Going Beyond Backscatter: Rethinking Low-Power Wireless Transmitters using Tunnel Diodes

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ABSTRACT

There is a stark disparity in the energy consumption for performing wireless transmissions and sensing/processing tasks in wireless embedded systems. The result is a dependence of these embedded devices on bulky batteries, which also last for a short period. To tackle this research challenge, we present our preliminary work to design a novel transmitter that enables transmissions at similar energy consumption as other operations in wireless embedded systems. This transmitter exploits the capability of tunnel diode oscillators to function as a self-oscillating mixer. We build on this property to design a transmitter that generates frequency-modulated transmissions at a peak power of well below 100 microwatts. Nevertheless, the transmitter trades off the stability of the carrier signal for low power, so we implement error correction codes to increase reliability. Our experiments demonstrate the potential of our transmitter to support short-range transmissions at low-power consumption.

1 INTRODUCTION

Over the years, wireless embedded systems (WES) have experienced remarkable growth, with millions of devices deployed globally. However, a major obstacle to this growth is the energy challenge, which refers to the significant difference in power consumption between wireless communication and other tasks in WES [8]. This challenge leads to frequent battery replacements that can be very burdensome, considering the enormous scale of deployment and limits the design possibilities for compact forms like stickers.

Conventional transmitters supporting standards like BLE, ZigBee, and WiFi consume power in tens of milliwatts [3, 5], far higher than sensors, such as those tracking motion and temperature measurements that require only a few microwatts. To understand the reasons for this stark difference, we need to examine the architecture of a transmitter. It can be broadly divided into analog and digital circuit blocks.

The analog block comprises oscillators, mixers and amplifiers and generates RF carrier signals. On the other hand, the digital block generates a baseband signal, which modulates an RF carrier signal produced by the analog circuits. Over time, the digital circuits in radio transmitters have become exceedingly energy-efficient due to Moore's law. However, we have yet to see similar improvements in circuits comprising analog block, which results in the significant power consumption associated with the radio transmitter.

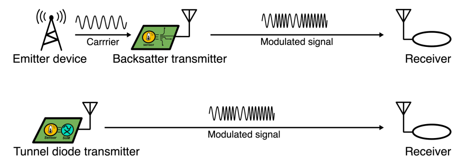

Figure 1: *Transmitter overview.* Unlike backscatter transmitters, our transmitter does not depend on an external carrier-emitting device. It generates a carrier signal and modulates it. Despite this, the power consumption of our transmitter remains comparable to that of a backscatter transmitter, operating at around tens of microwatts.

Backscatter communication. One promising solution to the energy challenge is backscatter mechanism [5]. This mechanism decouples the energy-intensive analog tasks from the transmitter and delegates them to an externally powered infrastructure, such as an edge device. They generate high-frequency carrier signals. Next, the backscatter transmitter only performs the digital baseband operations. It alters the state of an antenna to reflect or absorb this carrier signal to modulate it with baseband information, thus generating reflections constituting the transmissions. In this way, backscatter transmitters can even generate wireless transmissions that are compatible with commodity standards while consuming tens of microwatts of power [3, 5].

Despite the potential and at least a decade of sustained research efforts, backscatter transmitters have had little impact on real-world deployments. We believe the primary reason for the lack of adoption of backscatter transmitters is the strong dependence on an emitter device that provides the necessary carrier signal to support backscatter transmissions [7, 8]. In most backscatter deployments, the emitter device has to generate a strong carrier signal, and still, it has to be located in the proximity (within a few meters) of the

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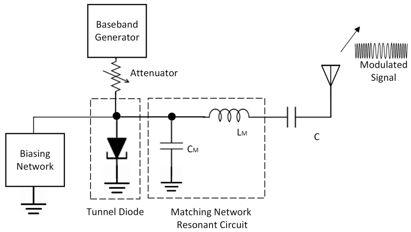


Figure 2: *Transmitter schematic.* The tunnel diode is biased in its RNR through a biasing circuit. It is coupled to a resonant circuit to ensure carrier signal generation in the 868 MHz band. The baseband signal is attenuated and mixed with the carrier signal generated by TDO using the SoM property of the TDO.

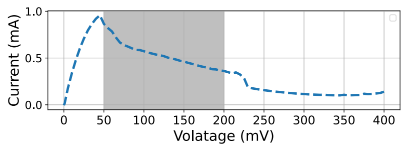


Figure 3: *I-V characteristics.* As we increase the bias voltage across the tunnel diode (1N3712), the current through the diode starts to drop (after a threshold voltage), demonstrating a region of negative resistance. We show this region with the shaded portion in the graph.

backscatter transmitter to achieve link metrics that outperform commercial transmitters [1, 3]. This limits the practical usefulness of the backscatter transmitters. Thus, there is a need to rethink low-power transmitters and go beyond the backscatter as a de-facto solution to the energy challenge.

Going beyond backscatter. One emerging solution beyond the backscatter mechanism is rethinking the analog circuits to lower the power consumption. These beyond-backscatter transmitters generate and modulate a carrier signal with baseband information [2, 4, 6, 8], similar to traditional transmitters. However, they make inevitable trade-offs in signal strength and oscillator stability that allow this task to be accomplished within the power budget of a typical backscatter transmitter or just slightly more. In particular, they take advantage of advances in the receiver's capabilities, particularly their ability to tackle noisy oscillators at the transmitter and achieve high receive sensitivity. As a result, like conventional radio transmitters, they require only two devices and eliminate the need for a carrier emitter, as shown in Figure 1. Thus, greatly simplifying the application deployments.

Varshney et al. [8] show that tunnel diodes can enable the design of low-power tunnel diode oscillator (TDO). TDO enables RF carrier signal generation at under 100 microwatts of power. We build on Judo transmitter in this work.

Tunnel diode transmitter. Tunnel diodes exhibit negative resistance and can be paired with a resonant circuit to generate oscillations. By leveraging this property, we develop a low-power TDO that generates a carrier signal using less than 100 microwatts of power. Generation of carrier signal usually represents the most power-intensive task in a radio transmitter which typically for calls for RF mixers for modulation with the baseband signal. In this regard, we take inspiration from Judo [8], utilizing the self-oscillating mixing (SoM) property of the TDO to mix the baseband signal with the locally generated carrier signal.

We must make tradeoffs to reduce power consumption. The TDO, for instance, is noisy and presents stability challenges. To address these issues, we explore using signal spreading and error correction codes in this work. Specifically, we implement Reed Solomon codes in combination with a convolutional encoder. Our early experiment demonstrates that this approach can result in communication with zero-bit errors under specific conditions, mirroring the capabilities of much more power-hungry transmitters.

We present early results. However, we believe they hold promise and can pave the way beyond backscatter as a defacto mechanism for low-power transmissions in WES.

2 DESIGN

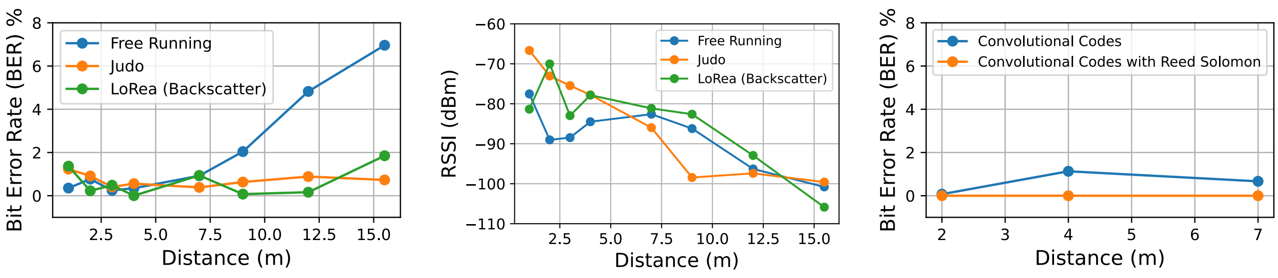
2.1 Transmitter

TDO. Tunnel diodes show regions of negative resistance (RNR). In particular, the RNR occurs at tens of millivolts of biasing voltage and a peak current consumption of a few milli-amperes. Consequently, they require a biasing power of only tens of microwatts. We use a tunnel diode, GE 1N3712, whose IV characteristics we show in Figure 3. We couple the tunnel diode with a resonant circuit tuned to generate frequency in the 868 MHz frequency band. It consumes under 100 microwatts for baseband generation. Next, the generated signal has to be mixed with baseband signal. We employ the SoM property of TDO to enable this mixing. In particular, we feed the baseband signal through an attenuator to TDO.

Baseband Generation. We use ESP32 with the ESP-IDF framework. We use LEDC (LED Controller) module to generate Pulse Width Modulation (PWM) signals, enabling generation of digital baseband signals through an external GPIO pin. It leverages FreeRTOS for task scheduling and inter-task communication. At core, we have two key tasks: *Packet Task* and *Timer*. The *Packet Task* generates packets containing header & payload data and periodically transmitting. Internally, it utilizes a queue to store the packet data's binary representation. The *Timer* task operates along an ESP timer, invoking the *Timer Callback* function at regular intervals. It retrieves the data from the queue and controls the PWM frequency and GPIO logic level to transmit the binary data.

Modulation. We use the Frequency Shift Keying (FSK) modulation scheme. We generate the two frequencies of 220KHz and 180KHz. This corresponds to deviation of 40 KHz, and an intermediate frequency of 200 KHz.

Enhancing reliability. Our experiments employed convolutional codes with a code rate of 1/2 and a constraint length of 7. For decoding, we use the receiver's built-in veterbi decoder. Despite utilising convolutional codes, we had packet loss and



(a) (b) (c)

Figure 4: (a) Link metrics as measured by BER for proposed transmitter (free running TDO), Judo and Backscatter (LoRea) transmitter with varied distances, (b) Received Signal Strength (RSSI) variation with distance, (c) Impact of Reed Solomon(Block Error Correcting Code) on BER for the proposed transmitter. Employing error correcting codes leads to significant improvement in link reliability.

burst errors. To handle this, we leverage reed-Solomon codes, interleaving, and convolutional codes.

2.2 Receiver

We use high-sensitivity receivers in our system to tackle the challenge of the relatively weaker signal strength of the transmitter. Specifically, we use the Texas Instruments CC1310 transceiver. It can operate with narrow bandwidths and can also utilize signal-spreading techniques. These increase receiver sensitivity and the link budget, thus extending the communication range. This receiver can also offset some frequency drifts from the TDO, enhancing link reliability.

3 EVALUATION

Setup. We conducted experiments in a university building. It is a complex radio environment with walls, furniture, and students sitting at the desk. We position the transmitter on a wooden cabinet, 1 meter above the ground. We employ omnidirectional antennas with 2dB gain. For performing the experiment with Judo/backscatter transmitter, we generate a carrier signal using a software defined radio, USRP B-200.

We configure the transmitter to a bitrate of 5 kilobauds (before coding and spreading), encoded with convolutional code (with code rate 1/2 and constraint length 7) and spread using direct sequence spread spectrum (with spread factor 2). We calculate the link metrics by sending 80-byte packets with a fixed payload. We perform two instances of experiments at each location. In each instance of the experiment, we collect over 1000 packets. We disable CRC checks and do not send checksum bytes. It permits packets with corrupt bits to be received, which the receiver would otherwise discard. We evaluate the received packets and compare them to the baseline sequence to calculate the bit error rate (BER).

Without coding. We evaluate the ability of the transmitter to communicate over short distances without employing any error correcting or spreading codes. We compare the transmitter to Judo and Backsctter(LoRea) transmitter. Figure 4a demonstrates that BER increases with distance from the transmitter. Furthermore, the BER for the proposed transmitter is much higher than Judo and LoRea. This is expected owing to the noisy nature of the TDO.

With coding. We examine improving link reliability by employing error-correcting code. In particular, we implement reed solomon (Block Error Correcting Code). Figure 4c shows the comparison of BER with proposed transmitter (free running) with/without Block Error Correcting Codes. We observe a significant improvement in reliability. In particular, convolutional codes do not correct burst errors and packet losses caused by the drift in TDO frequency. Especially for correcting errors caused due to this reason, we employ reed-solomon codes with interleaving on top of convolutional codes. However, we note that reed-solomon does not work effectively when packet losses exceed 8%.

Conclusion. We have introduced our work on designing a transmitter that overcomes the limitation of backscatter. it employs tunnel diodes to design a highly energy-efficient RF oscillator. However, it comes with trade-offs in stability and phase noise. To mitigate these constraints, we have explored using ECC and shared promising initial results.

REFERENCES

[1] Ensworth et al. 2017. BLE-backscatter: Ultralow-power IoT nodes compatible with Bluetooth 4.0 low energy (BLE) smartphones and tablets. *IEEE T-MTT* 65, 9 (2017), 3360–3368.
[2] Z. Renjie et. al. [n. d.]. SlimWiFi: Ultra-Low-Power IoT Radio Architecture Enabled by Asymmetric Communication. In *USENIX NSDI 23*.
[3] B. Kellogg et. al. 2016. Passive Wi-Fi: Bringing Low Power to Wi-Fi Transmissions. In *USENIX NSDI'16*. USENIX Association, 151–164.
[4] A. Kupferman, S.; Yehezkely. 2020. Low energy transmitter. US Patent 10,769,511.
[5] V. Talla at. al. 2017. LoRa Backscatter: Enabling The Vision of Ubiquitous Connectivity. *ACM IMWUT* (2017), 105:1–105:24.
[6] A. Varshney et. al. 2019. TunnelScatter: Low Power Communication for Sensor Tags Using Tunnel Diodes. In *ACM MobiCom '19*.
[7] A. Varshney et. al. 2020. Tunnel emitter: Tunnel diode based low-power carrier emitters for backscatter tags. In *ACM MobiCom'20*. 1–14.
[8] A. Varshney et. al. 2022. Judo: Addressing the energy asymmetry of wireless embedded systems through tunnel diode based wireless transmitters. In *ACM MobiSys'22*.