Tunnel Emitter: Tunnel Diode based Low-Power Carrier Emitters for Backscatter Tags

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ABSTRACT

Backscatter enables transmissions at orders of magnitude lower energy consumption when compared to conventional radio transmitters. Backscatter tags achieve this by the reflection or absorption of carrier signal generated from emitter devices. However, backscatter systems are limited by these emitter devices, as they are significantly energy-expensive when compared to the tags. While backscatter tags can operate without requiring batteries, relying on the minuscule amounts of energy harvested from the ambient environment. However, the emitter devices, are commonly tethered to an external power supply or operate on large batteries.

We present Tunnel Emitter: a tunnel diode oscillator based system that enables the generation of carrier signals at a peak biasing power of tens of µW. Thus, for the first time, it allows battery-free emitter devices. The key enabler to the design is a phenomenon exhibited by tunnel diode oscillators that we call *back injection*, and we are the first to demonstrate. Back injection enables the emitter devices to amplify (up to 20 dB) and relay the backscattered signal. Our results show that Tunnel Emitter when operating together with a tag from long-range backscatter system, facilitates multi-floor communication. Tunnel Emitter, due to the back injection phenomenon, achieves this with a carrier signal that is orders of magnitude weaker than used in state-of-the-art systems. We believe Tunnel Emitter overcomes the key constraint restricting backscatter systems and thus can make backscatter systems ubiquitous.

CCS CONCEPTS

• **Hardware** → **Wireless devices**; **Sensors and actuators**; *Networking hardware*; • **Computer systems organization** → **Embedded and cyber-physical systems**.

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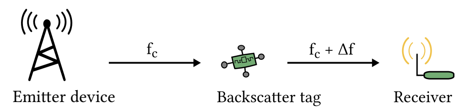
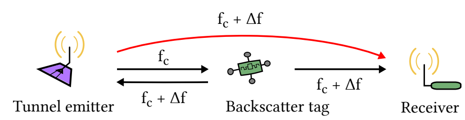


(a) Conventional Backscatter System



(b) Tunnel Emitter System

Figure 1: *Overview.* Tunnel Emitter generates carrier signal which is reflected by the backscatter tag. Tunnel Emitter due to the back injection phenomenon amplifies and relays the backscattered signal towards the receiver. Backscattered signal relayed by the Tunnel Emitter is significantly stronger.

1 INTRODUCTION

Backscatter enables wireless transmissions in the order of few tens of µWs [33, 48, 53] of power consumption. It allows this by reflecting or absorbing the carrier signal. The backscatter systems comprise three devices: an emitter device to generate carrier signal, a tag which reflects or absorbs this signal, and an edge device (receiver) to receive these reflections. We show this setup in Figure 1(a).

Among different components of backscatter systems, we find that tags are energy inexpensive. They can operate without batteries on minuscule amount of energy harvested from the ambient environment [33, 35, 49, 55]. However, the emitter device and the edge device are many orders of magnitude more energy expensive. They are generally reliant on batteries or an external power supply. High range achievable with recent systems [21, 39, 48, 53] allows flexibility in the edge device's placement, e.g., near a power outlet. In contrast, the emitter device is located close to the tag [28, 58] or/and generate strong carrier signal [48, 53]. A strong carrier signal can interfere in the network [19, 20], also make emitter devices energy expensive and bulky. We believe the high power consumption of emitter devices limits the application scenarios and consequently ubiquitous deployment of the backscatter systems.

We overcome above constraints of emitter devices and design a low-power device that we call Tunnel Emitter. It generates the carrier signal at orders of magnitude lower power consumption when compared to emitter devices used in existing backscatter systems. We show the low-power consumption of Tunnel Emitter enables its operation on harvested energy or minuscule batteries without compromising on the range (refer Section 5.1).

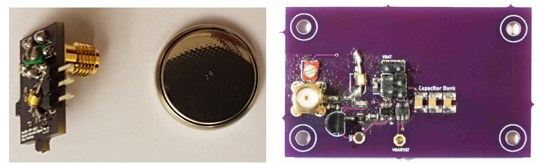
Our approach in designing Tunnel Emitter is to reduce the radiated power to only a few tens of µW. We base this on the fact that modern transceivers have a high receiver sensitivity [52], e.g., LoRa transceivers can receive a faint signal up to a strength of −149 dBm [48]. A transmitter radiating a weak signal may still lead to a significant range (hundreds of meters) because of high link budgets. However, we face two significant challenges; *First*, we find that reducing the radiated power does not reduce the overall power consumption of the emitter device. They consume considerable power (upward of tens of mWs). This is because they use transceivers designed using energy expensive components [23, 44]. These components, such as amplifiers or high-speed ADCs part of the transceivers, are active even when they are not required. *Second*, backscatter mechanism involves several losses. It thus achieves practical range only when the carrier signal is close to maximum permissible strengths (see Table 1). Hence, the weak emitter, despite the high sensitivity of transceivers, might result in limited range.

Contributions. To reduce the power consumption of the emitter device, we adopt an approach to design a device only tasked with generating the carrier signal. We strip down the emitter to only the required components, which mainly comprise an oscillator. We build on TunnelScatter [56] and design a low-power tunnel diode oscillator (TDO). This enables us to generate carrier signal in the 868 MHz band at a peak biasing power of tens of µW. Varshney et al. [56] and others have previously explored TDOs. However, we went beyond these efforts as we also tackled associated challenges such as enabling frequency changes of TDO, power management and integration of the TDO in Tunnel Emitter. In its simplest form, the Tunnel Emitter comprises only a handful of components and is smaller than a coin cell battery, as we show in Figure 2.

TDO achieves low-power consumption because of the weak carrier signal. This should affect the range. However, on the contrary, we find that a weak carrier signal does not limit the range of our system because of a phenomenon we call *back injection*. Despite several decades of history of tunnel diodes and TDOs [46], we believe we are first to show and evaluate back injection phenomenon.

Back injection is based on the concept of injection locking oscillators [30, 43, 56]. This occurs when an external signal influences an oscillator near its resonant frequency. This enables a significant gain in the strength of this external signal injection-locked onto the oscillator. With the back injection, the external signal influencing the oscillator is the backscattered signal, that was itself generated by reflection of the carrier signal transmitted by the oscillator. We illustrate this concept in the Figure 1(b). The tag reflects the carrier signal from the co-located Tunnel Emitter. Next, the reflected signal from the tag propagates towards the receiver and back towards the Tunnel Emitter. To the TDO on the emitter device, the backscattered signal appears as an external signal near its resonant frequency. It injection locks onto this signal which also causes amplification of the weak backscattered signal. The emitter then relays the amplified signal: we call this behaviour *back injection*. This signal is orders of magnitude stronger than the one propagating from the tag. As a result, we find that unlike existing systems; we receive the strongest reflections from the emitter device and not from the tag.

We evaluated the back injection phenomenon, and our results show that it can lead to the gain of ≥ 20 dB over reflecting a similar signal strength carrier signal generated from a software defined radio (refer Section 5.4). To evaluate the impact of this effect on backscatter systems, we designed a tag based on LoRea [53]. We co-located (2 m) this tag with Tunnel Emitter operating on small batteries and evaluated the range. Our results show that we could transmit to multiple floors of our building. We could only achieve similar capability with a software defined radio as an emitter device when the carrier signal was orders of magnitude higher in strength, and the emitter device was externally powered.



(a) Form comparison (b) Prototype

Figure 2: *Physical form.* Tunnel Emitter can be smaller than a coin cell. Due to its low power consumption, it can operate continuously for years (without duty cycling) on it.

Recent systems TunnelScatter [56] and Amato et al. [3–5] have designed reflection amplifiers using tunnel diodes. They integrate them in a custom-designed tag. This enables backscattering of the weak carrier signal with a significant gain and allow them to achieve high range despite a weak carrier signal. Our system is complementary to these designs and also differs. As opposed to these systems, Tunnel Emitter requires no alteration to the design of tags. It also generates a smaller spread of undesirable harmonics (refer Section 3.2). Further, reflection amplifier based tag works with Tunnel Emitter and enhances the back injection region.

We encounter several challenges in designing Tunnel Emitter. *First*, the back injection enhances the harmonics generated during the backscatter process. This happens when the tag is located near the Tunnel Emitter. To tackle this challenge, we designed a communication mechanism that we call Tunnel to Tag which notifies the tag that it is in proximity and prevents its transmission (refer Section 4.2). *Second*, supporting many Tunnel Emitter, and concurrently transmitting tags can be challenging. Thus, we also provided a sketch of MAC layer design (refer Section 4.4).

TDOs enable the generation of high frequency RF signals at power budgets similar to a backscatter tag. As showed by TunnelScatter [56], this might enable the design of low-power transmitters. Does this eliminate the need for the Tunnel Emitter system? We examined and found that Tunnel Emitter system offers advantages over this design (refer Section 7.1). When operating in a tiered architecture (Tunnel Emitter supporting several tags), it provides significant energy savings in the network. Further, unique properties of the Tunnel Emitter system can enable new application scenarios (refer Section 6). For example, the small range of back injection phenomenon can be advantageous to enable the design of devices that help maintaining social distancing (refer Section 6.1).

Summary of novel contributions. We are the first to explore the idea of ubiquitous battery-free carrier emitters by significantly lowering their power consumption. We have made several contributions: (1) we design a battery-free carrier emitter using TDO, (2) we are the first to demonstrate and evaluate back injection phenomenon, (3) we tackle challenges such as altering the frequency, power management, harmonics problem, medium access control, and 4) we extensively evaluate our system and demonstrate unique properties that enable novel application scenarios.

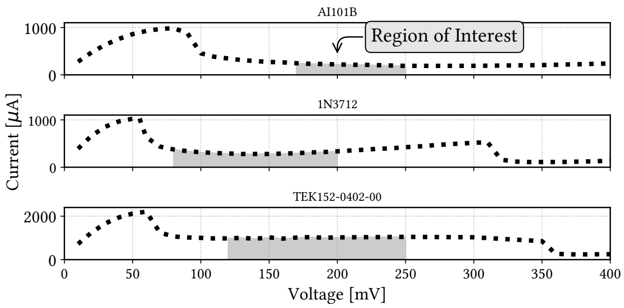


Figure 3: *Tunnel diodes I-V characteristics.* The highlighted part shows the region of interest for this work.

2 BACKGROUND AND RELATED WORK

In this section, we provide background to tunnel diodes. We also discuss relevant work to our system.

2.1 Background

Tunnel diodes are P-N junction devices first fabricated in the 1950s, and the first semiconductor device to show the phenomenon of quantum tunneling [46]. This enables subatomic particles to overcome and pass through a high energy barrier. This barrier is insurmountable following the laws of classical physics. Quantum tunneling enables tunnel diodes to show a region of *negative resistance* which allows their usage for the design of RF devices [46]. Tunnel diodes have found their usage in designing devices such as amplifiers [37], switches and oscillators [47] because of negative resistance and their ability to work at high RF frequencies.

Negative resistance is a property that causes the current (I)-voltage (V) characteristics of the tunnel diode to be non linear. When we forward bias the tunnel diode and increase the voltage across it, we find that the current goes through several thresholds. First, the current rises with voltage reaching *peak*. Next, it falls even as the biasing voltage continues to increase, and it reaches *valley*. Afterwards, the current continues to rise with the bias voltage. The tunnel diode shows negative differential resistance in the region between *peak* and *valley*. This is because, a negative differential resistance defined as $\frac{\Delta V}{\Delta I}$ is negative because as V increases, ΔV is positive; however, I decreases which makes ΔI and $\frac{\Delta V}{\Delta I}$ negative.

In Figure 3, we show the I-V characteristics and the region of interest for tunnel diodes we use in the work, AI101D [45] , Tektronix 152-0402-00 [50] and General Electric 1N3712 diode [14]. We find that the negative resistance region occurs at a biasing voltage of up to a few hundred mV, with current consumption up to 2 mA. This results in low biasing power consumption. We use the tunnel diode 1N3712 in this work, which we find consumes a peak biasing power of 57 μWs (refer Section 5.1).

2.2 Related Work

We discuss works that are most relevant to our system.

Tunnel diodes in communication systems. Tunnel diodes have been used to design low-power communication mechanisms. Recently, they were used to enhance the backscatter tags. Amato et al [3–6] design a tunnel diode reflection amplifier, and further integrate the reflection amplifier with a tag. This enabled them to enable communication to significant distances, even when the incident carrier signal was weak at the tag. TunnelScatter [56] enhanced tag, however, also presented a design of a TDO showing ability to communicate even without reflections by generating a carrier signal. While we build on the insights offered by these systems, we tackle a different problem. These systems require an energy expensive emitter device. Further, they need a redesign of tags with tunnel diodes, which can be an expensive operation. We design a low-power emitter device complementary to all these systems.

System	Tag Location from ACS Emitter (Meter)	Emitter Device Strength (dBm)	Communication Range (Meter)
Passive WiFi [28]	2	30	30.5
LoRea [53]	1	28	3400
LoRa Backscatter [48]	5	30	2800
BLE Backscatter [15]	0.9	15	9.4
Interscatter (BLE) [25]	0.3	20	27.4
Interscatter (ZigBee) [25]	0.6	5	4.5
HitchHike [58]	1	30	54
PLoRa [39]	0.2	21	1100

Table 1: *Comparison between state-of-the-art backscatter systems employing conventional RF-switch at the tag.*

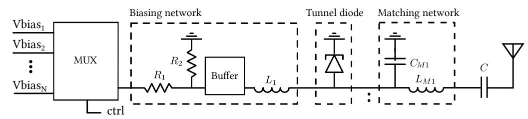


Figure 4: *Schematic of Tunnel Emitter.* Matching network and multiplexer helps to configure the TDO frequency.

Backscatter systems. Ambient backscatter systems do not require carrier emitters, as they reflect signals present in the environment. Recent systems show ability to transmit by reflecting — television [33, 38], FM [11, 12, 57], WiFi [58, 59], LoRa [39], ZigBee [59] or BLE [59] — signals. TV signals enable tag-to-tag communication only near TV towers. FM signals are pervasive, but analogue FM is being phased out. Other ambient backscatter systems exploit wireless protocols, such as WiFi or LoRa. They require proximity between the tag and the wireless device. Our system does not require ambient wireless signals. It enables low-power generation of the carrier signal, which enables the perpetual deployment of tags and emitter device, and consequently, backscatter applications.

We relate our work to backscatter systems, and in particular, long-range backscatter systems, LoRa backscatter [48] and LoRea [53]. The range of these systems scales with the carrier signal strength. Hence, they operate the emitter device at maximum permissible strength (few W's), as we had shown in the Table 1. Tunnel Emitter shows the *back injection* phenomenon that grants similar abilities while consuming orders of magnitude lower power for the carrier signal generation. This enables battery-free emitter devices.

Emitter device deployment. It is limited by the cost, complexity and power constraints. Recent systems tackle this challenge, Interscatter [25] and LoRea [53] generate carrier signal through commodity devices,e.g., WiFi routers, smartphones. These devices, however, are complex, bulky, and powered by large batteries, or tethered to an external power source. Another approach is to devise scheduling mechanisms [41, 42] minimizing the duration of the carrier signal generation. However, these require significant computation at the edge/cloud device which limits the scenarios. We tackle this challenge by lowering the power consumption, which may even enable continuous operation of carrier emitters for years on a coin cell battery without requiring such mechanisms.

3 TUNNEL EMITTER

We discuss design and implementation of the Tunneling Emitter with a focus on the back injection phenomenon.

3.1 Carrier Signal Generation

Emitter devices are commonly SDRs [15, 28, 48], RFID readers [36] or devices such as smartphones with commodity transceivers [25, 53]. Usually, they generate carrier signals of maximum permissible strength through the use of power amplifiers [53]. A strong carrier signal is necessary as the range of backscatter systems scales with its strength [53], and the backscatter process has inherent losses. As a result, carrier signal generation is the most energy-expensive operation in backscatter systems, as it is shown in Table 1. We precisely overcome this limitation: we lower the power consumption for the emitter device without compromising the range.

Our approach to lower the power consumption for the emitter device is to reduce the carrier signal strength significantly. However, this is not straightforward as reducing the signal strength on an SDR or commodity transceiver does not reduce the overall power. In fact, it would continue to consume up to tens of mWs because these devices are general purpose and not designed explicitly for carrier signal generation. For instance, they mount energy-expensive components not used in carrier signal generation, and can not even be disabled, e.g., high-speed ADCs, amplifiers, processor.

Implementation. We lower the power consumption of the emitter device by limiting the design to only necessary components. In its simplest form, carrier signal generation requires an oscillator operating at RF frequencies whose signal can then be radiated through an antenna. We build on the design of the TDO presented in TunnelScatter [56]. It consist of three major components, namely, tunnel diode, SMA connector, and passive components (DC filtering capacitor, matching network, and RF filters). We design it using the tunnel diode GE 1N3712 [14]. It enables the generation of a carrier signal with a strength of approx. −19 dBm , or 12.59 µWs of radiated power within 868 MHz band. It consumes a peak biasing power of 57 µWs. We also design TDO with tunnel diode Tektronix 152-0402-00 [50] and AI101D [45]. We show a Tunnel Emitter prototype in Figure 2(b) and show its schematic in the Figure 4.

Changing frequency. Frequency changes of carrier signal are essential to support frequency hopping mechanisms [8]. To support this functionality, we built on the insight that small changes in the bias voltage will cause a shift in the frequency of the TDO [56]. We designed a circuit that generates different bias voltages using a resistor network and select using a low-power multiplexer chip, namely, ADG704 [7]. We illustrated the feasibility by connecting the TDO (AI101D) to a spectrum analyzer through a cable. Then, we changed the biasing voltage and recorded the spectrum. The results reported in Figure 5 confirm this ability of the TDO.

Power management. The power management block has two functions: maintaining a stable voltage supply and support battery-free operations. Managing a steady voltage supply is crucial as small changes in bias voltage lead to significant changes in the frequency of the carrier signal generated through TDO. However, maintaining steady voltage is challenging on battery-free systems, as the voltage across the capacitor varies during the charging/discharging phase. We mitigate this behavior through a low-power regulator,

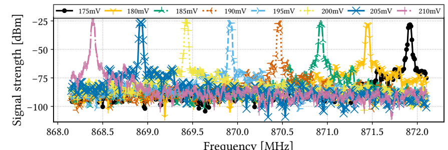


Figure 5: *Changing frequency of the Tunnel Emitter.* Changes in the bias voltage alters the TDO's resonant frequency.

e.g., S-1313 [1], to maintain a stable voltage and ensure the stability of the carrier frequency generated from the TDO.

Another vital function of the power management block is to harvest energy from ambient sources to enable battery-free operation. It harvests energy and stores it onto a supercapacitor. The low-power consumption allows operation of the Tunnel Emitter through ambient sources such as light, waste heat, RF signals. In the experiments that we conducted, we powered the Tunnel Emitter using a small credit card-sized solar cell, when operating battery-free, or tiny batteries, otherwise. The energy harvester in the block is either S-8823A [2] or BQ25570 [51] chip, because of their functionality and low-power consumption. Finally, we stored the harvested energy into a supercapacitor of 330 µF of capacity.

Cost. Tunnel Emitter can be designed using only few components. Among these, the most expensive part is the tunnel diode, as they are not produced commercially at a large scale, and can be challenging to procure. We bought tunnel diode from an antique radio electronics store, and paid approx 20 USD for a 1N3712. The cost to design the PCB through OSH park was approx. 9 USD. Finally, the cost of all the remaining components was under 10 USD. We can substantially reduce the cost if we develop at scale.

Challenges. A weak carrier signal generated through Tunnel Emitter poses two challenges. First, the carrier signal is not strong enough to power the tag through RF energy harvesting. Consequently, we decouple the RF energy harvesting and communication, which enables tags powered from other energy harvesting sources, e.g., light. We describe this aspect further in Section 5.1. *Second*, we would expect the range to suffer, as the range of backscatter systems scales with the strength of the carrier signal. However, this does not happen due to back injection which we describe next.

3.2 Back Injection

Back injection is based on the concept of injection locking of an oscillator. Injection locking occurs when oscillators synchronize to each others frequency. This phenomenon was first demonstrated by Christiaan Huygens in 1666 when he noticed that two pendulum clocks synchronized to each other. TDOs also exhibit this phenomenon [46, 56]. Recently, this has been used in backscatter systems to enhance the ability to operate under weak carrier signal conditions [3–6, 56]. When there is an external wireless signal close to the TDO's resonant frequency, the TDO gets influenced by this signal and injection locks onto it. In these conditions, it reflects the injection-locked weak signal with a significant gain. As an example, Amato et al. [4, 6] and Varshney et al. [56] demonstrated high gain while backscattering a weak carrier signal.

In this section, we ask the following question: *what happens when the tag reflects the carrier signal generated by the TDO, and such signal reaches back the same TDO ?* We find that the Tunnel Emitter latches onto the backscattered signal and relays it, as shown

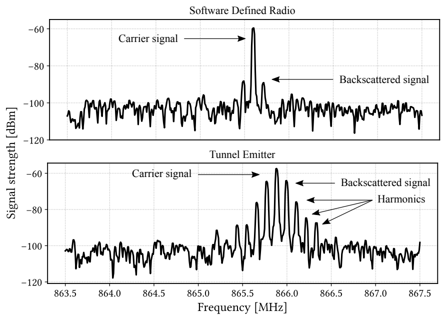


Figure 6: *Back injection gain.* Reflecting carrier signal generated from Tunnel Emitter results in a significantly stronger backscattered signals when compared to reflecting similar strength carrier signal generated from an SDR.

in Figure 1. This results in a significant gain in the strength of the backscattered signal despite the weak carrier signal strength.

Mechanics of back injection. Tunnel Emitter generates a carrier signal at a frequency f_c. We represent this signal as $x(t) = e^{j2\pi f_c t}$. Next, if we ignore the changes suffered due to the propagation of the signal, the backscatter tag modulates this signal with some information $s(t)$. Further, to reduce self-interference [60], the tag frequency shifts this signal at an offset of Δf from the carrier signal. Consequently, we can represent the backscattered signal as $x_1(t) = s(t)e^{j2\pi(f_c+\Delta f)t}$. Finally, $x_1(t)$ propagates towards the edge device (receiver) and also back towards the Tunnel Emitter.

We find through our experiments that when the reflected signal $x_1(t)$ is stronger than a certain threshold B_{th}, it influences the TDO on Tunnel Emitter. The TDO, thanks to the back injection property, amplifies and relays back this signal, that we define as $x_2(t)$. At the edge device (receiver), two signals are received: (i) from the tag, like a conventional backscatter system ($x_1(t)$) and (ii) from the Tunnel Emitter, a signal amplified as a result of the back injection process ($x_2(t)$). We find empirically that $x_2(t)$ is significantly stronger than $x_1(t)$. Consequently, unlike existing backscatter systems, it is the emitter device that is the source of the strongest reflection.

Experimental illustration. We illustrate back injection through an experiment. We set up the experiment in an anechoic chamber to reduce the impact of interference and other wireless signals. We used a tag that employs a standard RF switch HMC190BMS8 [22] to reflect the carrier signal and is used in many state-of-the-art systems [25, 28, 53]. We programmed this tag to frequency shift and backscattered the carrier signal at an offset of 100 kHz. This offset reduces self-interference significantly [53]. We kept the backscatter tag in proximity to the carrier signal emitter at a distance of 0.5 m. To observe the reflected signal, we positioned a spectrum analyzer at a distance of 1.5 m from the carrier signal emitter. This ensures that the spectrum analyzer is in the far-field region of the Tunnel Emitter and does not influence the measurement. We performed the first experiment with Tunnel Emitter as carrier signal emitter and, in the next experiment, we replaced Tunnel Emitter with a USRP B200 software defined radio (SDR) [17]. We programmed the SDR to generate a carrier signal of similar strength to the Tunnel Emitter. In both experiments, we captured the output of the spectrum analyzer, and the results are showed in Figure 6. The figure clearly shows that, even though the carrier signal from both the Tunnel Emitter and SDR was similar in strength, there was a significant improvement ($\geq$ 20 dB) in the strength of the backscattered signal when reflecting the carrier signal generated by the Tunnel Emitter. This is the result of the back injection phenomenon. Furthermore, this also enhances the strength of the harmonics produced during the process, a challenge we discuss further in Section 4.1.

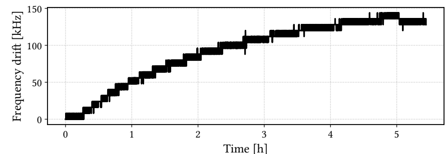


Figure 7: *Drift under back injection.* Tags location is fixed from Tunnel Emitter. The TDO only slightly drift over time.

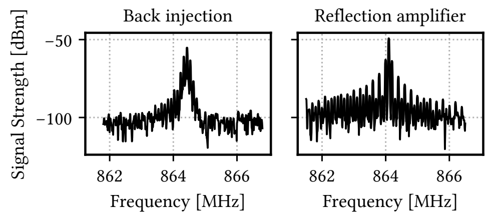


Figure 8: *Back injection vs. reflection amplifier.* Back injection generates significantly lesser spread of harmonics.

Threshold. For the back injection to happen, the reflected signal has to be stronger than a threshold B_{th}, that we found to be between −90 dBm and −100 dBm in our experiments, for tunnel diode 1N3712. We believe B_{th} is dependent on the quality of the matching network and the I-V characteristics of the tunnel diode. This is because each tunnel diode has a minimum voltage that causes changes in the current in the negative resistance region which impacts the injection locking gain. The threshold B_{th} dictates the range of the back injection phenomenon. We can extend this range with the use of directional antennas or reflection amplifiers at the tag.

Back injection vs. Reflection amplifier. Back injection and the reflection amplifier are both based on the concept of injection locking of the TDO; however, there are substantial differences. *First*, integrating reflection amplifier in the tag requires modifications, so this would be challenging and expensive, requiring a redesign of most of the existing deployed tags. Tunnel Emitter showing back injection phenomenon can function with unmodified tags, thus lowering deployment costs. *Second*, the Tunnel Emitter and the reflection amplifier based tag designs are complimentary. This can expand the range where the back injection phenomenon occurs. *Finally*, in our experiments, we saw that the back injection produces fewer harmonics compared to the reflection amplifier design. To verify the aforementioned, we set up an experiment.

We kept a tag using standard RF switch at a distance of 40 cm from the Tunnel Emitter. We positioned the spectrum analyzer at a distance of 1 m from the setup. Next, we replaced the tag with a reflection amplifier based tag, and the Tunnel Emitter with an SDR generating a similar strength carrier signal. We kept the parameters consistent across the experiments. We recorded the spectrum and showed the result of the experiment in Figure 8. We observed that the back injection causes a lower spread of harmonics while producing a stronger backscattered signal under the same conditions.

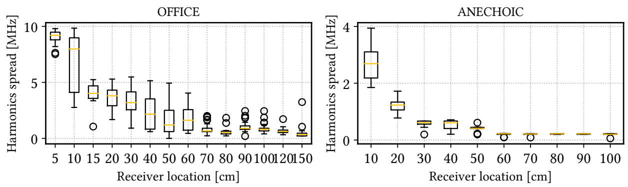


Figure 9: *Harmonics spread.* Tag very close to the Tunnel Emitter enhances the spread of harmonics.

4 REST OF THE DESIGN

We discuss generation of unwanted emissions during back injection phenomenon, and a solution to mitigate this challenge. Additionally, we discuss the design of tag. Finally, we present scalability challenges and directions to support concurrently transmitting tags.

4.1 Harmonics Challenge

The mixing process of backscatter systems [25, 28, 34, 48, 53, 56, 58, 59] results in unwanted harmonics [25, 48, 58] or mirror copy [25, 58]. This is challenging for our system because the back injection enhances these unwanted emissions, as we show in Figure 6. Further, the harmonics may spread outside the license-free ISM band or cause interference [48, 53]. Next, we investigate this aspect.

We experimented in two environments, namely, office and anechoic chamber. We kept the spectrum analyzer at a distance of 1.5 m from the Tunnel Emitter, a faraway distance from the near field region. Next, we programmed the tag to backscatter at a frequency offset of 100 kHz from the carrier signal. We used this offset building on related works [53, 56]. We varied the location of the tag from the Tunnel Emitter and, at each location, we performed three experiment instaces, collecting 15 samples each.

Figure 9 shows that the frequency spread of the harmonics is proportional to the location of the tag. At proximity (10 cm) the harmonics are spread over a larger bandwidth, and vice-versa. When the tag and Tunnel Emitter are reasonably apart, the spread is small and does not exceed the regulation for operation on the license-free ISM band. We observe this as the strength of the backscattered signal at Tunnel Emitter influences the back injection gain, that affects the strength of the harmonics. At close proximity, the amplified signal from the Tunnel Emitter is further reflected by the tag and we believe this severely aggravates the harmonics problem. We next discuss a mechanism to prevent the large spread of harmonics.

4.2 Tunnel to Tag

To prevent the large spread of harmonics, we enable the tags to detect proximity to the emitter device and stop backscattering. We build Tunnel to Tag on the insight that most tags usually employ envelope detectors for reception [19, 23, 27, 33, 36, 44, 58]. They are energy detectors and enable the reception at almost no energy cost. These envelope detectors sense the strength of the carrier signal generated by Tunnel Emitter and hence detect proximity.

The challenge we face is that the envelope detectors are designed with discrete components, and have reduced sensitivity [19, 24, 56]. Consequently, envelope detectors need the signal to be sufficiently strong for the reception. However, we found that in our experiment, the weak carrier signal generated from Tunnel Emitter was sufficient to excite envelope detectors at short range.

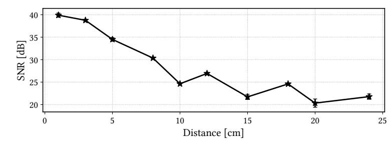


Figure 10: *Tunnel to Tag.* Envelope detectors are sensitive to carrier signal from Tunnel Emitter at short distances.

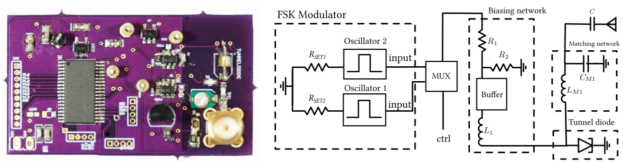
We designed an envelope detector building on Liu et al. [33], and created six stages charge pump using the HSMS 286C diode. Next, we connected the output of the envelope detector to an analog logic analyzer. We placed the receiver at different locations away from the Tunnel Emitter. Figure 10 shows that we could receive with sufficient SNR at proximity (up to 25 cm). This is precisely the short distance where we encountered the harmonics challenge. Thus, we used the reduced sensitivity of the envelope detector and the weak carrier signal strength of Tunnel Emitter to our advantage. We could then detect proximity to Tunnel Emitter and prevented the transmissions limiting the harmonic spread.

4.3 Backscatter Tag

Tunnel Emitter provides carrier signal to tags without requiring any modifications to their design. To exemplify this, we designed a backscatter tag using a standard RF switch similar to one employed in most recent systems, and we call this tag (conventional). Tunnel diode reflection amplifiers improve the ability to reflect a weak carrier signal, which is beneficial as the carrier signal generated by Tunnel Emitter is inherently weak. Hence, we also designed a tag using tunnel diodes, that we call tag (tunnel diode).

Implementation. We designed the tag building on LoRea [53]. We enhanced it to support reflection amplifier using the design presented by TunnelScatter [56]. We show the actual hardware prototype designed on a PCB of FR4 material in Figure 11(a), and present the schematic in Figure 11(b). At a high level, the tag works as follows; the tag generates a narrow bandwidth FSK transmissions using configuration from LoRea [53]. We kept the deviation between the two frequencies at 11 kHz, and transmitted at a low bitrate of 2.9 kbit/s. We kept the intermediate frequency at 100 kHz to reduce self-interference from the carrier signal. We used an MSP430 as a microcontroller for baseband processing due to its low power consumption. We used the low-power oscillator Linear Technology 6906 [32] for generating baseband frequencies. We used HMC 190BMS8 [22] as an RF switch on tag (conventional), and GE 1N3712 tunnel diode for reflection amplifier in tag (tunnel diode).

Powering tags. Backscatter systems commonly delegate energy delivery and communication to the same carrier signal [36]. For example, RFID readers generate a strong carrier signal, from which the tag harvests energy and then reflects it to enable transmissions. However, recent systems diverge from these designs by decoupling energy harvesting and communication, as there is significant asymmetry between the harvesting and communication range. This problem is further exacerbated for our system, as Tunnel Emitter generates a very weak carrier signal. Consequently, it is difficult (if not impossible) for our system to support harvesting energy on this carrier signal. Hence, tags in our system either operate on small batteries, or they harvest from other ambient sources, e.g., light.



(a) Prototype (b) Schematic

Figure 11: *Tunnel diode based backscatter tag.* It reflects a weak carrier signal with a significant gain.

Reception. We received backscatter transmissions using the highly sensitive Texas Instrument CC1310 transceiver [52, 53]. It has high sensitivity (−124 dBm), low-cost, and is highly configurable. We used the Launchpad board equipped with antenna of gain of 3 dBi.

4.4 Network and Scalability

Supporting several Tunnel Emitters and tags is vital to enable many applications, but this requires the design of a MAC layer protocol. We next present a sketch to support this functionality.

Multiple Tags. Backscatter tags are usually simple, and it is challenging to support sophisticated medium access control (MAC) mechanisms employed on their battery-powered counterparts, e.g., carrier sense or having the notion of time required by TDMA-based protocols. They often delegate part of this functionality to the emitter device or an edge device (receiver). However, delegation to the emitter device in unfeasible in our case since it is also resource-constrained. Thus, we have to devise a MAC mechanism that relies only on the capabilities of the tag and the edge device.

Within these constraints, we explored two approaches to support concurrently transmitting tags. *First*, we can use spreading techniques such as Direct Sequence Spread Spectrum (DSSS)[54] or Chirp Spread Spectrum [21, 48], which have been applied to backscatter systems. These techniques enable concurrent and reliable transmissions leveraging the powerful nature and processing ability of the edge device to separate and recover transmissions. We saw in our experiments that Tunnel Emitter can support DSSS-based narrow bandwidth FSK transmissions. *Second*, we can devise a scheme similar to Frequency Division Multiplexing (FDM). This can work together with the spreading techniques or in isolation. Here each of the backscatter tag can operate at a separate non-overlapping channel. In a concrete implementation scenario we can devise a mechanism as we describe below.

we program the tags with a list of non overlapping frequency channels. The tags have unique seed numbers or may derive such values from the environment. These can help select channels from the list of non overlapping channels, and the tags could cycle through these channels to avoid interference. If despite this, two or more tags select the same channel, we can allow the receiver to infer the interfering transmissions leveraging its powerful nature. Further, the tags may embed node identifier information to distinguish each other's transmissions. We explored the feasibility of this approach with an experiment. We kept three backscatter tags at a distance of 0.5 m from the Tunnel Emitter. Next, we positioned the spectrum analyzer about 8 m from the setup. We programmed these tags to derive unique frequency channels. Figure 12 shows the spectrum obtained and demonstrates that we could see three distinct transmissions. We also confirmed this by receiving these

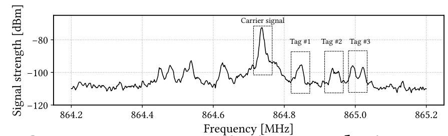


Figure 12: *Concurrent transmission.* We design a FDM mechanism to allocate distinct channel to each tag. This enables them to transmit concurrently with Tunnel Emitter.

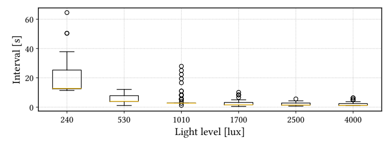


Figure 13: *Operation on harvested energy.* Improved light conditions enable frequent wake-up.

transmissions on a CC1310 receiver, and we did not observe any detrimental impact on the reliability of the transmissions.

Supporting Multiple Tunnel Emitters. In our system, emitter devices are resource-constrained like the tags. Hence, they encounter similar challenges as the tags. We had earlier shown the ability to change the resonant frequency of the TDO. We can leverage this to design FDM based medium access mechanism borrowing the earlier design presented for the tag.

Mitigating Harmonics. Harmonics are generated because of the use of square signal in the mixing process of backscatter systems [13]. These harmonics are amplified during the back injection phase. Mitigating the generation of these harmonics during the mixing process also helps to reduce their spread. In this respect, we can use designs presented by Zhang et al.[58], Iyer et al.[25] and Talla et al.[48]. We can also explore integration of passive SAW filters in the design of the Tunnel Emitter to suppress these harmonics.

5 EVALUATION

In this section, we evaluate different aspects of our system in a range of conditions. The key highlights are:

- Low-power consumption enables the Tunnel Emitter to operate on minuscule batteries, or without batteries on the energy harvested from a credit card-sized solar cell.
- Tags reflecting carrier signal generated from Tunnel Emitter achieve a significant gain of ≥ 20 dB when compared to reflecting a similar strength signal from an SDR.
- Tag based on LoRea [53] supports multi-floor communication when co-located with Tunnel Emitter.

5.1 Energy

In this section we evaluate the power consumption and we discuss experiments with Tunnel Emitter operating on harvested energy.

Power consumption. We measured the power consumption by connecting components to the Keysight power supply [29]. In Tunnel Emitter, the voltage regulator and the harvester are active components. Among these, the voltage regulator (S-1313) and harvester (BQ25570 consume just a few-μW of power. However, the harvester (S-8823a) consumes slightly higher power when operational. To measure the power consumption of the TDO, we bias it into the negative resistance region by adjusting the bias

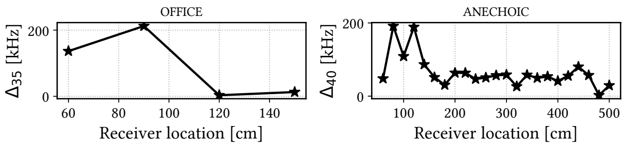
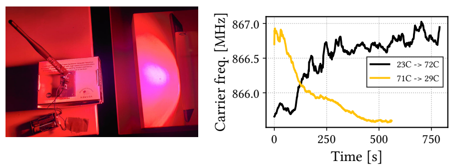


Figure 14: *Stability under back injection.* TDO drifts with the location of the tag due to changes in the strength of reflected signal and impedance changes.



(a) Tunnel Emitter (left) and infrared lamp (right)

(b) TDO's frequency drifts.

Figure 15: TDO stability under temperature changes.

voltage. This starts the oscillation, and we found the power consumption at the highest point of the IV-curve which we call *peak biasing power*. We found that the TDO consumes 57 µW (1N3712) for the generation of the carrier signal. We base the tag's design on LoRea [53], and it consumes approx. 70 µWs for transmission while the receiver (CC1310) consumes tens of mWs of power.

Harvested energy. We evaluated the ability of the Tunnel Emitter to operate on harvested energy. We performed this experiment using a small credit card-sized solar cell (Powerfilm thin film [40]) as an energy source, and we connected it to the harvester on the Tunnel Emitter. We positioned a spectrum analyzer about 10 meters away from the Tunnel Emitter and recorded the emissions. Next, we varied the light levels on the solar cell. We kept track of the light levels using a light meter (Texas Instruments sensor tag).

In this experiment, the Tunnel Emitter harvested energy from the ambient light. Once sufficient energy was harvested, it woke up and provided the carrier signal. Once the capacitor depleted, Tunnel Emitter went back to sleep. We expected that as we increase the light levels, the wake-up interval should decrease. Figure 13 shows the result and confirms our hypothesis. We found that, under light levels encountered in indoor environments (approx. 1000 lux), the Tunnel Emitter woke up every few seconds, that may be sufficient to support many sensing applications. In this experiment, Tunnel Emitter was active only for a few tens of milliseconds. This is due to the intermittent behaviour of the energy harvester chip that we employed. We saw that Tunnel Emitter could remain active without duty cycling for significantly longer periods on the BQ25570 harvester which does not have this intermittent behaviour.

5.2 Stability

In this section we evaluate the trade off between low-power consumption and stability of the TDO.

Stability under Back Injection. Earlier works have investigated the stability of TDO, and showed that it could deviate by tens of kHz over a few hours [56]. In this experiment, we investigated it during the back injection phenomenon. We set up a Tunnel Emitter and kept the conventional tag at a different location away from the Tunnel Emitter. We kept the spectrum analyzer approx. 1 m away from the Tunnel Emitter, and kept track of the frequency of the

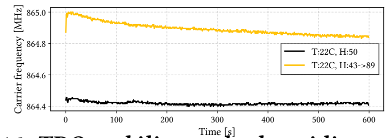


Figure 16: *TDO stability under humidity variations.*

carrier signal and the backscattered signal. We experimented in our office and an anechoic chamber. We looked at the deviation of the resonant frequency of the TDO from the initial position, i.e., when it was kept in proximity to the Tunnel Emitter.

We show the result in Figure 14. We found that the frequency of the TDO deviates by 100–200kHz with the tag location. This would require the receiver's frequency to be re-configured to receive transmissions. We also investigated the long term stability under the back injection phenomenon, when the location of the tag does not change in an anechoic chamber. Figure 7 shows that similarly to Varshney et al. [56], the frequency of the TDO changes slowly over a few hours. We did not see a significant drift in the frequency of the TDO when the tag and the environment are kept stationary.

Stability under Temperature Changes. In this experiment, we investigated the impact of temperature variations on the TDO's frequency. We changed the temperature of the tunnel diode using an infrared lamp approx 20 cm away from the Tunnel Emitter. Next, through a non-contact infrared thermometer, we kept track of the temperature of the tunnel diode at the start and the end of the experiment. We turned off the infrared lamp to cool the temperature of the tunnel diode. Finally, to keep track of the TDO's frequency, we positioned a spectrum analyzer approx. 8 m away from the entire setup. We show the setup and results of the experiment in Figure 15(a) and 15(b), respectively. We observed that, as the temperature increased from 26 to 72 degrees Celsius, the frequency of the TDO also increased. On the other hand, cooling the tunnel diode caused the opposite effect, and the frequency decreased.

Stability under Humidity Changes. We investigated the impact of humidity variations on the TDO's frequency. We changed the humidity by enclosing a Tunnel Emitter with a small humidifier, and we kept track of the humidity levels with a humidity sensor placed within the enclosure. Further, we kept track of the TDO's frequency through a spectrum analyzer. In the first run, the humidifier was off while in the second run the humidifier was on. Figure 16 shows the effect of humidity variations on the TDO's frequency. When the humidifier was off, we observed little or no change in the TDO's frequency. However, when the humidifier was on, the TDO's frequency decreased.

The drift in the TDO's frequency induced by changes in temperature and humidity has several implications. *First*, this requires that the receiver accounts for these drifts and re-configures its center frequency. As the receiver device is powerful and externally powered, it may estimate these drifts (e.g., temperature trends during day) and compensate for them. *Second*, it requires designing a suitable enclosure to house the Tunnel Emitter to reduce the impact of the surrounding environment. *Finally*, to support tags through frequency shift mechanisms, we could allocate a guard band between the channels and already account for these unwanted drifts.

Why does TDO drift?. Impedance of the tunnel diode is a function [6, 10] of the frequency (f), the bias voltage (V), the RF input power (P_{RF}), and humidity and temperature (T), i.e., $Z_L(f, V, P_{RF}, T)$.

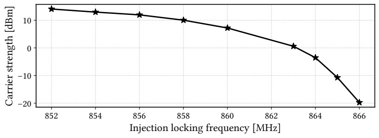


Figure 17: *Interference locking range.* A stronger interfering signal can influence the TDO even when it is far apart from resonant frequency of the TDO.

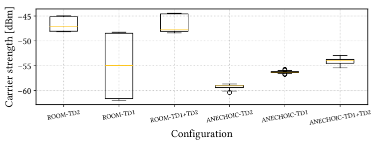


Figure 18: *Concurrent Tunnel Emitter.* It does not significantly enhance the carrier signal strength.

Changes in the backscattered signal strength changes the P_{RF} and cause alterations in the tunnel diode's impedance. This results in changes in the TDOs frequency.

5.3 Interference and Concurrent Emissions

We evaluate the impact of external interference. Further, we also investigate having concurrent transmissions from Tunnel Emitter.

Ambient Interference. Signals present near the resonant frequency of TDO influence them. This property helps us with back injection. However, this can also lead to unwanted ambient signals influencing the Tunnel Emitter. We investigated such conditions and experimented in an anechoic chamber. The Tunnel Emitter and the spectrum analyzer was kept approx. 1 m above the ground and separated them by 1 m. Next, we positioned an SDR 4 m away from the Tunnel Emitter and programmed it to generate an interfering signal. We generated interfering signals at different offsets away from the resonant frequency of the TDO. At each offset, we found the interfering signal strength influencing the Tunnel Emitter.

Figure 17 shows that when the interfering signal present near the resonant frequency, it influenced TDO even when the signal was weak, and vice versa. We found that the interfering signal had to be within a few MHz. We found that some signals, e.g., cellular, are at a large offset away from the license-free band where we operated and can not influence the TDO or interfere with it.

Concurrent transmissions. We investigated whether we could improve the carrier signal strength through concurrently transmitting Tunnel Emitter. In a practical scenario, we could place several Tunnel Emitters together near the tag to improve the carrier signal strength, which may enhance range. We performed this experiment in our office and an anechoic chamber. We co-located two Tunnel Emitters, that we call TD1 and TD2. We performed three runs of the experiment and kept track of the carrier signal strength using a spectrum analyzer. Figure 18 shows that contrarily to our expectations, we found that having two concurrently transmitting Tunnel Emitters did not improve the signal strength. The experiment conducted in our office made the signal weaker. We believe such behaviour could be because of destructive interference.

5.4 Gain and Comparison with the SDR

We evaluated the gain because of back injection phenomenon.

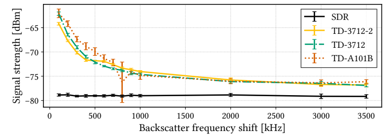


Figure 19: *Gain with frequency shifts.* Back injection gain decreases with magnitude of frequency shifts.

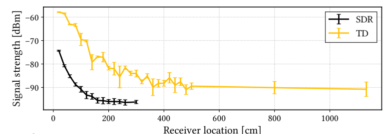


Figure 20: *Back Injection Gain.* Reflecting carrier signal from Tunneling Emitter results in a significant gain when compared to reflecting a similar strength signal from SDR.

Frequency Shift (FS) backscatter. This mechanism mitigates self-interference by keeping the backscattered and carrier signal apart in frequency [15, 28, 53, 60]. In this experiment, we evaluated the impact of FS-backscatter on the amplification gain achieved with the back injection phenomenon. We performed this experiment in an anechoic chamber using three distinct types of tunnel diodes that we discussed earlier in Section 2.1. We kept the conventional backscatter tag at a distance of 33 cm from the Tunnel Emitter. We kept the spectrum analyzer at a distance of 120 cm from the Tunnel Emitter and recorded the spectrum. We programmed the tag to backscatter at different frequency offsets from the carrier signal. First, we experimented with Tunnel Emitter. Next, we replaced it with an SDR generating a similar strength carrier signal.

We show the results in Figure 19. We found that there was no change in the strength of the backscattered signal with the frequency offset when reflecting carrier signal generated from an SDR due to the lack of the back injection phenomenon. When reflecting carrier signal generated from Tunnel Emitter, we saw a significant gain in the strength of the backscattered signal at lower frequency offsets (a few hundred kHz), which decreased as we shifted the reflected signal away from the resonant frequency of the TDO. We expected this as the back injection gain depends on the frequency separation of the external signal from the resonant frequency of the TDO, the strength of the external signal, and the quality factor of the TDO [6]. This variation in the gain with the shifts of the backscattered signal can impose challenges in supporting complex modulation schemes, a limitation that we discuss in Section 7.2.

Comparison with SDR. We experimented in an anechoic chamber where we kept the Tunnel Emitter and tag at a distance of 1 m above the ground. The signal strength was measured using a Keithley Spectrum analyzer [26] located 1 m away from the Tunnel Emitter. We programmed the tag to backscatter at an offset of100 kHz. As an emitter device, we used a USRP B200 [17]. We equip VERT900 [18] antenna with a gain of 3 dBi on tag and emitter device.

First, we experimented with Tunnel Emitter as emitter device. Next, we replaced it with an SDR generating similar strength signal. We recorded the strength of the backscattered signal and the carrier signal through a spectrum analyzer. Next, we position the tag from the emitter device at increments of 20 cm. We expect when backscattering the carrier signal from Tunnel Emitter, we could achieve a significant gain because of the back injection process.

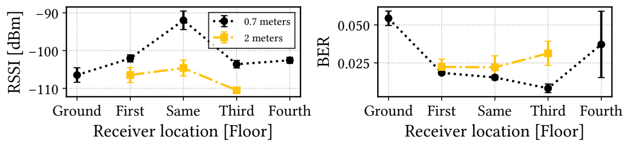


Figure 21: *Coverage with tag (conventional).* We cover several floors with the tag kept in proximity to Tunnel Emitter.

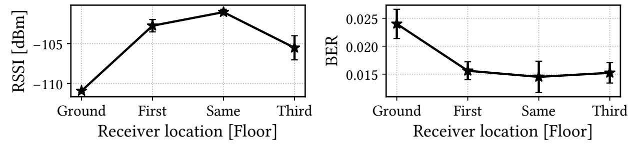


Figure 22: *Coverage with tag (tunnel diode).* We enhance the range of back injection phenomenon (12 m)

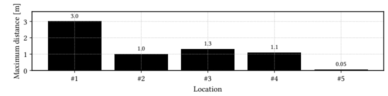


Figure 23: *Coverage without back injection.* We achieve much smaller range at larger distance away from the tag due to lack of back injection phenomenon.

Figure 20 shows that we could transmit up to a considerable distance of approx 10 m when reflecting the carrier signal from Tunnel Emitter. However, when we used an SDR to generate a carrier signal, we approached the noise floor of the spectrum analyzer at a distance of a few m. We noticed a consistent gain (average of 20 dB). This experiment showed that the back injection could lead to a significant improvement in the SNR of the backscattered signal and, as we will see in the next section, in the range. We used a standard RF switch in the backscatter mechanism as this represents the worst-case scenario, and also it is utilised by a large number of deployed tags. We expected tunnel diode based tags to increase the range up to which we can benefit from the back injection.

5.5 Coverage with Back Injection

We evaluated the ability to communicate using the long range backscatter tag in a challenging environment.

Setup. We experimented indoors and kept the emitter device and tag 1 m above the ground. This ensures that reflections from the ground do not affect us. We used a USRP B200 as a carrier signal emitter. As we used the long-range tag, we used the CC1310 as a receiver. In each run of the experiment, we sent random payload and, at the receiver, we kept track of the received signal strength (RSS) and the payload. We performed three independent runs of the experiment at each location. In each run, we transmitted 1200 packets. Similar to related work [53, 56], we used as a metric, bit error rate (BER) and RSSI for link quality. We powered it using a small battery of only a few millimeters in size used for powering hearing aids (PR70) [9]. Because of the limited peak current draw, it is challenging to operate conventional emitters using such batteries.

Tag (conventional) and SDR. We performed this experiment with a conventional emitter device, e.g., an SDR. This provides a baseline for improvements. We generated carrier signal of similar strength as our Tunnel Emitter, e.g.., ≈ -19 dBm. Next, we placed the tag at a distance of 0.7 m and 2 m from the SDR. Because of the weak carrier signal, we could transmit only up to a distance up to 15 m. We could achieve this at a BER of 0.144 and 0.167. We expected this result as systems like LoRea [53] generated many orders of magnitude stronger carrier signal to achieve a significant range.

We also performed one experiment with tag based on tunnel diode. We found that, because of the injection locking phenomenon, we achieved better range and we could support multi-floor communication (we omitted these results for brevity).

Tag (conventional) and Tunnel Emitter. In this experiment, we evaluated scenario with the tag reflecting a carrier signal generated from the Tunnel Emitter to assess the amplification gains achieved due to the back injection. We kept the tag near the Tunnel Emitter as the backscattered signal had to be strong at the Tunnel Emitter for obtaining the benefits of the back injection phenomenon.

Figure 21 shows that when the tag was at a distance of 0.7 m we could transmit to all four floors of our university building. As we moved the tag away from the Tunnel Emitter, the strength of the reflected signal decreased. At a distance of 2 m, we could only transmit to the adjacent floors (above or below us). In all these scenarios, the BER remained low and comparable to the related long-range backscatter systems that use energy expensive and powerful carrier signal emitters [53, 56]. At a distance of 3 m from the tag, we achieved a communication range up to 5 m, as the reflected signal was too weak for the back injection phenomenon to occur. This is less than observed in the anechoic chamber, as many factors were not present and could impact the wireless signals.

Tag (tunnel diode) and Tunnel Emitter. We investigated tunnel diode equipped tag and Tunnel Emitter. This should extend the region of occurrence of the back injection. We expected a large range even while operating at distances far away from the Tunnel Emitter. We kept the Tag (tunnel diode) at a distance as far as 12 m from the Tunnel Emitter, and achieved multi-floor communication, as we show in Figure 22. BER did not change significantly when compared to the earlier experiment involving conventional tag.

5.6 Coverage without Back Injection

We evaluated coverage under conditions when the tag is located far away from the Tunnel Emitter. This causes the backscatter signal at the Tunnel Emitter to be weak and insufficient in signal strength for the occurrence of the back injection phenomenon.

Setup. We experimented indoors within the premises of our university building and kept the Tunnel Emitter at a fixed location. We kept tag at five spots on the same floor, at distances of 8, 15, 18, 20 and 32 m. At each location, we evaluated the maximum range up to which we could receive the transmissions from the tag with signal strength just above the noise floor.

Result. We show the results of the experiment in Figure 23. We found that at a distance of up to 20 m from the Tunnel Emitter, we could communicate up to a range of 1 m. This reduced to few centimetres in Location #5m, which is about 30 m away from the Tunnel Emitter. To verify our results, we replaced the Tunnel Emitter with an SDR generating carrier signal of similar strength and observed a comparable range. We expected a small range because of a weaker carrier signal when compared to related systems [48, 53]. Further, because of the weak backscattered signal, we did not get amplification gains from the back injection phenomenon.

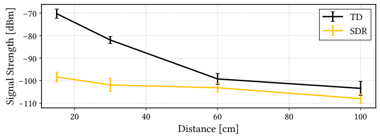


Figure 24: *High Bitrate (100 kbps) and back injection.* We observe a significant gain due to the back injection phenomenon even when backscattering at high bitrates.

5.7 Back Injection and Bitrate

We investigated whether the back injection occurs at high bitrates.

Setup. We experimented in our university where we varied the location of the tag from the emitter device. We programmed the tag to backscatter at a high bitrate of 100 kbps. First, we generated carrier signal through an SDR and, next, we replaced it with Tunnel Emitter. We positioned the receiver CC1310 approx. 8 m away.

Result. Figure 24 shows the result of the experiment. We observed a significant improvement in the strength of the backscattered signal when reflecting the carrier signal generated from Tunnel Emitter when compared to reflecting similar strength signal from SDR. We conclude that back injection phenomenon enables gain even when backscattering at high bitrates.

6 APPLICATION SCENARIOS

Tunnel Emitter has several distinct features that makes it distinct existing systems which can facilitate novel scenarios.

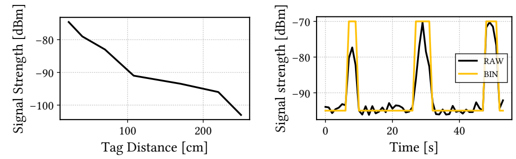
6.1 Proximity and Social Distancing

Back injection occurs at short distances from the Tunnel Emitter. This results in a zone around Tunnel Emitter where a tag can reflect the carrier signal with a gain. This is unique to the Tunnel Emitter system and can enable applications requiring proximity detection. Due to low-power consumption of Tunnel Emitter and backscatter tag, the system can be battery-free. Currently, this would only be achievable with an active radio or other energy expensive mechanisms requiring battery-powered devices.

We demonstrate the concept of proximity zone with an experiment; we placed the spectrum analyzer 8 m from the Tunnel Emitter and we varied the distance of the tag from Tunnel Emitter. Then, we kept track of the backscattered signal strength at the spectrum analyzer. The results from Figure 25(a) show that, as the tag moved away from the Tunnel Emitter, there was a significant drop in the backscattered signal strength. After a distance of 2 m, the strength was close to the sensitivity level of the spectrum analyzer. Consequently, we failed to detect the backscattered signal as the tag moved outside this region, that we call *proximity zone.*

To show the feasibility, we attached a backscatter tag to an object. Next, we brought the object in/out the proximity zone, and repeated the experiment ten times. We could detect all the events and we present a snapshot of processed spectrum data in Figure 25 showing detection of three events. Proximity zones can help with several application scenarios among which we describe one next.

Preventing spread of viruses requires maintaining a social distance of 1-2 m, that coincides with the proximity zone. We exploit this property to detect if proper social distancing is being maintained. We envision a scenario where people wear a device which raises an alarm when they cannot maintain social distance. At a



(a) Signal strength drops significantly outside the proximity zone (b) Events Detected

Figure 25: *Proximity property.* As tag moves outside the back injection region, there is a significant drop in the strength of the backscattered signal.

high level, these devices work as follows; a Tunnel Emitter and a backscatter tag are integrated in the device. The Tunnel Emitter and tag are activated sequentially. This prevents the tag reflecting signal generated from the same device. Next, when the devices encounters each other, the carrier signal is reflected by the tag integrated in this other device. Finally, a mobile phone or other devices can receive the backscattered signal and raise an alarm.

6.2 Back Injection Gain

Tunnel Emitter's low-power consumption and high gain due to back injection phenomenon lead to several application scenarios.

Factories. We envision Tunnel Emitter to have an impact in the next generation of smart factories. For example, backscatter tags are deployed at scale in factories for scenarios such as inventory management and asset tracking. However, the RFID readers used to interrogate them at present are bulky and energy expensive. Low power consumption and small size of the Tunnel Emitter could allow small drones to carry them and interrogate these tags. The large range due to the back injection phenomenon would further facilitate such deployment, enabling flexibility of placement of the receiver edge device within the factory floor.

Smart contact lenses. There is a growing interest to develop contact lenses with sensing, communication and other functionalities. Backscatter communication is a promising transmission mechanism [25, 48] for them. However, at present, backscatter enabled contact lenses function in an environment with a powerful carrier emitter device located in vicinity. This limits the scenarios mostly to an indoor environment. We envision that our system can support these scenarios. As an example, Tunnel Emitter can be integrated into earphones or sunglasses frame and provide the necessary carrier signal to the contact lens.

7 DISCUSSION

7.1 Tunnel Diode Transmitters (TDT)

Tunnel diode oscillators generate high-frequency RF signals at tens of µWs. This, as already demonstrated in TunnelScatter [56], enables the exciting potential of what we call tunnel diode transmitters (TDT). TDT can transmit at a similar power budget as a backscatter mechanism; however, it achieves this without reflections, thus not requiring a carrier signal emitter device. We ask and answer the following question: *do we still need backscatter systems ? Or should we replace the backscatter tags with TDTs ?*

The Tunnel Emitter system offers several advantages over TDTs. *First*, there are a large number of backscatter tags deployed, redesigning and replacement with TDTs requires a significant and

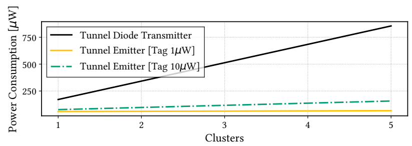


Figure 26: *Power consumption: TDO vs. TDT.* Tunneling Emitter operating in tiered architecture consume significantly lower power when compared only employing TDTs.

likely prohibitive effort. Tunnel Emitter can provide a carrier signal to such unmodified tags. *Second*, backscatter mechanism enables transmissions at few μWs of power, which is at least one order of magnitude lower than Tunnel Emitter. Deploying Tunnel Emitter system may lead to significant energy saving when Tunnel Emitter operates in a tiered architecture with tags. *Finally*, recent backscatter systems support complex modulation schemes such as ZigBee [25], WiFi [25, 28], BLE [15] and LoRa [48]. Currently, TDT designs transmit using ASK modulation scheme [56]. It is unclear whether complex modulation schemes can be supported and what will be the power consumption of such designs. In fact, we tried to design a TDT supporting FSK scheme, and experienced challenges that we now present in the form of failed effort.

Experiences in designing TDT. We attempted to design a TDT supporting FSK modulation adopting two approaches. In the first approach, we built on the insight that changing the bias voltage causes an alteration in the resonant frequency of the TDO. We can represent two frequencies for FSK modulation with two distinct voltage levels. We found that a minor change of 1 mV can lead to hundreds of kHz drifts of the TDO. This makes it challenging to generate narrow bandwidth FSK transmissions which require finer changes in the resonant frequency (few to tens of kHz). Our second approach attempted to mimic the backscatter mixing process and integrate an RF switch with the TDO. This approach resulted in severe and limiting spread of harmonics.

Power consumption. TDOs consume at least one order of magnitude higher power than the fundamental operation for backscatter, which is toggling the state of an antenna. A TDT would require, at the bare minimum, a TDO in its design and most likely need additional components, e.g., mixers, filters. We expect TDTs to consume significantly higher power than only TDOs serving as carrier signal provider. This would further widen the difference in power consumption between TDTs and backscatter tags. Thus, a backscatter system supported by Tunnel Emitter may consume considerably lower power compared to TDT-based tags only.

We took as an example the TDT design presented by TunnelScatter [56] that employs ASK modulated transmission at a peak biasing power of 57 μW. We consider this an optimistic baseline consumption for TDT. For uniformity, we considered the tag supporting ASK modulation scheme. In the simplest form, such a tag would involve toggling a state of an antenna which leads to a power consumption of 1 μW. Further, we may also frequency shift and backscatter; in this case, we estimate the power consumption to be 10 μW. This power consumption is similar to state-of-the-art tags, and we expect an IC implementation to be even lower. We had seen earlier in Section 4.4 that Tunnel Emitter can support at least three concurrently transmitting backscatter tags. Therefore, we assume a cluster formed by three tags and one Tunnel Emitter. An equivalent cluster with TDTs comprise four TDTs equipped tags. Figure 26 shows a plausible outlook of the power consumption of Tunnel Emitter and TDT-based systems according to network size. We find that the power consumption grows linearly with number of clusters, and it is noticeable that Tunnel Emitter system can have lower power consumption when compared to a TDT only system.

7.2 Limitations and Trade offs

Tunnel diodes availability. Tunnel diodes were first fabricated in the early 1950s; currently, their usage has declined and very few (if any) manufacturers produce them, which makes them difficult to buy. However, tunnel diodes have a long shelf life [16], and this enabled us to use tunnel diodes manufactured several decades ago. We believe tunnel diodes have significant potential for designing low-power communication mechanism, as showed by ours and other recent works [3–6]. This re-motivates large scale fabrication of these fascinating devices.

Frequency drift and unstable reference. TDO's frequency deviates with changes in the tag's distance or it drifts over extended time periods. This can be also caused because of motion near the TDO. These drifts are challenging as the tags often rely on the carrier signal from emitter device for stable clock reference. In this respect, we may use external signals such as light [19, 31] for providing stable clock reference to the backscatter tag.

Ambient interference. Injection locking phenomenon can amplify any signal that is present close to the resonant frequency of the TDO. As an example, RFID carrier signal or its reflections present near the resonant frequency may also influence the TDO. This may cause these ambient wireless signals to be amplified and relayed back in the network with a gain increasing the contention.

Modulation schemes. We have shown that Tunnel Emitter can operate together with a tag using FSK modulation scheme. In some of our initial experiments, we have also seen that tags employing ASK and OOK modulation schemes are supported. However, it is unclear whether complex modulation schemes are supported. For example, there may be challenges related to the back injection gain magnitude depending on frequency shifts. For instance, this might cause different sub-carriers of OFDM having different gains, affecting the overall SNR.

8 CONCLUSION

We presented Tunnel Emitter, a system that tackles the major limitation hindering the widespread deployment of backscatter systems, namely, energy-expensive emitter devices. For the first time, we demonstrate the back injection phenomenon of tunnel diode based oscillators. This phenomenon enables to achieve a comparable capability to the state-of-the-art systems while consuming orders of magnitude lower power for carrier signal generation.

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