Demo: Enabling Ubiquitous Connectivity for Embedded Systems through Audio-Broadcasting Low-power Tags

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Figure 1: AudioCast enables low-power connectivity for embedded systems by broadcasting sensor data as audio in whitespaces present in FM-broadcast spectrum. It achieves upto 130 m range while consuming under 200 µW, and leverages existing FM receivers enabling ubiquitous communication.

ABSTRACT

Wireless connectivity challenges hinder large-scale deployment of embedded systems. We introduce AudioCast to address two critical issues: *spectrum scarcity-induced contention* and *high power consumption of radio transmitters*. The decline of FM-broadcast stations and the ubiquity of FM-receivers motivate the design of AudioCast. By leveraging the negative differential resistance of tunnel diodes—which occurs at low power—AudioCast rethinks the conventional transmitter design. Combined with their self-modulation capability, tunnel diode oscillators enable frequency modulated transmissions while consuming under 200 µW. The transmitter achieves upto 130 m range in line-of-sight and tens of meters in non-line-of-sight environments.

CCS CONCEPTS

• **Hardware → Sensor devices and platforms**; **Wireless devices**; *Networking hardware*; *Sound-based input / output*; • **Computer systems organization → Sensor networks**.

KEYWORDS

FM-broadcast spectrum, Wireless transmitters, Embedded systems, Internet of Things, Tunnel diodes

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1 INTRODUCTION

Wireless transmission remains the most energy-intensive task performed by embedded devices, consuming atleast an order of magnitude energy more than processing and sensing tasks [6, 9]. This stems from the need to generate radio frequency signals [1, 7], which involves power-hungry analog components such as oscillators, amplifiers, and mixers.

Backscatter transmitters offer a promising alternative and have attracted significant research interest over the past decade [1, 7, 9, 10]. By offloading energy-intensive analog operations to external devices, backscatter drastically reduces the power burden at the transmitter. This shift allows the transmitter to handle only low-power baseband processing and digital tasks. The required carrier signals can be sourced from dedicated infrastructure—such as readers and routers—or from ambient signals in the environment [7, 9–11]. However, despite numerous advances and significant research efforts, backscatter has seen slower adoption than expected. This is caused due to several challenges such as dependence on external infrastructure like dedicated carrier emitters and precise positioning of the tag [10]. Ambient backscatter systems, which utilize existing radio signals in the environment, often suffer from extremely weak carriers, resulting in impractically short communication ranges. Moreover, spectrum sharing makes these systems vulnerable to interference from more powerful devices using the same spectrum, resulting in packet losses, increased latency, and reduced reliability.

We present AudioCast, to address these spectrum and energy challenges in embedded systems. The critical contribution of the AudioCast is conceptualizing a novel transmitter architecture that moves beyond the constraints of backscatter mechanisms by eliminating the need for emitter devices. It addresses these challenges by using unoccupied FM-radio broadcast frequencies and leveraging existing FM-receivers for communication.

2 DESIGN

AudioCast [5] instantiates a beyond-backscatter architecture as an FM-compatible transmitter, leveraging the underutilized radio broadcast spectrum. It encodes data as frequency-modulated signals enabling reception by ubiquitous FM radios without hardware modifications as shown in Figure 1.

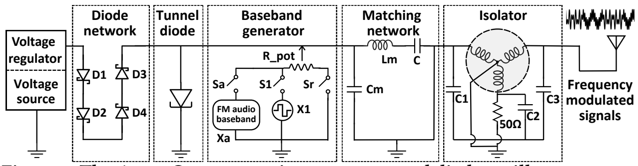

Figure 2: The AudioCast transmitter uses a tunnel diode oscillator to generate frequency-modulated signals in the FM band. An RF isolator and diode network ensure oscillator stability.

Building on prior work [8, 11], we design a tunnel diode oscillator (TDO) with the tunnel diode acting as the negative resistance element, and a resonant circuit consisting of an inductor, capacitor, and the parasitics in the board. By tuning the resonant circuit, the oscillator can operate across radio-broadcast bands. TDOs make several trade-offs to generate low-power carrier signals: weak output signals, high phase noise, and frequency instability.

Operating at lower-frequency. We observed that operating TDOs to generate lower-frequency carrier improves oscillator stability. Hence, we explore radio broadcast bands —FM (88–108 MHz) and TV (300–700 MHz)— that occupy the lower frequency spectrum as promising candidates. As broadcast services are being phased out in many regions, these bands are increasingly underutilized. Additionally, ambient backscatter systems that rely on FM/TV carriers may become infeasible in such scenarios. Prior work has leveraged underutilized TV white spaces [4] and FM bands [2]. In our work, we specifically configure the resonant circuit for the FM-broadcast band. AudioCast can utilize community-maintained databases [3] to identify active channels and dynamically adjust transmission frequencies. Alternatively, low-power envelope detectors [7] and scan-and-select mechanisms [4] can be used to detect and avoid active stations.

Self-modulation of tunnel diode oscillator. To enable reception using commercial FM radio receivers, it is necessary to frequency-modulate the carrier. We leverage the self-modulation property of TDOs [8] to transmit audio. In effect, the oscillator simultaneously generates the carrier and performs frequency modulation with the baseband signal, eliminating the need for additional circuitry.

Transmitter design. Through a combination of various design choices including, operating at lower frequencies, incorporating a dedicated diode network, using a voltage regulator, and adding an RF isolator—we stabilize the oscillator without relying on injection-locking [11]. Coupled with the self-modulation property, this conceptualizes the design of the beyond-backscatter transmitter, as illustrated in Figure 2.

Modulating sensor data as audio broadcasts. We draw inspiration from data-over-sound techniques. AudioCast transmits data using a combination of FSK and frequency multiplexing over the FM band, encoding data as distinct audio tones. First, we split the data into n-bit chunks and apply Reed-Solomon coding for error correction. We transmit T distinct, equally spaced tones at each transmission instance, conveying $n \times T$ data bits per instance. The frequency of the tones is given by $F_i = f_0 + (i * 2^n + (data)_{10})\Delta f$, where F_i is the frequency of the tone for the ith data chunk, f_0 is the base frequency, Δf is the frequency spacing and $(data)_{10}$ is the decimal value of data. Each audio frame is sum of T tones given by $m(f) = \sum_{i=0}^{T-1} F_i$, transmitted for a fixed duration.

To receive, commercially available FM radio receivers can demodulate the audio tones. The current transmitter prototype consumes less than 200 µW and can achieve a communication range of upto 130 m in outdoor LoS conditions as shown in Figure 3 and a summary of results is reported in Table 1.

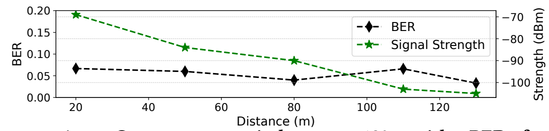

Figure 3: AudioCast can transmit data up to 130 m with a BER of 0.033.

Environment	Setup	Distance (m)	RSS (dBm)	PRR	BER	PESQ
Indoor	NLoS	14	-83	-	-	1.29
Indoor	LoS	45	-78	0.87	0.069	-
Semi-Outdoor	LoS	110	-109	0.89	0.1067	-
Outdoor	LoS	130	-105	0.9	0.033	-

Table 1: Summary of AudioCast range, PRR, BER and PESQ performance in different experimental settings.

3 DEMONSTRATION

We demonstrate AudioCast's ability to transmit frequency-modulated audio over the FM band using the described encoding scheme. A microcontroller encodes data as audio tones and generates the baseband signal, which is fed into the TDO for modulation and transmission. For ease of demonstration, we use a combination of USRP SDR and a COTS FM-radio as receiver to perform demodulation and decoding. AudioCast can be extended to support multiple tags by assigning non-overlapping bands, though the current demo uses one transmitter.

The demo will work as follows: The AudioCast transmitter broadcasts the audio encoded data in the FM band. The FM receiver will receive, demodulate and decode the transmission. The decoded data is then displayed and the audio is played in real-time.

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