



ZeroScatterPico: Bluetooth Low Energy (BLE) Backscatter Using Only Raspberry Pi Pico Digital I/O Pins

STUDENT: KEVIN HO, STANLEY ZHANG

Background and Motivation

Backscatter modulation enables ultra low-power wireless communication for mobile devices. Backscatter devices modulate an incident RF carrier by presenting a time-varying impedance to their antenna, rather than generating their own carrier wave as is done in conventional active transmitters. This eliminates their reliance on power-hungry RF oscillators, frequency synthesizers, and amplifiers, and enables them to achieve a level of power consumption that is orders of magnitude lower than that of conventional transmitters.

Recent work has focused on integrating backscatter communication with Bluetooth Low Energy (BLE), enabling compatibility with billions of devices deployed worldwide in smartphones, tablets, smart watches, etc. Existing backscatter modulators rely on digital logic driving external RF switches¹⁻⁵, field effect transistors (FETs)⁶⁻⁷ or other external components to provide a time varying impedance to the antenna.

This work employs the ZeroScatter approach⁸⁻⁹, which eliminates reliance on discrete components and instead uses a single input/output (IO) pin to achieve distinguishable RF impedances. We leverage a widely available and low-cost Raspberry Pi RP2350 as our ZeroScatter modulator.

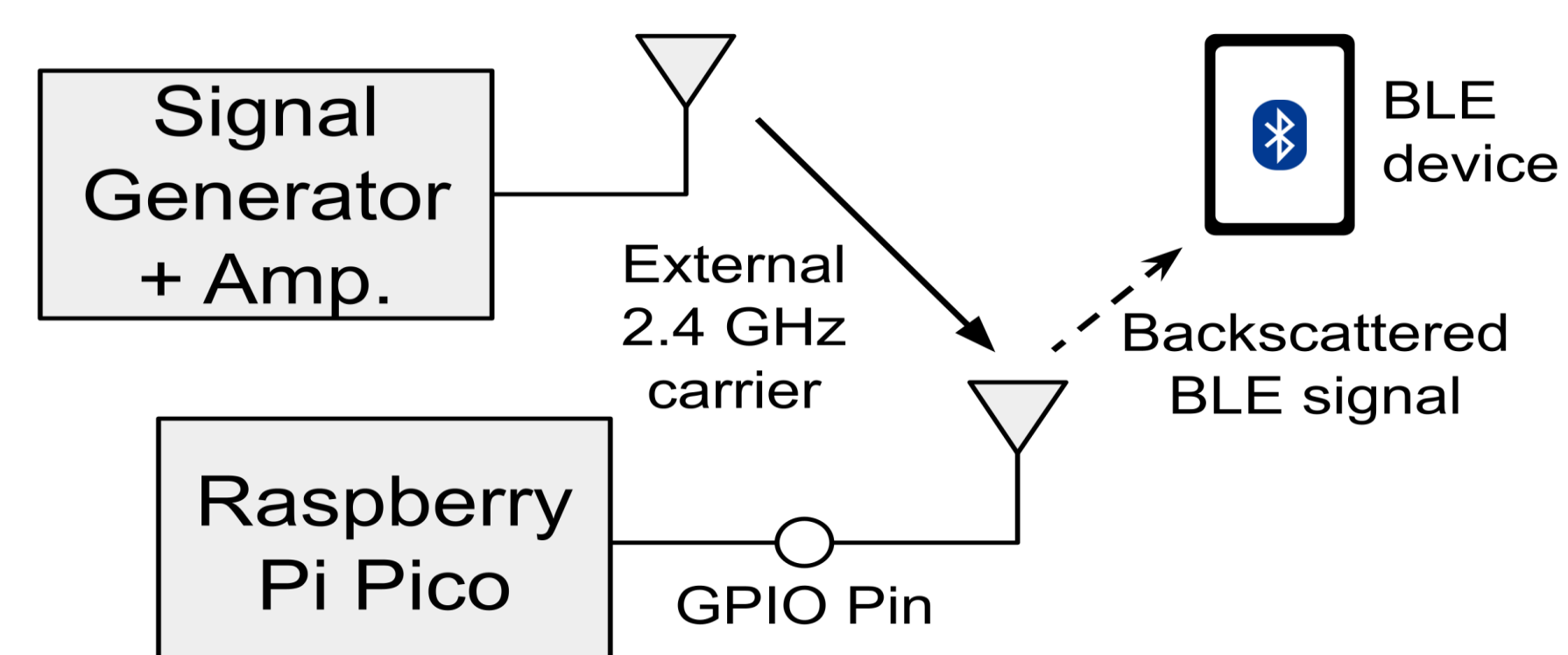


Fig. 1: Block diagram of Raspberry Pi Pico-based ZeroScatter BLE backscatter modulator

A four-layer, FR-4 printed circuit board (PCB) was constructed to expose a general-purpose input/output (GPIO) pin from the RPi Pico to an SMA connector. GPIO pin 6 was selected as the ZeroScatter modulator to minimize RF losses, as the PCB trace length from the RP2350 itself to the edge of the Pico board is the shortest.

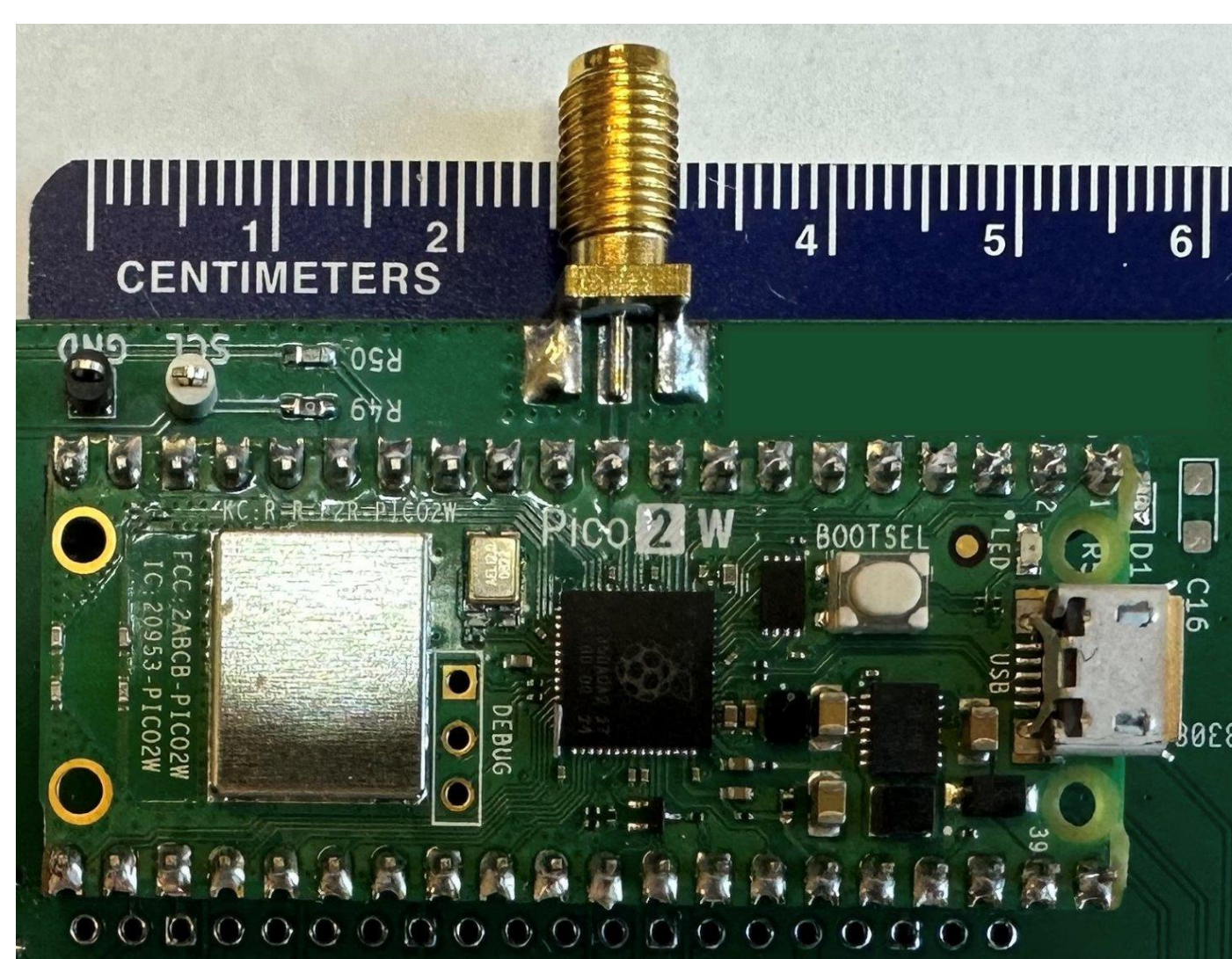


Fig. 2: Photo of evaluation test board

System Overview

The ZeroScatter approach exploits the two distinct impedance states inherent in switching between the input and output states of the GPIO pins on the RPi Pico. In typical RPi Pico programming architecture, the CPU handles general-purpose computation while the PIO state machines are designed for precise timing control and bit-level manipulation of GPIO pins. This programming structure is implemented as seen below in Figure 4. The PIO block is programmed to accept a binary bit-string holding a BLE advertisement packet. It then generates a frequency-shift keying (FSK) modulation using 2 MHz and 3 MHz subcarriers, representing data bits '0' and '1', respectively.

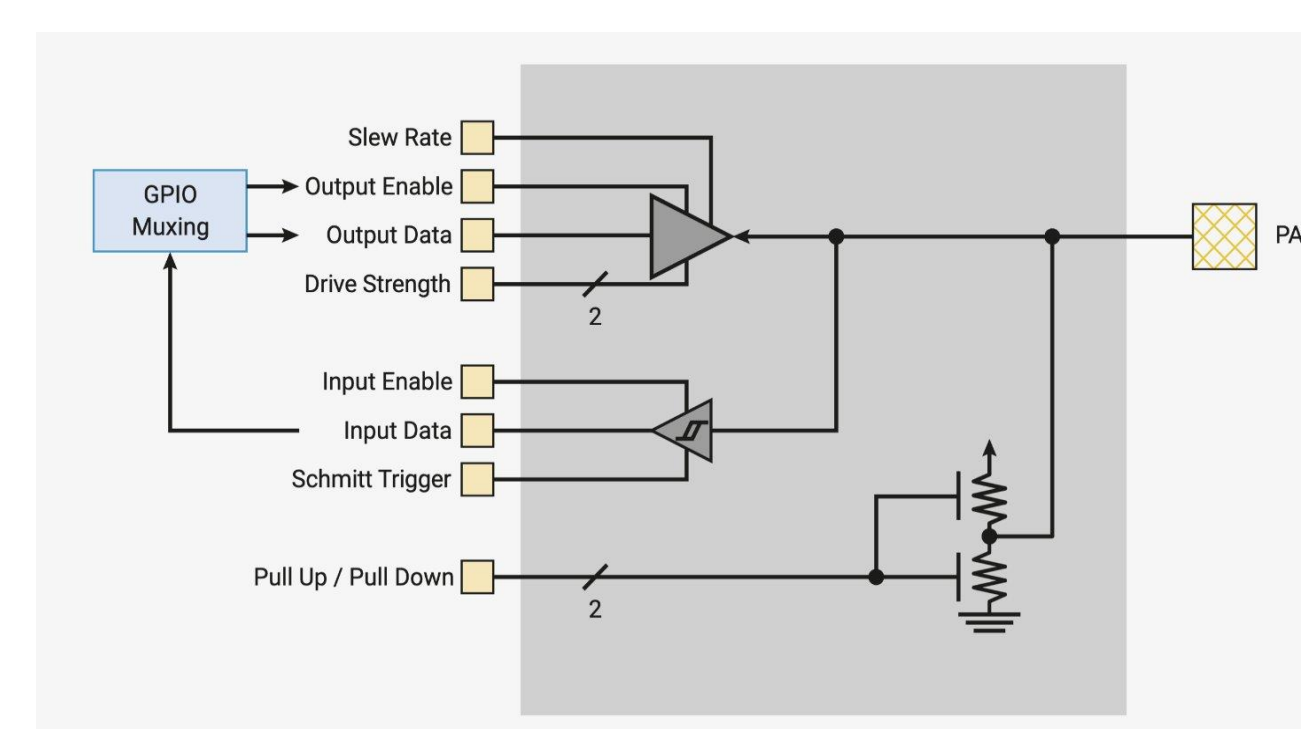


Fig. 3: RP2350 GPIO pin structure¹⁰

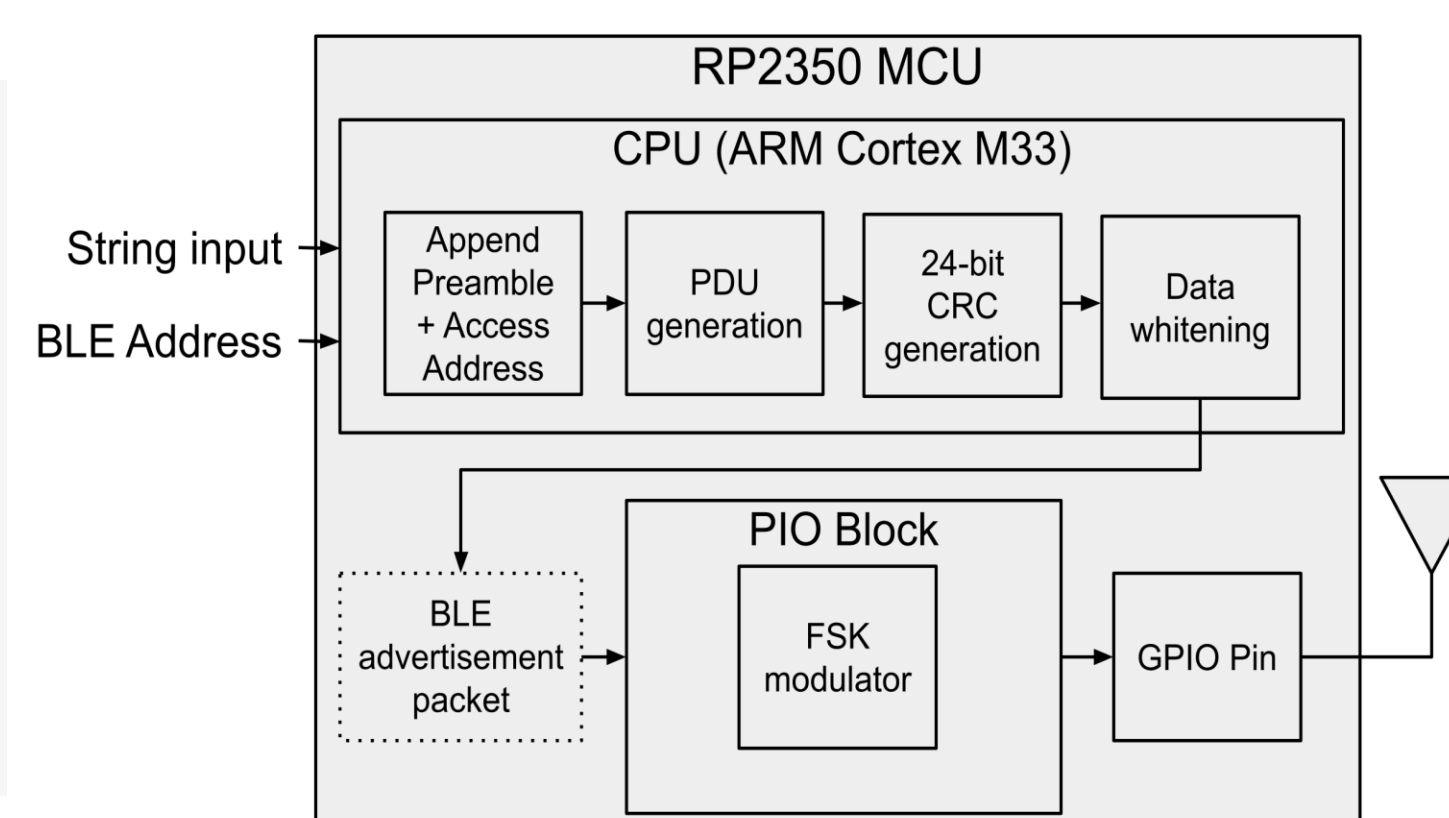


Fig. 4: Block diagram of RP2350 code structure

Experimental Validation

A bistatic configuration was set up in a typical office environment, using a 2423.5 MHz carrier from an external carrier wave (CW) source and an unmodified Apple iOS device used as a BLE receiver via a commercial BLE scanner app. The separation distance was fixed at 1.6 meters, and to measure the Received Signal Strength Indicator (RSSI), the RPi Pico was moved between the CW source and BLE receiver.

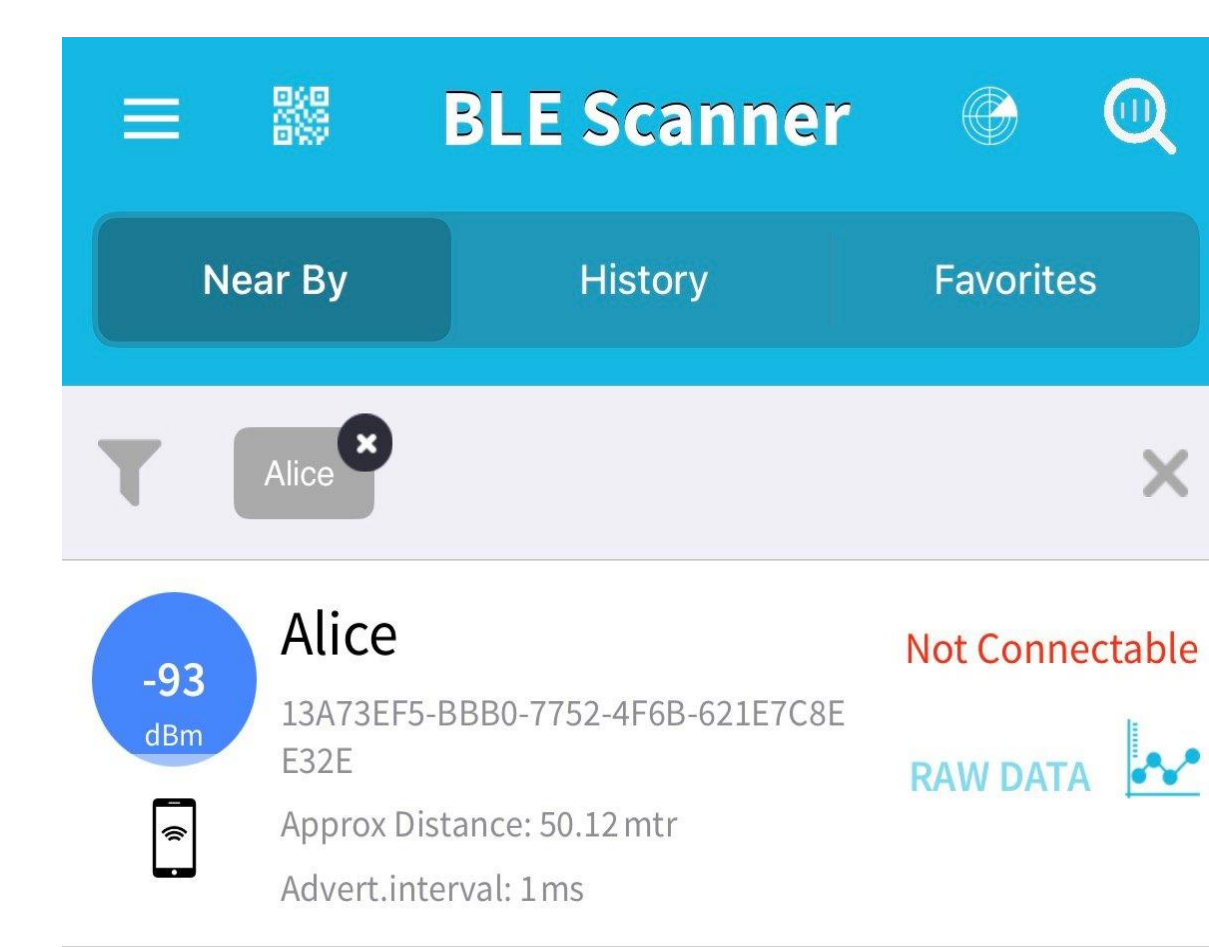


Fig. 5: Sample screenshots of BLE scanner app receiving a packet called "Alice"

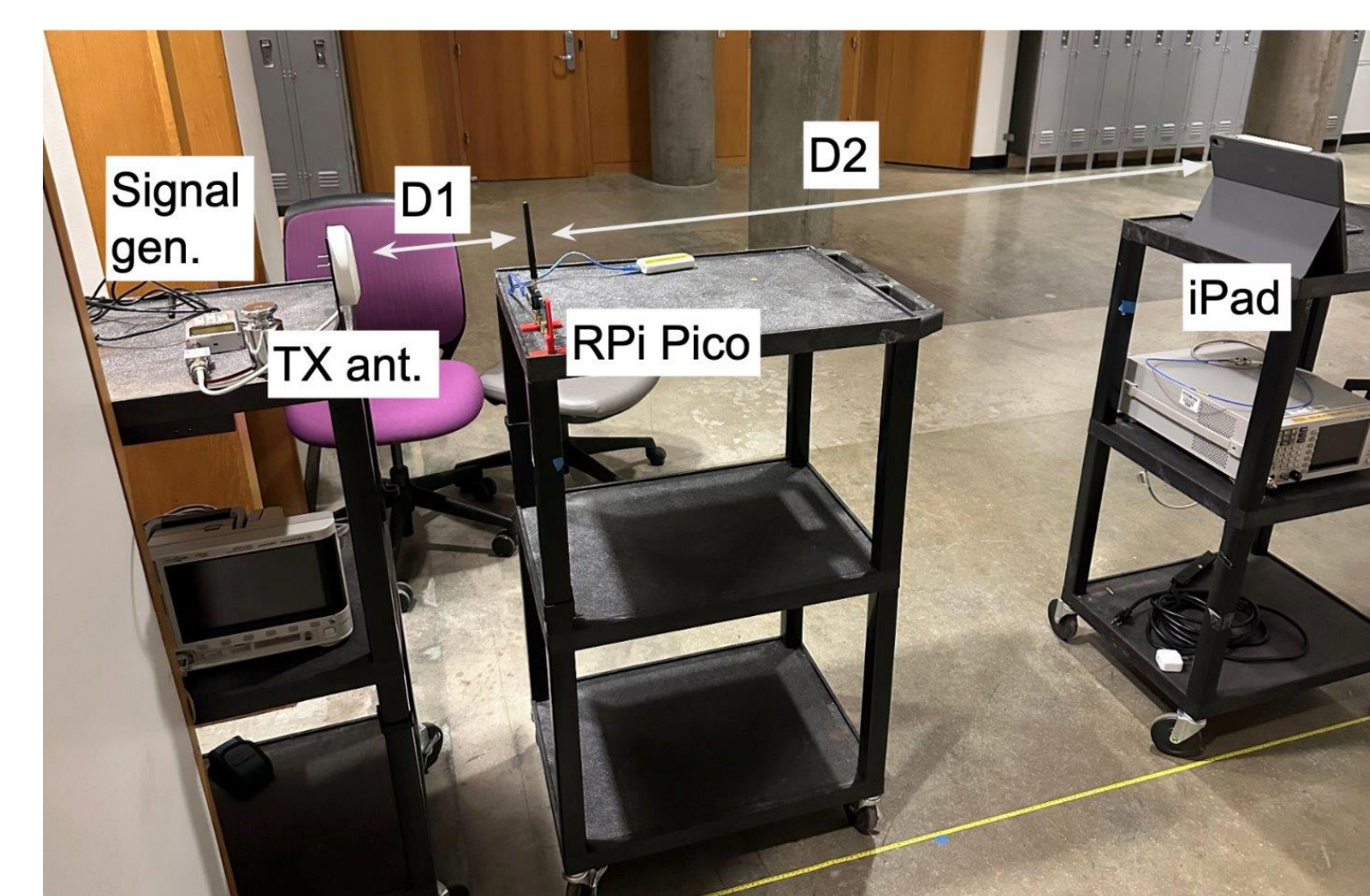


Fig. 6: Photo of bistatic experimental setup

Results Analysis

A vector network analyzer (VNA) measured the complex reflection coefficients of the two different GPIO impedance states. The two impedances corresponding to the output high and input (pull-down) GPIO pin states are discernible. These yield an average differential reflection coefficient, $|\Delta\Gamma_{50\Omega}|$ of 0.039 across the 2.4 GHz ISM band.

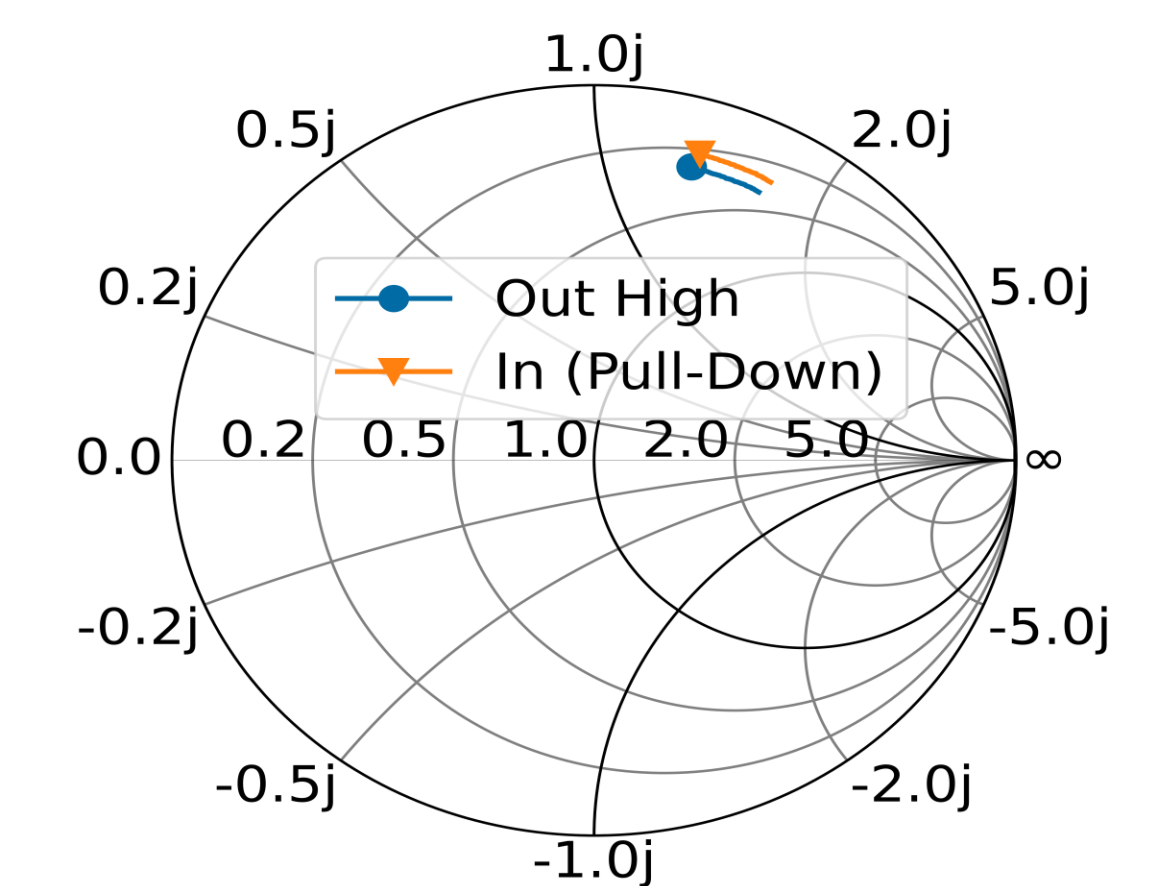


Fig. 7: Normalized Smith chart representation ($Z_0 = 50 \Omega$) of the measured reflection coefficients from 2400-2483 MHz.

The link budget for the RSSI measured by the iPad follows the equation⁹:

$$RSSI_{iPad} = P_{CW} + G_{TX} + G_{D1} + G_{tag} + G_{mod} + G_{tag} + G_{D2} + G_{iPad}$$

The modeled vs. measured RSSI results, with +20 dBm conducted carrier power and 1.6 m total bistatic separation, are plotted below. In general, the measured results qualitatively agree with the modeled link budget given the multipath-heavy test environment in the building.

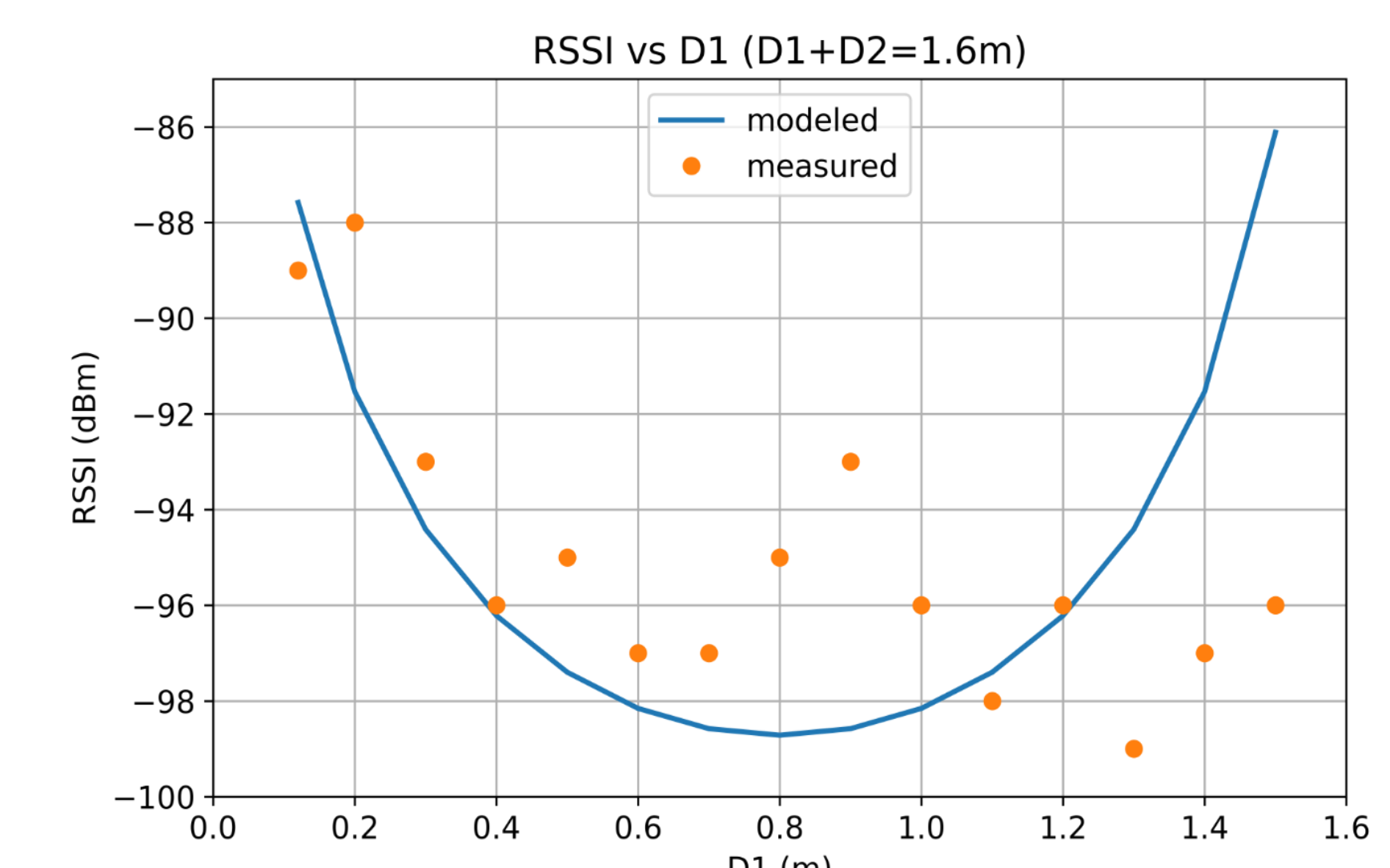


Fig. 8: Measured vs. modeled over-the-air RSSI vs D1(D1+D2=1.6 m) with +20 dBm output power.

Next Steps

- Adjust GPIO pin states and/or other pin parameters such as slew rate and output drive strength to potentially improve the backscatter communication range
- Miniaturizing the size of the tag by using smaller off-the-shelf RP2040/RP2350 evaluation boards like the Tiny 2350

References

¹Ensworth et al., *IEEE Trans. Microw. Theory Techn.*, 2017. ²Chen et al., *IEEE/ACM Trans. Network.*, 2021. ³Zhang et al., *Proc. ACM MobiSys*, 2021. ⁴Besnoff et al., *IEEE Access*, 2024. ⁵Dong et al., *Proc. Mobile Comp. Network.*, 2025. ⁶Ensworth et al., *IEEE Int. Conf. RFID*, 2015. ⁷Reynolds, *IEEE Microw. Wireless Comp. Letters*, 2017. ⁸Dadhkhan et al., *IEEE Top. Conf. WISNeT*, 2019. ⁹Reyes et al., *IEEE Int. Conf. RFID*, 2024. ¹⁰Raspberry Pi Ltd, 2025.

