

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

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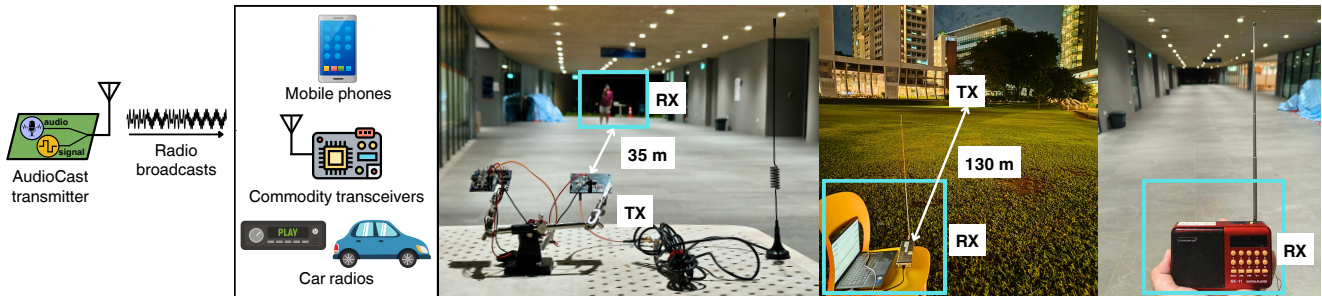


Figure 1: AUDIOCAST broadcasts information over audio in the FM broadcast spectrum. These transmissions travel up to a range of 130 m in line-of-sight environments and upto tens of meters in non-line-of-sight environments, while consuming only under 200 μ W of power. These transmissions are compatible with being received on commodity FM-radio receivers, found in cars and smartphones, thus enabling ubiquitous connectivity with existing infrastructure.

Abstract

The challenges in wireless connectivity continue to hinder the widespread, scalable, and sustainable deployment of embedded systems. We introduce AUDIOCAST to address the issues of *spectrum scarcity-induced contention* and *high power consumption of transmitters*. It leverages the availability of FM radio receivers operating within the 88–108 MHz spectrum, taking advantage of the superior radio-wave propagation characteristics afforded by lower-frequency bands. Specifically, AUDIOCAST achieves at least a 10 $\times$ reduction in path loss compared to the 2.4 GHz and 5 GHz ISM bands. This capability enables reliable long-distance communication while minimizing congestion and interference. AUDIOCAST employs a single tunnel diode oscillator to generate carrier signals, which are then self-modulated with data encoded in baseband audio signals. This results in frequency-modulated transmissions that consume under 200 μ W of power, yet travel over 130 m in line-of-sight conditions. Unlike backscatter-based systems, AUDIOCAST does not require an external carrier or depend on ambient signals, introducing a new category of transmitters termed **Beyond-Backscatter** transmitters, all while maintaining similar low power consumption.

*Co-primary authors with equal contributions to this work.

CCS Concepts

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

Keywords

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

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1 Introduction

Embedded systems are ubiquitous, with applications ranging from sensors that monitor our environment [11, 12] to communication systems that transmit or receive data [10]. As these systems are deployed at a large scale, their long-term sustainability has become a growing concern [5]. Wireless communication is the most power-intensive task performed by embedded devices, consuming at least an order of magnitude more power than sensing and processing [8, 16]. This high cost arises from the need to generate and amplify radio signals [6, 9], which involve power-hungry analog components such as oscillators, amplifiers, and mixers. Transmission consumes more power than reception due to its reliance on



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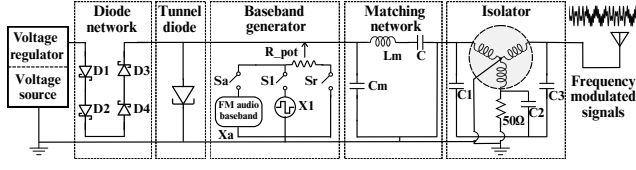


Figure 2: The AUDIOCAST circuit comprises a tunnel diode with a resonant circuit to generate a carrier signal locally thus, forming a tunnel diode oscillator. To maintain a stable resonant frequency, a biasing circuit ensures that the tunnel diode remains in its negative resistance region, also preventing resonant frequency fluctuations due to supply voltage changes. An RF isolator further stabilizes the TDO by blocking radio signals leaking back to the resonant circuit.

power-hungry amplifiers to produce strong signals. Since embedded systems generally transmit more frequently than they receive, mitigating the cost of transmissions can substantially reduce the overall power consumption.

Transmitters using backscatter mechanism emerged as a promising approach, attracting significant research interest over the past decade [6, 8, 9, 16, 18]. Backscatter transmitters reduce power consumption by shifting the energy-intensive analog tasks away from the transmitter, allowing it to focus solely on low-power baseband processing and digital tasks. The necessary carrier signals can be provided by powerful devices, such as readers and routers, or even ambient sources [9, 16, 18, 20]. Despite numerous advances, backscatter has experienced slower adoption than initially expected.

Several challenges have hindered the broader adoption of backscatter transmitters. In particular, they often require dedicated carrier emitter devices, which must typically be placed in close proximity to the transmitter, which limits their deployment [18]. Given that, the transmission range is often limited to tens of meters. Although some approaches attempt to leverage ambient signals, they face significant limitations, particularly in indoor environments where weak ambient signals, combined with the inherent losses of the backscatter process, lead to impractically short ranges [9, 22]. Furthermore, operating in a shared wireless spectrum introduces additional complications. Inherently weak backscattered signals are highly susceptible to interference from more powerful coexisting devices, resulting in packet loss, latency, and reduced reliability.

We introduce AUDIOCAST, to address these spectrum and energy challenges of embedded systems. The critical contribution of 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 [14] introduces a beyond-backscatter architecture as an FM-compatible transmitter, using the underutilized radio broadcast spectrum (88–108 MHz). It encodes data as frequency-modulated signals, allowing reception by existing FM radios without any hardware modifications, as shown in Figure 1.

Building on prior work [13, 20], we have designed a tunnel diode oscillator (TDO) in which the tunnel diode itself serves as the negative-resistance element, and a resonant circuit—composed of an inductor, a capacitor, and the board’s parasitic components that determine the oscillation frequency. TDOs trade off output power for low-energy operation, resulting in relatively weak signal strength, higher phase noise, and reduced frequency stability. We make the following design choices to improve frequency stability.

Low-frequency operation. We found that generating a lower-frequency carrier with TDOs enhances oscillator stability. Therefore, we investigate radio broadcast bands—FM (88–108 MHz) and TV (300–700 MHz)—which lie in the lower-frequency spectrum, as promising options. Since broadcast services are being discontinued in many areas, these bands are becoming increasingly under-used, leading to a whitespace in the spectrum. Moreover, ambient backscatter systems dependent on FM/TV carriers could become impractical under such conditions. Previous studies have exploited vacant TV white spaces [3] and FM bands [22]. In our approach, we tailor the resonant circuit specifically for the FM-broadcast band. AUDIOCAST can leverage community-maintained databases to detect active channels and adapt transmission frequencies in real time. Alternatively, low-power envelope detectors [9] or scan-and-select techniques [3] can identify and avoid occupied stations.

Biasing circuit. Tunnel diodes are highly sensitive to bias voltage variations, which impacts the oscillator stability [19]. We use a diode network of low-forward-voltage barrier diodes in series to drop the supply voltage efficiently while isolating the oscillator from external noise. This diode network, combined with a low-power voltage regulator (1.2–1.3 V), stabilizes the oscillator and mitigates motion-induced resonant frequency drifts.

Isolators and EMI shielding. TDOs are susceptible to RF loading and electromagnetic interference [17], which can affect oscillations. We used an RF isolator and an EMI shielding enclosure to decouple the oscillator from load impedance changes and external EMI variations, ensuring a stable output frequency. We show the design schematic in Figure 2.

Putting it all together. Through the combination of above mentioned 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 [20]. In addition we use the self-modulation property of TDOs. To enable reception using commercial FM radio receivers, it is necessary to frequency-modulate the carrier. We leverage the self-modulation property of TDOs [13] 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 like mixers or modulators.

Modulating data as audio tones. We draw inspiration from data-over-sound techniques. AUDIOCAST transmits data using a combination of frequency-shift keying (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

$$F_i = f_0 + (i \times 2^n + (\text{data})_{10}) \Delta f,$$

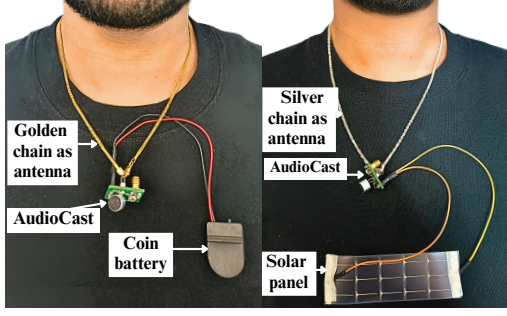


Figure 3: Metallic objects like chains can function as FM transmission antennas, enabling applications with AUDIOCAST in novel, wearable form factors like a pendant.

where F_i is the frequency of the tone for the i th 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 μ W.

Metallic objects as antennas. FM telescopic antennas are generally about 50 cm to 1.5 m long. This makes them inconvenient to use in FM transmitters for wearable applications. Metallic objects like chains and surfaces also possess the properties of antennas due to their electrical conductivity. Hence, we discover to repurpose gold and silver metallic chains as antennas to the AUDIOCAST transmitter as shown in Figure 3. Thus, the transmitter can be worn as a pendant and the metallic chain serves as the antenna. This enables various AUDIOCAST to used in wearable applications. Owing to its lower resistivity, the silver chain ($\rho = 15.9 \text{ n}\Omega \text{ m}$) provides stronger radiated power compared to gold ($\rho = 22.4 \text{ n}\Omega \text{ m}$). The signal strength of the generated carrier was measured using a spectrum analyzer placed 1 m away from the user wearing the transmitter. The signal strength for the silver chain was found to be -38 dBm , while the gold chain had a signal strength of -42 dBm , which is sufficiently strong for reception using commodity FM-receivers.

Power consumption. Since, the transmitter i.e. the baseband generator and the frontend, together consume about 200 μ W, they can operated on a coin cell or harvested energy from a solar panel. A CR2032, lithium coin cell rated at 3V is sufficient to power the system for over 100 days.

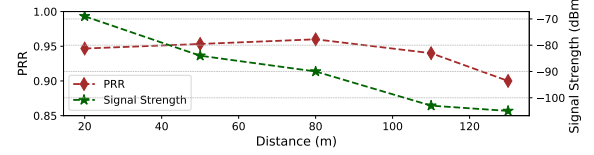
3 Evaluation

We evaluate AUDIOCAST in various environments and compare its performance to other systems.

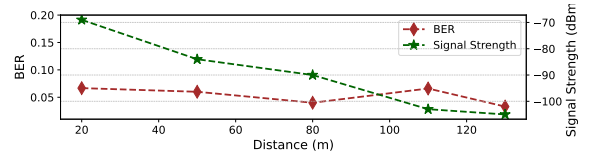
LoS evaluation. We evaluate AUDIOCAST in a fully outdoor environment with line-of-sight (LoS) conditions in an open field, as illustrated in Figure 4(a). There are minimal obstructions and controlled vegetation, which helps us evaluate the maximum operating range of our transmitter. The transmissions from AUDIOCAST are still successfully decodable at 130 m with a signal strength of -105 dBm , a packet reception ratio (PRR) of 0.9, and a bit error rate (BER)



(a) Outdoor LoS environment



(b) Packet reception ratio (PRR)



(c) Bit error rate (BER)

Figure 4: In an outdoor field environment with LoS setting, even with potential strong interference from ambient FM broadcasts, AUDIOCAST maintains high link quality. It successfully transmits data up to 130 m, achieving a received signal strength of -105 dBm , PRR = 0.9, and BER = 0.033.

of 0.033, as shown in Figures 4(c) and 4(b) respectively. This shows that our transmitter is robust and can reach high ranges while maintaining reliable link quality even in the presence of ambient signals and potential interferences.

NLoS evaluation. We also evaluated AUDIOCAST in a non-line-of-sight (NLoS) university environment. This represents a complex and multipath rich environment. The transmitter was kept inside an empty room and the receiver was placed in various adjoining and distant rooms to ensure a clear and discernible audio quality. Thus, even in the presence of strong reflections and interferences from the wall and rooftop, we notice that the system could support audio transmissions up to 14 m with discernible audio.

Comparison with other systems. Compared to transmitter systems operating in the similar frequency band, AUDIOCAST achieves higher range but a much lower power consumption. Further AUDIOCAST does not depend on a carrier emitter for transmission. It trades off range for lower data rates from 368 to 10.7 kbps, but this is still comparable to other systems. With denser modulation schemes like OFDM, we aim to further push the bitrate. The results are summarized in Table 1

4 Application Scenarios

Voice assisted tracker. Voice tracking using microphones enables various applications like note-taking, activity logging, and health

System	External Carrier	Frequency (MHz)	Range (m)	Power (μ W)	Bit Rate (bps)	Speech Quality (PESQ)
FM Backscatter [22]	Ambient carrier	88–108	6	11.07	3.2k	≈ 2
FM Backscatter [7]	Ambient carrier	88–108	19.6	150	1k	NA
Judo [20]	Carrier emitter	868	100	100	100k	NA
TunnelRadio [13]	Not required	88–108	24	150	NA	NA
AUDIOCAST	Not required	88–108	130	200	368–10.7k	> 1.29

Table 1: Comparison of AUDIOCAST with existing backscatter based systems and low-power transmitters. The AUDIOCAST transmitter can reliably transmit up to 130 m while maintaining the overall power consumption below 200 μ W.

monitoring [2, 4, 23]. These microphones are often found in phones, watches, and earbuds. However, they drain the battery when continuously recording/streaming and must handle speaker separation, direction, and noise. AUDIOCAST addresses this with a low-power FM-band tracker that directly self-modulates the carrier signal generated by the TDO from a microphone signal without needing any amplifier or heavy on-node processing. Figure 5 shows the tracker prototype. Later, an edge device performs automatic speech recognition (ASR) using models such as OpenAI Whisper and other computations, as shown in Figure 5(b). Moreover, as demonstrated in Figure 3, AUDIOCAST as a vocal tracker can be realized in wearable pendant-like form-factors ensuring its flexibility.

Sensor data communication in farms. Farms require low-cost, robust telemetry from distributed sensors (e.g., soil moisture, temperature, humidity) for crop monitoring, paving the way for data-driven agriculture [21]. These passive sensors can be interface with multiple AUDIOCAST transmitters to send sensor data over long distances to commodity receivers—such as a smartphone or tractor radio. Compared with cellular links that are often unreliable in rural areas, AUDIOCAST can broadcast data and complement long-range IoT stacks like LoRaWAN already used in agriculture. Further, this data can also be offloaded to commercial backhauling networks like Apple’s Find My [1, 15] for extended connectivity.

5 Demonstration

In this demonstration, we present AUDIOCAST, a system that enables low-power wireless connectivity by transmitting frequency-modulated audio signals over the FM band without the need for an external carrier signal. This system highlights its capability to encode and transmit data in real-time, utilizing a microcontroller-based low-power platform. Our goal is to showcase the potential of using audio broadcasting for data communication in embedded and resource-constrained devices.

The demonstration allows attendees to interact directly with the system. They can input custom data, either alphanumeric strings or live sensor readings, which are then processed for transmission. A microcontroller serves as the baseband generator, encoding this data into a series of audio tones. These tones create the baseband signal, which is subsequently fed into the TDO frontend for frequency modulation and transmission over the FM band.

To emphasize the robustness of our system, the transmitter can be positioned several meters away from the receiver. This setup may include both LoS placements within the same room and NLoS placements from a different room. This spatial flexibility showcases the system’s ability to operate under diverse real-world conditions without significant degradation in performance.

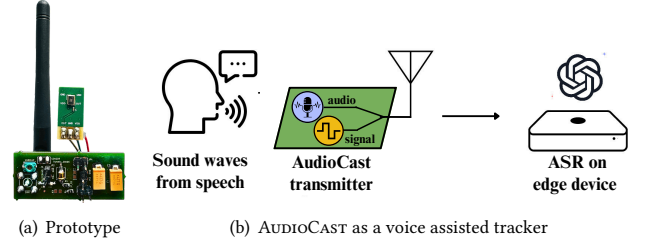


Figure 5: AUDIOCAST enables the realization of a tracker for monitoring vocal interactions. A microphone is coupled with the transmitter, which directly modulates the carrier signal to produce a frequency-modulated signal. Thus, AUDIOCAST serves as a vocal interface that connects with edge devices capable of running ASR.

On the receiver end, we employ a combination of a software-defined radio (SDR) and a commercial off-the-shelf (COTS) FM radio. These receivers are responsible for capturing the transmitted FM signals, demodulating them, and decoding the audio-based data. Once decoded, the information is displayed in real time on a screen, and the corresponding audio tones are played back, providing an immediate audio-visual representation of the transmission process.

This end-to-end demo illustrates how existing FM spectrum can be repurposed to create a practical and energy-efficient wireless communication channel for embedded devices. It highlights AUDIOCAST’s feasibility and opens up opportunities for low-power, scalable connectivity in ubiquitous and wearable computing.

6 Conclusion

We presented AUDIOCAST, which enables ubiquitous and sustainable connectivity for embedded systems. It tackles the energy challenge of wireless transmitters. The main idea stems from ideating the Beyond-Backscatter transmitter, which operates at low-power under 200 μ W and does not require a carrier emitter device or additional infrastructure for frequency modulation. AUDIOCAST achieves communication ranges of up to 130 m in LoS and 14 m in NLoS environments, while consuming under 200 μ W of power. These transmissions are further easily decodable by commodity FM receivers present in cars and smartphones. We realize AUDIOCAST in a wearable or compact form factor which opens up applications like an on-body voice-assisted tracker and also sensor data communication in farms. This motivates towards widespread sustainable embedded deployments. The code is released as open-source, with design files and other artifacts available at the following repository: <https://github.com/weiserlab/AudioCast>

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