GateHaul: A Gateway Architecture using Backhauling Networks to Address the Connectivity Challenges of Embedded Systems

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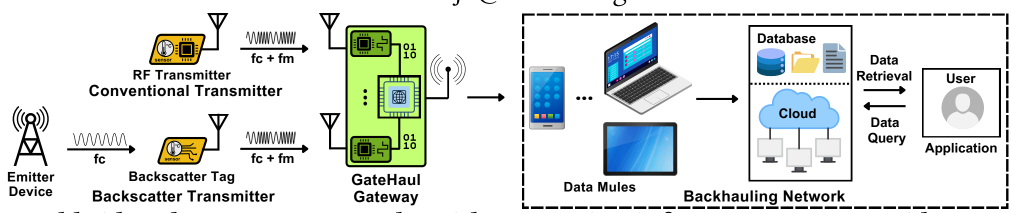

Figure 1: GateHaul bridges low-power networks with computing infrastructure. It provides carrier signals for low-power transmitters, while also collecting sensor data and backhauling it opportunistically to remote servers.

Abstract

Significant efforts to address the energy challenges of embedded systems have resulted in the design of new low-power transmitter architectures. These transmitters utilize backscatter or tunnel diode-based mechanisms to enable low-power transmissions by delegating energy-intensive tasks to external infrastructure. However, their widespread adoption is hindered by the need for specialized deployment setups, such as the precise placement of carrier-emitting devices. To overcome this, we are developing GateHaul–a low-cost gateway architecture that provides the required carrier signal, coordinates with other gateways, collects sensor data, and backhauls the information. Notably, GateHaul can backhaul sensor data without conventional networks utilizing emerging opportunistic backhaul networks. We demonstrate an early prototype of GateHaul that collects information from backscatter and conventional devices and backhauls the collected information using Apple's FindMy network.

CCS Concepts

• **Networks** → *Programming interfaces*; • **Hardware** → **Networking hardware**; **Wireless integrated network sensors**; **Wireless devices**.

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1 Introduction

Wireless communication remains a challenge in the sustainable deployment of embedded systems as it is energy-expensive [12]. Emerging radio architectures [5, 7, 8] lower communication energy costs but face adoption challenges due to the need for specialized infrastructure in deployments.

Emerging radio architectures delegate the energy-intensive task of generating the transceiver's local oscillator to external infrastructure [5, 7, 8], with dedicated devices like RFID readers providing the carrier signal. However, reliance on such dedicated carrier-emitting devices, a non-standard modality, complicates the setup [17] and necessitates precise positioning of the emitter relative to the tag, further exacerbating deployment challenges. Another challenge is integrating these systems with broader computing infrastructure. Sensor data needs to be communicated to remote servers for processing, but these transmitters often rely on non-standard protocols, complicating integration. While some efforts have addressed this by supporting standard protocols [3, 9, 19] like WiFi [6] or BLE [4], offloading sensor data to remote servers for processing remains a significant unaddressed challenge.

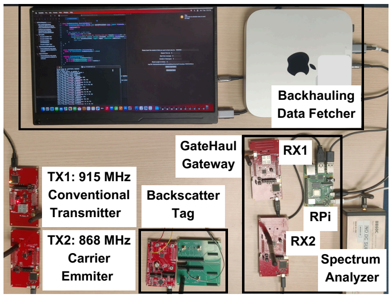
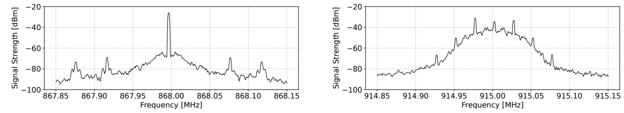


Figure 2: Demonstration setup includes the GateHaul prototype, a backscatter sensor, a conventional transmitter, and a computer for retrieving information.



(a) 2-FSK Backscattered signal (b) 2-GFSK Traditional RF signal

Figure 3: The spectrum of signals backhauled by GateHaul. We backhaul the 2-FSK modulated signal from low-power embedded devices in the demonstration.

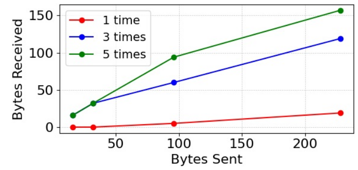


Figure 4: Packet reception rate improves with the number of mules and transmission rate at the gateway.

We address these challenges by designing a gateway architecture called GateHaul. This system facilitates the collection of sensor data from low-power embedded devices, including those equipped with backscatter transmitters. GateHaul manages the intricacies of these devices, for example, by providing necessary carrier signals. Moreover, GateHaul enables the offloading of collected data even without traditional backhaul networks like cellular connections. It achieves this by using networks such as Apple's FindMy.

2 Background and Design

Background. State-of-the-art backscatter transmitters support Wi-Fi [6, 7, 10], BLE [4, 10], and ZigBee [11, 22] standards, and some can communicate over vast distances [13, 16, 18]. Recent transmitters diverge from backscatter mechanisms by designing low-power oscillators using components such as tunnel diodes [14, 15, 23]. However, the challenge of collecting data from large deployments remains unaddressed.

GateHaul also builds on progress in gateway devices for embedded systems. Zachariah [20, 21] and Dutta [2] argue that embedded devices face challenges with gateways due to heterogeneous standards, necessitating a unified gateway platform. GateHaul extends these arguments to low-power networks. Beyond traditional gateways, efforts have been made to use commodity devices as data collection mules. For instance, Apple's FindMy network uses everyday Apple devices to offload tracker information. Recent works have repurposed these networks to send custom information. GateHaul extends on these efforts, building on TagAlong [1].

Design. GateHaul receives radio waves modulated by schemes such as on-off keying, frequency shift keying, and chirps. They form basis for standards commonly used in embedded systems, such as LoRa, BLE, etc. We instantiate an early prototype of GateHaul, as shown in Figure 2. It receives transmissions from low-power transmitters using backscatter [18] or tunnel diode based mechanisms [5]. We implemented support for frequency shift keying modulation, with symbol frequencies of 80 kHz and 120 kHz, at a baud rate of 10 kbps.

A commodity transceiver (TI CC1310) receives transmissions on the gateway. To support low-power transmitters that require an ambient carrier signal, we equipped the gateway to generate this signal using the CC1310's test mode, building on LoRea [18]. The gateway thus uses two CC1310 transceivers. We use a single-board computer for local processing, interfacing with the transceiver, and offloading information to the backhauling network. This ensures a low-cost, compact form factor suitable for ubiquitous deployment. In particular, we use a Raspberry Pi 4B, which is serially connected to the transceiver via UART. The gateway stores sensor information, identifies available backhauling networks, and offloads sensor data accordingly. For backhauling without conventional networks, GateHaul uses Apple's FindMy network. We compress sensor information and transmit it through bluetooth advertisements. Commodity Apple devices acting as mules receive these transmissions. The reception success rate depends on the transmission frequency and nearby mules in scanning mode. Frequent retransmissions improve the reception rates, as shown in the Figure 4 .

3 Demonstration

We demonstrate the GateHaul gateway's ability to demodulate both a backscattered signal at 868 MHz and a conventional signal at 915 MHz, each using 2-FSK modulation. The gateway then backhauls the information using nearby Apple devices, leveraging a modified version of TagAlong [1]. We show successful retrieval of the information from a computer located at some distance away from the gateway. The demo video can be viewed at: *https://youtu.be/UnxT9HFTJoQ*

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