Beyond Broadcasting: Revisiting FM Frequency-band for Providing Connectivity to Next Billion Devices

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ABSTRACT

Wireless communication remains a significant power-consuming task for embedded systems. When exacerbated by increased wireless contention, it results in frequent re-transmissions and, consequently, rapid battery depletion in wireless embedded systems. We introduce TunnelRadio, which is our ongoing effort to design low-power radio transmitters that achieve significant energy efficiency compared to commodity radio transceivers. TunnelRadio leverages tunnel diodes to design energy-efficient oscillators that generate a carrier signal and mix it with a baseband or audio signal, operating at microwatts of power consumption. Specifically, we design TunnelRadio to broadcast signals in the FM broadcasting band. In this work, we demonstrate that TunnelRadio can broadcast an audio signal up to a distance of 24 meters while consuming fewer than 150 microwatts. Additionally, we showcase the transmitter's capability to transmit complex baseband signals, such as those modulated with chirps. Our preliminary work aims to pave the way towards more widespread use of the FM band, thereby enabling large-scale deployments of wireless embedded systems.

CCS CONCEPTS

• **Hardware** → **Wireless devices**; *Wireless integrated network sensors*; • **Computer systems organization** → **Embedded and cyber-physical systems**.

KEYWORDS

Low-Power Communication, FM communication, Tunnel Diodes, Internet of Things (IoT)

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1 INTRODUCTION

The energy challenge poses a significant obstacle to the rapid growth of wireless embedded systems (WES). Wireless communication is a power-hungry task, consuming orders of magnitude more energy than sensing and processing tasks [12, 14, 16, 22, 24].

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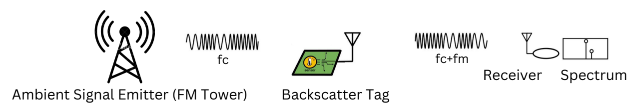
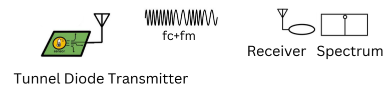


(a) FM-backscatter System



(b) TunnelRadio System

Figure 1: *Overview of the system.* TunnelRadio requires fewer than 150 microwatts of power consumption and can broadcast sensor data and audio streams within the FM band. These emissions can be received using commodity transceivers or pre-existing receivers in smartphones, cars, and other devices. TunnelRadio, if required, can operate solely on the energy harvested from the ambient environment. Unlike FM-backscatter systems, TunnelRadio does not require ambient FM broadcasts, as it generates signal locally.

This can lead to the rapid depletion of device batteries, necessitating frequent battery replacements throughout the deployment period. This issue escalates as WES are deployed at scale, with many of WES devices situated in hard-to-reach places [3, 27].

There has been considerable interest in energy-efficient transmitters and receivers to address the energy challenge associated with WES [9, 11, 12, 14, 17, 20–24]. Among the recent advances, the most energy-efficient transmitters employ a backscatter mechanism. By reflecting and absorbing ambient signals, these transmitters can significantly reduce power consumption compared to commodity transmitters [14, 22]. Notably, recent systems demonstrate the capability to generate transmissions compatible with certain standards [8, 12, 20], consuming merely tens of microwatts of power.

Backscatter challenge. Backscatter systems have seen limited adoption. A significant constraint is a requirement for backscatter tags to be located close to a carrier-emitting device to achieve a reasonable range [11, 12, 29]. Some systems have managed to overcome this challenge by trading off bitrate [20, 22]; however, this compromises their energy efficiency per-bit basis and limits their application. Another approach to this problem leverages tunnel diodes to design reflection amplifiers [1, 7, 23] and transmitters [15, 24]. While we build upon these efforts, these system also face the challenge of operating in a spectrum used by ever-increasing wireless devices. This leads to high contention for weak signals that are emitted from the tunnel diode transmitters, impacting link quality.

A promising solution involves backscattering the ambient wireless signals surrounding us, from television and radio broadcasts to cellular signals. The need for a dedicated carrier emitter could be

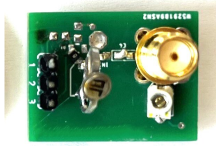


Figure 2: *TunnelRadio hardware.* It is designed with a minimal number of components. The dimensions of the board are on the centimeter scale. The small form factor and low power consumption can facilitate usage in WES.

eliminated if these ubiquitous signals can be effectively reflected and absorbed. Indeed, some systems have adopted this method, leveraging ambient signals such as WiFi [11, 29] and television [14]. However, reflecting these ambient signals leads to poor range due to their unfavourable propagation characteristics or poor coverage in urban environments. Furthermore, these systems necessitate specialized receivers, rendering them infeasible for most devices.

FM-band backscatter. The frequency band in which FM radio signals fall typically ranges between 60 and 108 MHz, depending on the regulations in each country. Due to their lower frequency, they excel in propagating through complex and challenging environments, including through walls and vegetation. Urban areas are also well served by FM radio signals. Given these advantages, there has been interest in FM backscatter systems [4, 25, 26] that leverage these benefits to address the energy challenges and constraints inherent in TV and WiFi backscatter systems.

Operating at lower frequencies offers several advantages for WES communication. They exhibit superior propagation characteristics, enabling signals to traverse greater distances with the same transmission power. Moreover, these signals can penetrate walls, vegetation, and other barriers more effectively, which benefits urban and indoor deployments. Additionally, these frequency bands, like TV whitespace [2], are predominantly designated for specific purposes, such as audio broadcasting. As a result, there is less chance of competition or interference among WES, ensuring reliable communication. In addition, many mobile devices, computers, and vehicles are equipped with FM receivers or can be easily instrumented to do so, simplifying the use of these bands.

While FM broadcasts remain prevalent, they are gradually being supplanted by alternative mediums (such as internet radio or DAB), with plans underway in many regions to phase out FM radio entirely. Indeed, the usage of FM radio on smartphones is also dwindling. In response to this challenge, we present our ongoing work on designing low-power transmitters, TunnelRadio. They can perform FM transmissions while maintaining a power consumption comparable to FM backscatter systems. This approach allows us to address the challenge posed by the phasing out of FM broadcasts, thereby unlocking this promising spectrum for WES deployments. Figure 1 shows a high-level overview of our system, and a centimetre-scale prototype of TunnelRadio in Figure 2.

TunnelRadio design. TunnelRadio is a low-power transmitter that can transmit either sensor or audio signals. The transmitter is low-power, and thus can operate on the energy harvested from the environment. The transmissions from the TunnelRadio can be received by devices around us, like computers, phones and cars.

The design of TunnelRadio, however, presents several challenges. When operating at lower frequencies, the antenna size increases. While this is true, considerable research has been done to develop compact antennas which operate within these bands. As highlighted by Wang et al. [26], FM antennas can also embrace innovative form factors. In addition, there are legal restrictions associated with transmitting in these bands. It is common for these bands to be regulated leniently, allowing low-power, unlicensed transmissions, which is in line with the design of our system. Due to tunnel diodes' inherent low power nature, they emit weak signals when used for designing of the tunnel diode oscillators (TDO), which fall within the regulatory limits in most parts of the world.

Tunnel diodes exhibit a quantum tunnelling effect, allowing them to display regions of negative resistance (RNR). Moreover, they operate on the order of microwatts of power cosumption. Leveraging this characteristics, we devised a low-power tunnel diode oscillator (TDO) to generate carrier signals within the FM band building upon recent systems such as Judo and TunnelScatter [23, 24].

Next, in a transmitter, the carrier signal needs to be modulated with baseband or audio signal. We use the self-oscillating mixing (SoM) characteristic of the TDO to modulate the carrier signal with a baseband signal [15, 24]. This allows us to efficiently mix the carrier signal with a baseband signal without requiring energy-intensive external components such as mixers. Specifically, TunnelRadio demonstrates an ability to mix the FM band carrier signal with a baseband signal employing chirps.

Depending on the application scenario, the carrier signal may be modulated to transmit audio information to ensure compatibility with FM audio receivers. As a result, we explore TDO's self-modulating capabilities. When applied at a low voltage, an audio signal within audible range can directly modulate a TDO-generated carrier signal. Through experiments, we demonstrate that it enables modulation and subsequent reception up to a distance of 23 metres using a commodity FM radio receiver.

Finally, the low power consumption enables operation on small amounts of harvested energy. Hence, in this early work, we empirically demonstrate the powering of the radio station through energy harvested from radio frequency (RF) radio signals.

Summary of results. We conduct extensive experiments, and offer the following key findings from our work:

- TunnelRadio can generate a carrier signal in the FM band, with a strength of approximately -40 dBm received at the Rx antenna.
- We could achieve a range of 23 meters when TunnelRadio is modulated with audio or complex baseband signals.

The rest of the paper is organised as follows. Section 2 delves into the relevant background and related work. In Section 3, we provide a concise overview of the system's design. Section 4 presents the experimental setup and the results obtained. Before concluding, Section 5 outlines potential future directions for the work presented and some issues related to the system proposed.

2 BACKGROUND

We discuss works that are closely related to TunnelRadio.

Ambient backscatter. There has been considerable effort devoted to developing backscatter systems to address the energy challenges of WES. More specifically, there has been substantial interest in developing ambient backscatter systems. These systems eliminate the need for a dedicated carrier emitter by utilizing ambient signals. Liu et al. [14] pioneered this approach by demonstrating the viability of ambient backscatter, showcasing that backscattering television signals could facilitate communication between embedded devices. Following this, Kellogg et al. [11] and Zhang et al. [29] demonstrated that WiFi signals can be utilized for low-power transmissions. In urban settings, ambient signals often encounter challenges related to range and coverage. Given their superior propagation characteristics and extensive coverage, FM backscatter systems [4, 5, 26] draw inspiration from these efforts and address some of their limitations.

FM-band backscatter. Wang et al. demonstrated the feasibility of backscattering ambient FM signals and the capability of commodity smartphones to receive these transmissions. Moreover, they designed several innovative applications [26]. Daskalis et al. and Dasklakis et al. utilized FM backscattering to transmit temperature differences for smart agriculture applications [4, 5]. Hu et al. proposed an FM backscatter tag using the tunnel diode as a reflection amplifier to enhance communication range [10].

Nevertheless, a common dependency and constraint across these works is their reliance on ambient FM signals. The anticipated discontinuation of FM broadcasts may render these applications untenable in the foreseeable future. In contrast, our approach designs low-power radio stations capable of autonomously generating FM broadcasts within the designated FM bands, eliminating the need for ambient FM broadcasts. As demonstrated in this paper, our energy consumption is comparable to that of FM backscatter systems, and it can be budgeted by harvesting ambient energy. Hence, we significantly advance beyond existing works, paving the way for using FM bands for the ubiquitous deployments of WES.

FM transmitters. FM transmitters are widespread across various applications, often facilitating the broadcast of audio from media players to headsets and other FM-compatible devices. These transmitters, however, consume a significant amount of power and are usually custom-made for specific applications. Our work resembles an early system developed during the nascent stages of tunnel diode's development in 1963 [13]. The authors propose a tunnel diode based FM transmitter for medical and laboratory telemetering. This design hadlimitations: its power consumption was significantly high at 1.6 mW, and it needed to address the complexities of modulating the carrier signal with digital information. The primary goal was to transmit analog medical data via FM, specifically electromyographic and electrocardiographic signals. In contrast, our approach not only facilitates the transmission of digital data but also modulates it over FM signals, catering to the needs of WES. The pioneering systems of over half a century ago have influenced our efforts; in many ways, they were well ahead of their time.

Tunnel diodes for WES communication. There has been a renewed interest in utilizing tunnel diodes for designing energy-efficient communication systems. In recent years, tunnel diodes have been employed as reflection amplifiers to extend the range of backscatter transmitters. For instance, Amato et al. designed and demonstrated the effectiveness of such a reflection amplifier on a 5 GHz backscatter system [1], while Varshney et al. explored the 868 MHz frequency bands [19, 21, 23]. In a separate effort, Dong et al. designed a relay to enhance GPS signal propagation indoors [6]. However, all these systems rely on reflecting existing ambient signals and do not address the potential future decline of FM broadcasts. Our work aligns most closely with recent systems demonstrating that tunnel diode oscillators can generate and modulate a carrier signal using their SoM properties [15, 24]. Building on them, we designed a transmitter suitable for the FM band and demonstrated its ability to mix the audio and baseband signals.

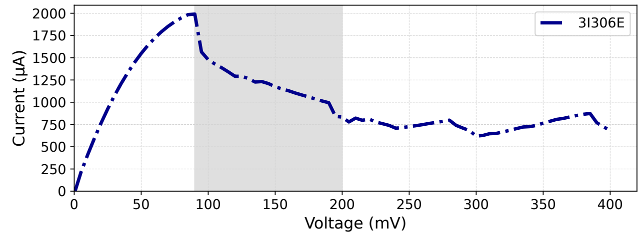


Figure 3: *I-V characteristics of 3I-306E Ga-As tunnel diode.* The tunnel diode exhibits a region of negative resistance at low voltages and currents. The overall power consumption of the diode remains well below 150 microwatts, which is sufficiently low to be powered by ambient energy sources

3 DESIGN

The TunnelRadio system comprises a radio transmitter and a receiver, as shown in the Figure 1. It operates through a series of steps: Initially, the device with the TunnelRadio transmitter harvests energy from the environment, such as from radio signals or light harvested using a solar cell, and stored onto a capacitor. It can also use an onboard battery. This energy is then channelled to power the TDO, facilitating the generation of a carrier signal within the FM band. Afterwards, the carrier signal is modulated with either a complex baseband signal or an audio signal. Finally, a device equipped with an FM receiver interprets these transmissions.

Tunnel diode. They are semiconductor devices first discovered in the 1950s, known for exhibiting quantum tunnelling due to their heavily doped P-N junctions [18]. This phenomenon endows tunnel diodes with several unique properties, including displaying a RNR and operating at RF frequencies with minimal power consumption. In the experiments presented in this paper, we utilized the tunnel diode 3I306E, with its RNR illustrated in Figure 3. As the bias voltage increased, the current flowing through the tunnel diode was monitored. We observed that the current through the tunnel diode decreased despite the increasing bias voltage beyond a certain threshold, indicative of the RNR. This tunnel diode exhibits this behaviour at tens to hundreds of millivolts and under two milliamperes of current. Tunnel diodes are, therefore, low-power devices; in our case, consuming less than 150 microwatts.

Designing oscillators. An RF oscillator is indispensable for generating carrier signals. It involves coupling a negative resistance element to a resonant circuit. Traditionally, negative resistance elements are often transistors, which consume considerable power. Building upon recent works [21, 24], we designed a tunnel diode oscillator (TDO) employing a tunnel diode as the negative resistance element. The resonant circuit comprises an inductor, a capacitor, and the inherent parasitics within the antenna, board, and tunnel diode. To ensure the generation of the carrier signal within the FM frequency band, we fine-tuned the parameters of the resonant circuit, and made careful selection of the tunnel diode.

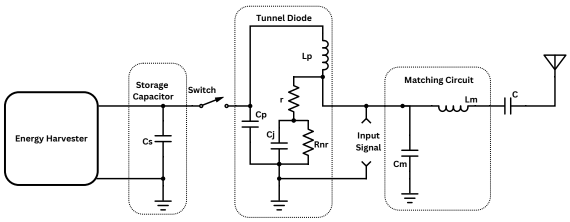


Figure 4: ***Schematic of the TunnelRadio.*** **The tunnel diode is coupled to a resonant circuit to generate oscillations in the FM band. The properties of the resonant circuit dictate the TDO frequency. Using the SoM and self-modulation property, the carrier signal is modulated with a baseband or an audio signal.**

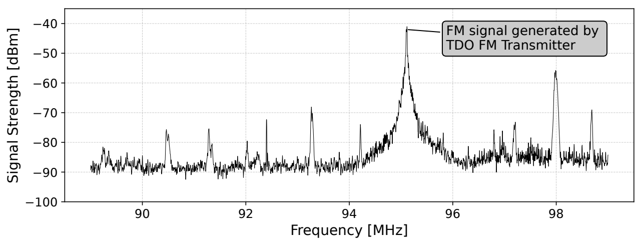


Figure 5: ***Unmodulated TunnelRadio spectrum.*** **We observe a carrier signal generated from the TunnelRadio at a center frequency of 95.1 MHz. We also observe FM stations present in the vicinity of TunnelRadio transmissions.**

Designing transmitter. The TDOs are fundamental to transmitter's design. We design TDO to radiate a carrier signal with a strength of -40 dBm, at a frequency of 95.1 MHz, a range falling within the FM frequency band for most parts of the world. The circuit's schematic can be seen in the Figure 4, while the spectrum, captured by coupling the tunnel diode to a Signalhound BB60c spectrum analyser, is shown in the Figure 5. It can be powered by energy harvested from the environment and stored in capacitors, or it might be powered for a prolonged period of time with a compact battery because of the transmitter's low power consumption.

Modulating with baseband signal. We exploit the TDO's capability to function as a SoM for carrier signal modulation [15, 24]. It is necessary for transmitting to FM transceivers. We can generate a mixed signal by feeding a low-voltage baseband signal into one of the TDO ports. We leverage it for transmitting chirps, with the corresponding experiments and results in Section 4.

Modulating with audio signal. FM radios, such as those in cars and mobile phones, are primarily used for audio broadcasts, so we must ensure they can detect our transmissions. This necessitates the modulation of the TDO with a lower-frequency audio signal. In addressing this, we unveil a distinctive property of TDOs, which, to the best of our knowledge, stands as one of the novel contributions of this work. We term this the self-modulation of the TDO. Our findings indicate that when we introduce a low-frequency signal, akin to analog audio, it can directly modulate the carrier of the TDO with the corresponding information. Contrary to the SOM property, this signal does not manifest as a sideband, which is pivotal in supporting the transmission of audio signals. We leverage this property to transmit audio information.

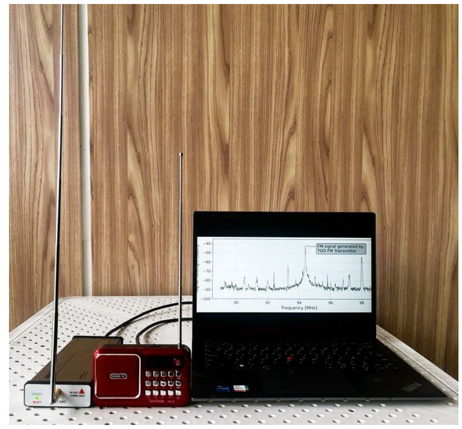


Figure 6: ***Receiving setup.*** **For receiving broadcasts, we use a COTS radio. To receive complex baseband broadcasts, we use a spectrum analyser.**

Receiving transmissions. We received the broadcasts using a commodity off-the-shelf FM radio receiver, as shown in Figure 6. To demonstrate the ability of our system to support a complex modulation scheme, we captured it using a spectrum analyser (Signalhound BB60c). In the future, we will investigate the use of commodity transceivers for receiving data transmissions.

4 EVALUATION

This section presents the results to evaluate TunnelRadio. The main findings from the results presented are as follows:

- Transmissions can be demodulated using COTS FM receivers.
- Transmissions can be modulated using audio or complex baseband signals. As measured by the metric discernible audio, we were able to transmit to distance of 23m.

Experiment setup. We conducted the experiments in an open university area. This ensured a clear, direct line-of-sight propagation for FM transmissions, which is crucial for determining the maximum transmission range and link metrics. Our transmitter drew power from RF energy harvested via a matched antenna in specific experiments. The transmitter, however, received power from an external supply during communication tests. The TDO front-end was tuned to the 88-102 MHz frequency band, the allowed FM broadcast frequency within our experiment locations. For experiments, as shown in Figure 4, we fed the modulating signal in the form of a low-frequency audio or a complex baseband signal generated using a waveform generator. We programmed the spectrum analyser to regularly collect a snapshot of the FM radio spectrum at an interval of 0.01 sec, the lowest supported for this particular device. We employ a monopole helical antenna for the FM radio transmitter. Figure 7 shows the actual setup for TDO-based FM transmitter, and Figure 6 exhibits the FM receiver and spectrum analyser.

Unmodulated transmitter. We investigated the ability of the transmitter to generate a carrier signal. We placed the spectrum analyser (Signal Hound BB60C) near the tunnel diode transmitter. We demonstrate the captured spectrum in Figure 5. We observed a clear peak from the carrier signal generated by the front-end at a frequency of 95.1 MHz, at a signal strength of around -40 dBm. We also observed FM broadcasts in the vicinity of our transmissions.

Figure 7: *TunnelRadio setup.* It is connected to standard FM antenna

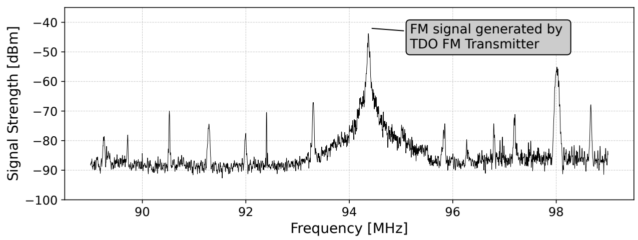


Figure 8: *TunnelRadio transmitter modulated with audio signal.* We observe transmission at the frequency of 94.4 MHz. Due to the self-modulating property, the carrier signal is modulated with the audio signal without sidebands.

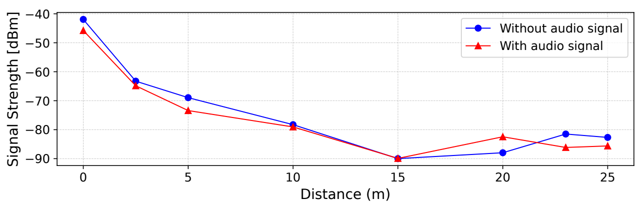


Figure 9: *TunnelRadio maximum range.* We observed that the signal strength of the received signal from the tunnel diode transmitter falls below the sensitivity levels of the receiver at a distance of 23 metres. This represents the range achieved in our experiments presented in this work.

They are much weaker than our transmitter owing to the proximity of the spectrum analyser with the transmitter.

Modulated with audio signal. We fed the transmitter with an audio signal. We provided this audio signal using a smartphone. Figure 8 shows the spectrum obtained with the carrier signal modulated using the audio signal. We did not observe the audio signal as a harmonic; instead, it modulated the carrier signal owing to the self-modulating property of the TDO. Furthermore, we observed that coupling the audio signal caused changes to the resonant property, leading the TDO to be centred at 94.4 MHz. However, the transmissions still fall within the permissible range.

COTS receiver range. We varied the distance between the FM receiver (COTS receiver and spectrum analyser) and the TunnelRadio transmitter from 0 to 25 metres. We show the strength of the transmissions from the FM transmitter at varying distances in Fig. 9. In this experiment, we evaluated the transmitter, which was unmodulated, and another instance in which it was modulated with a low-amplitude audio signal. While broadcasting audio signals, we evaluated the discernability of the audio signal. We could hear a discernable audio up to 23 m from the receiver. Fig. 9 shows that the strength of the signal varies between around -41 dBm and -82 dBm for the FM signal without any modulation and between -45 dBm and -86 dBm for the FM signal modulated with an audio signal. Our results are promising as they represent a reasonable range to support many scenarios, such as, smarthomes.

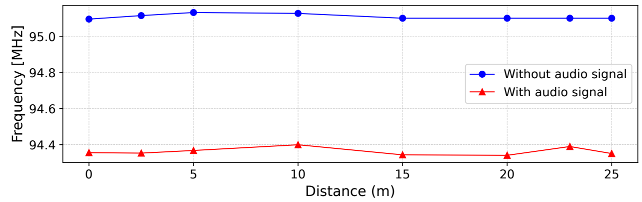


Figure 10: *Stability of the resonant frequency of the TDO.* The frequency remains stable and exhibit minimal drift during the course of the experiment.

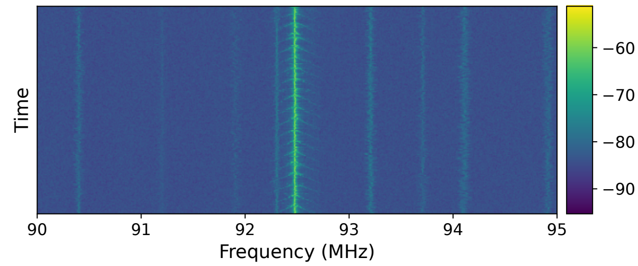


Figure 11: *Modulating TunnelRadio with complex baseband signal.* We observe the chirps in the waterfall plot. They are generated as we mix a chirp-modulated baseband with the carrier signal generated from a TDO.

TDOs are prone to drifts in their resonant frequency [21, 24]. This can adversely impact the link reliability. We analysed the collected logs and note that in Figure 10, the TDO frequency remained stable with deviations in the order of 10^{-2} MHz. We will investigate the improved stability at lower frequency in our future work.

Modulating with complex baseband. We evaluated the TunnelRadio transmitter's ability to be modulated using a complex baseband signals. We modulated the TDO with a chirp-modulated baseband signal, with the chirps changing in frequency from 1 KHz to 250 KHz every second. Due to the SoM property, this would result in the signal being mixed with the carrier signal, resulting in the generation of sidebands. Figure demonstrates the waterfall plot obtained using the spectrum analyser. We observed the chirp-modulated sidebands and their mirror image in the spectrum. This experiment demonstrates the feasibility of the transmitter for supporting complex baseband.

Supporting operations on harvested energy. To demonstrate the low-power functionality of the transmitter, we employed an RF energy harvester setup to harvest 868 MHz signals and enable transmission using a tunnel diode transmitter in the FM band. Our setup consisted of a software-defined radio (SDR), Ettus USRP B200 generating a carrier signal at the 868 MHz frequency band. This signal was harvested using the RF harvester, and the energy was stored in the capacitor. Next, we used the stored energy in the capacitor to power the transmitter. Figure 12 demonstrates the brief period for which the transmitter switched on. This was due to the very small capacitor employed for this particular experiment. Furthermore, the

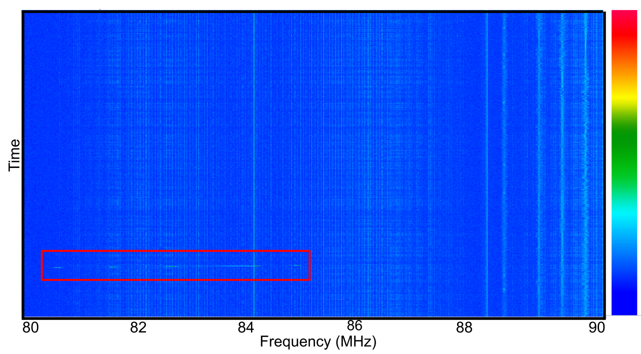


Figure 12: ***Operations on harvested energy.*** **We can power the TunnelRadio transmitter on energy harvested from RF signal. Owing to the small size of the capacitor, the transmitter was turned on for short period of time, and can be see through a horizontal line in the waterfall plot. The change in the capacitor voltage leads to change in the resonant frequency.**

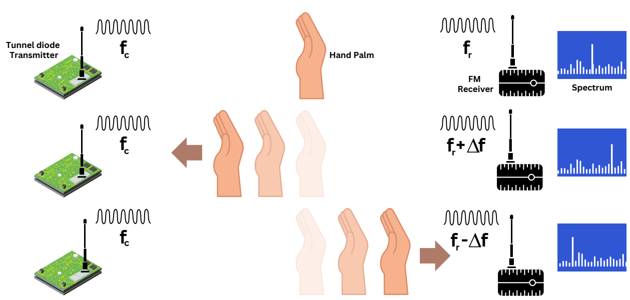


Figure 13: ***TunnelRadio can also help with sensing.*** **Macroscopic motion in the vicinity, such as, hand gestures alter the frequency of these emissions. For applications like vital sign monitoring and gesture recognition, these frequency variations can be tracked and analyzed by a COTS FM receiver.**

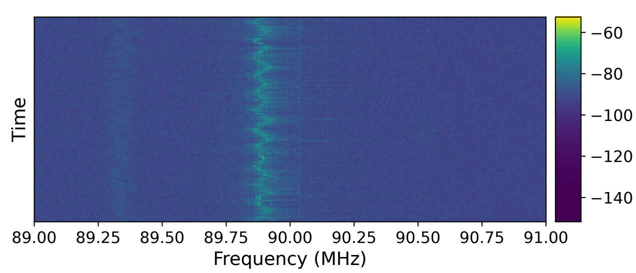


Figure 14: ***TunnelRadio frequency variations.*** **We observe deviations in the frequency of the TDO due to hand gestures in the vicinity of the TunnelRadio. This is due to the sensitivity of the TDO to the changes in the environment.**

resonant frequency of TDO changes with bias voltage [21]. Hence, as the capacitor discharges, we observe a change in the frequency. This can be rectified by employing a regulator. This experiment demonstrates the ability of the TunnelRadio to function from small amounts of harvested energy.

5 DISCUSSION

We discuss constraints and our future-efforts.

Ubiquitous low-power sensing. TDOs are sensitive to environmental changes, including temperature and humidity variations [21] and motion around them [24]. Specifically, macroscopic motion near the oscillator can cause its resonant frequency to exhibit distinct patterns. For instance, it is possible to correlate TDO frequency patterns with nearby hand gestures [28]. Utilising the FM bands to design wireless interaction devices [25] is a promising avenue due to the excellent propagation traits and the widespread presence of FM receivers on the mobile devices that surround us.

We experimented with our designed radio stations to validate the potential for sensing. We show a high-level overview of our proposed system in Figure 13. We performed hand gestures near the transmitter at a distance of around 10 cm and monitored the frequency changes of the tunnel diode oscillator. Figure 14 displays the experiment's outcome collected from the spectrum analyser placed around 50 cm away from the transmitter. The frequency of the TDO showed variations corresponding to the hand motions. Additionally, we noticed changes in the intensity of the audio on the FM radio receiver. These preliminary findings are encouraging, and we intend to explore this avenue further to enable gesture sensing and possibly even the detection of vital signs, like breathing rates.

Stability challenges. The TDO's frequency stability might need to be revisited for communication systems. While FM receivers are generally forgiving of frequency deviations, receiving baseband data for communication could be challenging. It is worth considering ways of stabilising the TDO. One potential method is the injection-locking technique [21, 24].

Availability of tunnel diodes. While tunnel diodes hold promise for designing low-power RF circuits, they remain an obscure semiconductor device. Procuring them can be challenging; our study used tunnel diodes from an online Soviet vintage electronics shop. Recent studies have shown that they can be beneficial for designing energy-efficient communication and sensing circuits [1, 6, 7, 19, 21, 23, 24]. We hope these findings will inspire renewed commercial interest in the large-scale fabrication of tunnel diodes.

6 CONCLUSION

We have presented our efforts to harness the FM bands for WES. We presented TunnelRadio, a low-power FM transmitter designed using tunnel diodes. TunnelRadio achieves a range of up to 23 meters while consuming less than 150 microwatts of power. Additionally, we demonstrated the transmitter's ability to modulate and mix audio and complex baseband signals. We highlight that the low power consumption allows the transmitter to operate on minimal harvested energy. These transmitters can enable numerous applications, including for sensing such as vital signs monitoring.

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