Beyond Backscatter: Rethinking Low-Power Wireless Communication to Tackle the Energy Challenge of Embedded Systems

C. Rajashekar Reddy
National University of Singapore
rajashekar.c@u.nus.edu

Abstract

Wireless communication remains the most energy-intensive component of embedded systems, often limiting their deployment in power-constrained or hard-to-reach environments. While backscatter communication offers energy efficiency by offloading carrier generation, it continues to face practical limitations, hindering widespread adoption. In this paper, we propose going beyond backscatter architecture that re-imagines both the transmitter and receiver using ultra-low-power components, such as tunnel diodes. Our approach eliminates the dependence on external emitters for transmission and moves beyond envelope detectors on the receiver side, resulting in significantly improved sensitivity and communication range.

CCS Concepts

• **Hardware** → **Wireless devices**; **Sensor devices and platforms**.

Keywords

Low-power wireless communication, Embedded systems

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1 Introduction

Embedded systems have become increasingly compact, widespread, and integral to daily life [1]. Despite significant technological advances, they continue to face a critical challenge: high energy consumption. Wireless communication remains the most energy-intensive task, often consuming an order of magnitude more energy than sensing or computation [2]. This is primarily due to the energy demands of generating radio waves, which rely on analog components such as oscillators, amplifiers, and mixers. Moreover, the growing number of devices competing for spectrum access—particularly in shared frequency bands—reduces communication reliability and increases latency and retransmissions [3].

Backscatter communication has emerged as a promising energy-efficient solution. It modulates ambient RF signals by toggling antenna impedance, enabling transmitters to offload power-hungry analog functions [2, 4]. Carrier signals are typically derived from external devices or ambient sources. On the receiver side, most systems use simple Schottky diode-based envelope detectors due to their ultra-low power requirements. Despite its promise, backscatter communication has seen limited adoption, prompting the question: *What has prevented the widespread deployment of the backscatter communication ?*

Several challenges have hindered broader adoption. Most backscatter systems require dedicated emitter devices to provide carrier signals, often necessitating precise placement near the transmitter tags [5], which limits their scalability. While some systems exploit ambient signals (e.g., FM or TV broadcasts), these are often too weak indoors and suffer from reflection losses, resulting in short communication ranges. Additionally, envelope detectors—though energy-efficient—suffer from poor sensitivity and limited selectivity, further constraining communication range and robustness.

Going beyond backscatter communication: To overcome these limitations, we propose eliminating the reliance on external carriers. Doing so would extend communication range, remove the need for dedicated carrier emitters, and optimize spectrum utilization—all while maintaining ultra-low power operation. One potential approach involves rethinking analog transmitter designs using components like tunnel diodes. These enable the generation and modulation of carrier signals embedded with baseband information at extremely low power levels [6–8]. Like conventional radios, such systems require only two devices, thereby removing the need for separate carrier sources.

While this may seem to contradict the traditional motivation behind backscatter—namely avoiding carrier generation—we argue that ultra-low-power, analog-based carrier generation using components like tunnel diodes offers a fundamentally different trade-off. Rather than fully returning to the complexity and power burden of conventional radios, our approach aims to retain much of backscatter's energy efficiency while dramatically improving range, robustness, and flexibility. In this sense, it represents a shift toward "**beyond-backscatter**" communication, combining the best of the both paradigms.

However, challenges remain—particularly related to signal strength and oscillator stability which reduce reliability and limit modulation to simple schemes. For example, TunnelScatter [7] uses a tunnel diode transmitter operating without an ambient carrier, employing OOK modulation. Judo [8] mitigates oscillator instability by injection-locking the tunnel diode oscillator (TDO) with a distant carrier emitter. Additionally, it leverages the self-oscillating mixer (SoM) property to combine carrier generation and mixing

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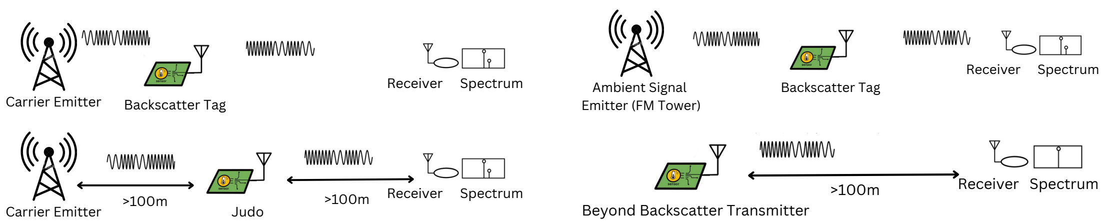

(c) Judo (Injection-locking)

(d) Our System - AudioCast

Figure 1: Traditional backscatter and ambient backscatter require external carrier emitters. Injection-locked systems like Judo improve range but require synchronization. Our system, AudioCast, avoids these constraints, transmitting FM-band signals up to 130 m with <200 µW power.

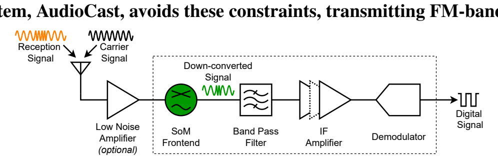

Figure 2: *SoMix* is a autodyning receiver architecture using the self-oscillating mixing (SoM) property of TDOs giving a high sensitivity (-67dBm) when compared to schottky diode-based envelope detectors while consuming less than 200 µW.

into a single component. However, it still depends on external emitters—albeit to a lesser extent than conventional backscatter systems.

2 Low-power Communication Beyond Backscatter

Tunnel diode oscillators (TDOs) offer ultra-low-power operation but suffer from poor frequency stability, resulting in phase noise and drift [7, 8]. Environmental factors like temperature, humidity [8], and nearby motion worsen this instability, degrading wireless reception. However, we found that this sensitivity can be repurposed for motion sensing. TDOs respond to nearby movements by shifting frequency—similar to a Theremin, where proximity affects oscillator capacitance. In our prior work, *TunnelSense* [9], we used this effect for respiration and gesture recognition.

Revisiting radio broadcast bands for embedded systems: We observed that operating TDOs at lower frequencies improves their stability. This led us to explore radio broadcast bands—specifically the FM band (88–108 MHz)—as promising candidates. Prior work has leveraged underutilized TV whitespaces [10] and FM bands [4]. However, with traditional broadcast services being phased out in many regions, ambient backscatter systems relying on FM or TV carriers may become infeasible. To address this, we introduced *TunnelRadio* [11], a µW-level FM transmitter capable of active FM transmission at power levels comparable to FM backscatter. Though FM use may raise regulatory issues, low-power, unlicensed FM transmission is permitted in many countries under regulations like FCC Parts 15.231 and 15.239. Moreover, regions phasing out FM (e.g., Norway) present new opportunities for spectrum-efficient, long-range communication for embedded systems.

Audio broadcasting low-power tags: Building on TunnelRadio and Judo, we recently developed *AudioCast* [12], a system that addresses both energy and spectrum challenges in embedded systems. It introduces a beyond-backscatter transmitter architecture that eliminates the need for external emitters, achieving sub-200 µW power consumption using off-the-shelf components—comparable to traditional backscatter tags. AudioCast operates in unoccupied FM radio bands and encodes sensor data as audio tones, enabling compatibility with standard FM radio receivers. It supports communication ranges of up to 130 m in outdoor line-of-sight (LoS) conditions.

Enabling bidirectional communication: Most embedded systems are designed primarily for upstream communication—transmitting sensor data to a central infrastructure. While AudioCast supports this effectively, it does not enable downstream communication, which is essential for actuation. Although prior work has demonstrated ultra-low-power transmissions (tens of µWs) over practical distances, efficient low-power reception remains a significant challenge. Traditional low-power receivers often rely on envelope detectors, which—despite their simplicity and energy efficiency—suffer from poor sensitivity and limited selectivity, ultimately restricting communication range and robustness. To address this, we developed *SoMix* [13], a tunnel diode-based receiver that exploits the autodyning property of TDOs to both generate a carrier and downconvert incoming signals using a single circuit. SoMix achieves a sensitivity of -67 dBm and can receive frequency-modulated transmissions over distances exceeding 100 m in outdoor LoS scenarios, all while consuming less than 100 µW at the receiver front-end.

3 Conclusion and Future Directions

In this paper, we examined key challenges limiting the widespread adoption of backscatter communication for low-power wireless transmission, with particular emphasis on the often-overlooked problem of low-power reception. While *AudioCast* represents a significant step forward by introducing a beyond-backscatter transmitter architecture, *SoMix* complements it with a low-power autodyning receiver architecture. Together, they enable long-range communication exceeding 100 meters. Looking ahead, we aim to build on these foundations to support two-way communication and advance towards realizing a fully integrated, ultra-low-power transceiver.

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