker reflection.**

nature of the tunnel diode, the TDO can generate a carrier signal of strength −19 dBm (12.5 µW) consuming sub-100 µWs of power.

Studies have demonstrated that the TDO is highly sensitive to even minor environmental changes. For example, the TDO resonant frequency may be affected by changes in temperature [6, 7], humidity [6, 7], or, as we demonstrate, by the motion of physical objects near the TDO. For communication systems, this is highly undesirable. As a result, recent systems rely on injection-locking mechanisms to lend stability to the TDO [6, 7]. However, this instability of the TDO is beneficial for designing RF sensing systems.

Our system operates in a free-running mode, i.e., the TDO is not injection locked to an external carrier signal. As a result, the TDO frequency is affected by the environment. We hypothesize that this is caused by reflected signals going back into the TDO circuit, altering the tunnel diode's impedance and thus resonant circuit, as shown in Figure 2. We observe that even with a weak reflection, the TDO's frequency may drift significantly. This drift in the frequency of TDO could convey information regarding the motion of an object, or it may indicate the permittivity of the material. As a result of this design, unlike existing sensing systems, the sensing information about the environment is not carried by the reflected signal strength or phase but by the TDO frequency. It allows us to perform sensing at low power consumption even when emitting weak signals. TDOs do not require power-hungry amplification stages. It also enables us to greatly simplify the receiver.

2.3 Receiver

Existing RF sensing systems utilize complex techniques to extract weak reflections from strong incident signals. As a result, it increases receiver complexity and cost, potentially hindering widespread adoption of these systems. Unlike these designs, our system tracks only the frequency of the incident carrier signal, not the reflected signal. We can use radio receiver to track the carrier signal generated by TDO. Receivers like these are widely used on

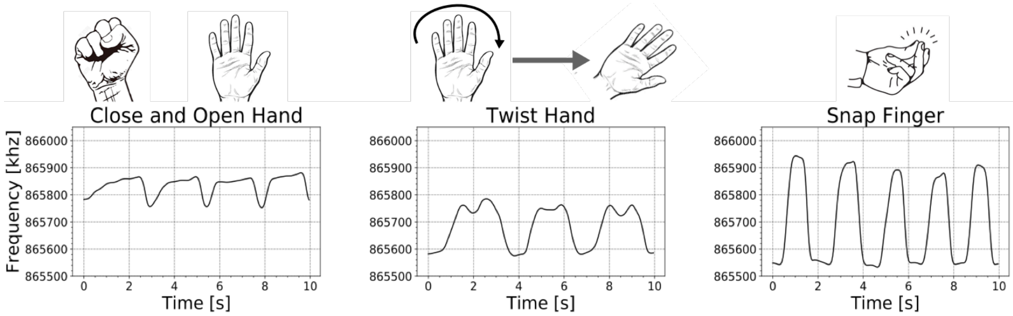

Figure 6: *Sensing hand gestures using a tunnel diode oscillator.* We perform three different hand gestures near the TDO. It causes unique drifts in the frequency of the TDO. We observe several distinguishable patterns in the frequency-time plot obtained from a RF spectrum analyser.

commodity wireless devices, costing only a few dollars each. Moreover, since the receiver only tracks the frequency of the carrier signal generated by the TDO, no complex algorithms or methods are utilized to infer sensing information.

2.4 Frequency as Sensing Metric

We present experiments to test and support hypothesis that objects in the environment causes drifts in the frequency of the TDO.

Experiment setup. We place a TDO on the desk. Next, we prepare cardboard boxes covered with different materials as sensing objects. We move them to marked positions whose distances range from 10 cm to 50 cm away from the TDO. An RF spectrum analyzer (Keithley 2810) placed 2 m away from the setup to monitor the frequency of the TDO. We perform three runs for each position. For each experiment, we first experiment without sensing object to find the baseline frequency of the TDO.

Impact of object size. We conduct the experiments in an anechoic chamber to eliminate the impact of the multipath effect and ambient RF noise. To estimate the baseline, in the absence of physical objects, the TDO tag emits a RF signal at f_{null}. Next, we place a small box at different distances from the TDO. We plot the frequency shift Δf ($\Delta f = f - f_{null}$) in Figure 3. The magnitude of frequency drift varies with the location of the sensing object. Next, we replace the box with a slightly larger box. We find that the magnitude of frequency drifts Δf also depends on the size of the box. We observe a higher frequency drift. This is because the amount of signal reflected is proportional to the size of the object; a stronger reflected signal leads to a larger amount of frequency shift $|\Delta f|$.

Impact of the material. Next, we investigate the impact of the material of the sensing object on the drift in the frequency of TDO. We use two boxes of similar sizes. We cover one of the boxes with copper foil and another with steel foil. We experiment in an anechoic chamber. We vary the distance between the TDO and the sensing object (box). Figure 4 shows the results. Compared to the copper material, a steel box's maximum Δf is higher. This is because steel has a higher reflective index and can reflect more RF signal, which results in more significant shifts in the signal frequency.

Indoor environment. As a final step, we experiment indoors. Our experiments take place in an office room with furniture around. According to Figure 5, we observe similar results as those obtained in anechoic chambers. We observe considerable drifts in frequency when the sensing object is made of steel. Furthermore, we noticed a more negligible drift when we kept the object far from the TDO. This is because of weaker reflections from the object, primarily due to the complex multipath environment of the room.

3 CASE STUDY

Our system can be used to enable many applications. We provide a preliminary result for an example of sensing hand gestures.

Experiment setup. The experiment takes place in an anechoic chamber. A user performs hand gestures near the TDO (0.5 m). To monitor the signal, the RF spectrum analyzer is placed 5 m from the setup. We capture the spectrum roughly every 25 ms, and record spectrum data for each gesture around 10 s. The subject periodically repeats the hand gesture. The TDO and receiver are equipped with 3 dBi omnidirectional antennas.

Hand gesture sensing. We perform the following gestures through one-hand; *close-open*, *twist* and *snap*. A *close-open* gesture stands for opening and closing the palm; *twist* represents opening the palm and rotating the wrist clockwise or counterclockwise, and a *snap* is a two-finger movement with the finger and thumb. We show the results in Figure 6. We find that each of these gestures leads to unique drifts in the frequency of the TDO, and we can observe and count these unique patterns in the frequency of the TDO.

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