All-Digital CSS Ambient Backscatter with 17.6 µW Power Consumption and a MISO Receiver

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***Abstract*— A fully-digital Chirp Spread Spectrum (CSS) backscatter system, is presented that consumes tens of microwatts and uses a Multiple-Input Single-Output (MISO) receiver. The system uses ambient FM signals as carriers to wirelessly transmit information. The receiver uses a portable low-cost Software-Defined Radio (SDR) that captures 6 MHz of spectrum, enabling reception from multiple FM stations to protect against outages, noise, and interference. The novelty of the tag design is removing the Digital-to-Analog Converters (DACs) and Voltage-Controlled Oscillators (VCOs) needed in similar works. Instead, the tag uses the Microcontroller's (MCU) Inter-IC Sound (I²S) peripheral to create digitally sampled CSS chirps that control the Radio-Frequency (RF) switch. A tag prototype was built and tested, showing successful packet decoding beyond 100 m at a bit rate of 273 bps while receiving backscattered signals from 3 FM stations. The design confirms the long-range and low-power capabilities (17.6 μW) of low-cost ambient backscatter approaches.**

***Keywords*— backscatter, chirp spread spectrum (CSS), energy-aware communication, Internet of Things (IoT), long range (LoRa) modulation.**

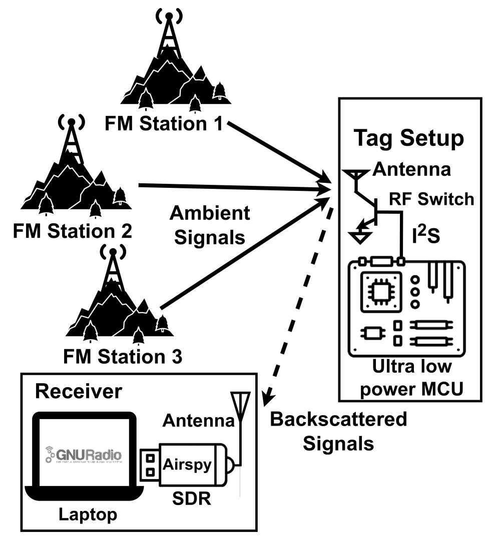

Fig. 1. LoRAB 2.0 system architecture showing ambient FM backscatter tag with I²S-based CSS generation and MISO receiver capturing reflected signals from multiple FM stations.

I. Introduction

In recent years, ultra-low-power wireless communication has become critical for Internet of Things (IoT) deployments. Backscatter communication represents one of the most promising paradigms in this field. It enables small devices to transmit data by modulating existing radio-frequency (RF) signals without generating their own RF carrier. This approach inherently reduces power consumption and hardware complexity of battery-free or ultra-long-lifetime sensor nodes.

Traditional backscatter systems use simple modulation schemes such as On-Off Keying (OOK) or Frequency-Shift Keying (FSK) [1]. To support higher data rates, longer ranges, and more robust links, recent research has explored higher-order modulation schemes and advanced waveform strategies. Recent work [2], demonstrated four-level pulse-amplitude modulation (4-PAM) for ambient FM backscatter. They exploit ambient FM signals with multi-level amplitude modulation for enhanced spectral efficiency in backscatter communications.

These advancements in modulation complexity have enabled long-range backscatter systems. Seminal research on Long Range (LoRa) Backscatter [3], demonstrated chirp-spread-spectrum (CSS) modulation over a dedicated RF source, achieving ranges up to 2.8 km with the tag being close to the source. However, this architecture requires a dedicated RF emitter with a complete CSS transmitter chain. The design includes a Digital-to-Analog Converter (DAC), a Voltage-Controlled Oscillator (VCO), a switch mapper, and a Single Pole, 8 Throw (SP8T) switch, resulting in significant hardware complexity.

Simpler baseband signal generator alternatives have been recently explored. Work in [4] uses Single Pole, Double Throw (SPDT) switches and Field-Programmable Gate Arrays (FPGAs) to generate LoRa-compatible signals. This reduces complexity but still needs Register-Transfer Level (RTL) coding and specialized hardware. An alternative approach [5], repurposes microcontroller (MCU) peripherals such as Serial Peripheral Interface (SPI) or Inter-IC Sound (I²S) to generate LoRa chirps. This shows that higher-order modulations can be created using only peripheral hardware and memory lookup tables without dedicated RF components.

Table 1. Comparison of ambient FM backscatter systems.

System	Modulation	Hardware Complexity	Range	Power
FM-OOK (2017) [6]	OOK-FM0	Low	5 m	2.84 mW
FM-FSK (2017) [7]	2-FSK	Med–High	18 m	11 μW
Switching Freq. (2018) [8]	Analog FM	Medium	26 m	24 μW
LoRAB (2022) [9]	CSS (SF 9)	High	130 m	100 mW [10]
FM Rider (2024) [1]	2-FSK	Low	107 m	1.44 mW
LoRAB 2.0 (This Work)	CSS (SF 7)	Low	121 m	17.6 μW

In parallel, ambient backscatter approaches exploit existing RF signals such as Frequency Modulation (FM), Television (TV), and cellular broadcasts as excitation sources. This technique eliminates the need for dedicated RF transmitters. First-of-its-kind work [11], leveraged ambient TV signals to demonstrate the feasibility of ambient backscatter communication. Subsequent implementations using ambient FM backscatter with Two-FSK modulation [1] achieved ranges exceeding 100 m. Recent ambient backscatter system LoRAB [9], exploiting in-band FM stereo channels demonstrated 130 m range with only 130 nA RF-front-end current consumption. However, this implementation still requires lab DAC equipment (NI MYDAQ) external processing for modulation generation, resulting in a bulky and expensive setup. Table 1 further shows a comparison of this work to some previous prominent ambient FM backscatter approaches. Building on the foundational work of LoRAB [9], this work presents LoRAB 2.0, which eliminates the need for an external DAC and addresses the hardware complexity and power consumption limitations through an all-digital ambient backscatter system using commercial off-the-shelf components.

II. System Design

The proposed system is shown in Fig. 1. The tag uses an ultra-low-power MCU that creates digitally sampled CSS chirps via its I^2S peripheral to drive an RF switch. This achieves simpler hardware and lower energy consumption compared to previous implementations that needed DACs and VCOs. The receiver uses a portable Software-Defined Radio (SDR) that captures a 6 MHz spectrum chunk. This enables simultaneous use of multiple ambient FM stations. Capturing several stations improves resilience to outages, noisy broadcasts and interference. The proof-of-concept prototype shows the feasibility of extremely low-cost, ultra-low-power, and low-complexity tags using purely digital signal synthesis.

A proof-of-concept system hardware is shown in Fig. 2. The nRF52833 development board is powered at 1.8 V using an nRF Power Profiler II Kit, which records instantaneous

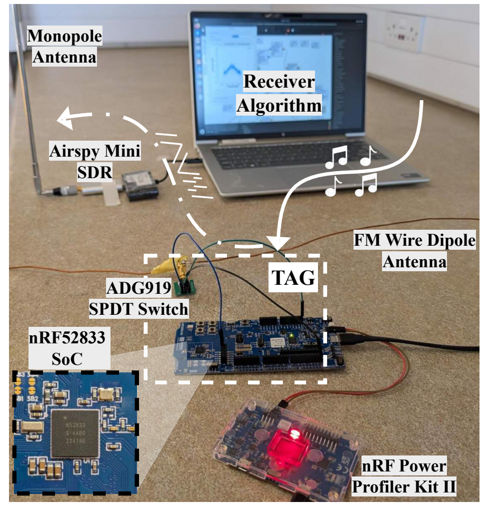

Fig. 2. Experimental setup with the nRF52833 backscatter tag, Airspy Mini SDR receiver, FM antennas, and laptop running the decoding algorithm.

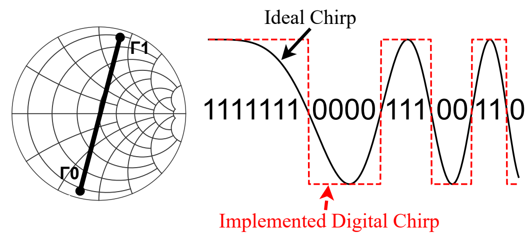

Fig. 3. Backscatter modulation principle showing the two reflection-coefficient states (left) and the resulting digital square-wave control signal sampled from the analog chirp (right).

and average current consumption. The MCU's I^2S peripheral bitstream output drives the control pin of the ADG919 SPDT switch, while VDD of the ADG919 was 1.8 V. The switch output is connected to a handmade 1.5 m copper-wire dipole (1.5 mm diameter), which reflects ambient FM signals with impedance-modulated backscatter. The receiver uses a standard FM monopole antenna connected to the Airspy Mini, which captures the reflected waveform for digital processing. After acquisition, GNU Radio and Python/MATLAB scripts perform demodulation, correlation-based CSS detection, and packet decoding.

The Nordic Semiconductor nRF52833 was selected as the main processing unit due to its ultra-low-power characteristics, especially deep-sleep current consumption below 1 μA. The MCU operates its I^2S interface at programmable sampling rates between 100 kHz and 16 MHz, enabling flexible chirp synthesis depending on required spreading factor (SF) and bandwidth. During operation, chirps are transmitted serially over the I^2S data line, while the Central Processing Unit (CPU) is mostly asleep. The Direct Memory Access (DMA) controller autonomously transfers the lookup-table samples to the I^2S peripheral, minimizing processor wake-ups. This has a major impact on the ultra-low-power consumption. The digital bitstream is generated by sampling an analog CSS chirp in the digital domain, yielding the square-wave control

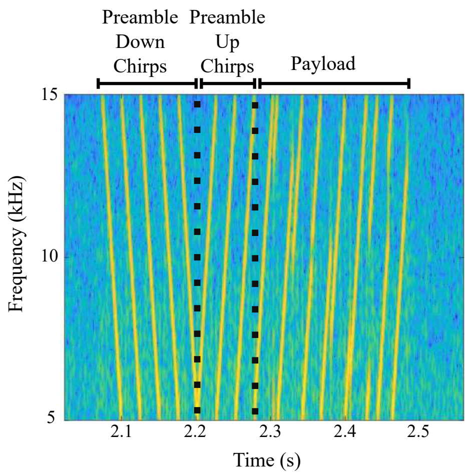

Fig. 4. Structure of a CSS frame showing preamble and payload chirps.

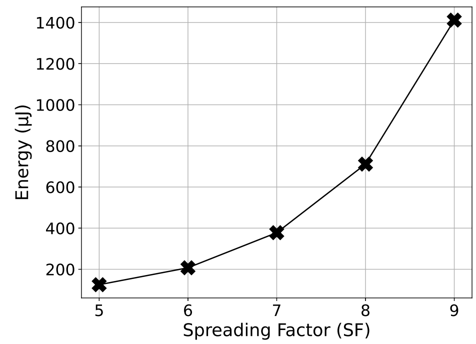

Fig. 5. Energy consumption for active transmission of a 4-byte packet (with 8 preambles) , shown as a function of spreading factor.

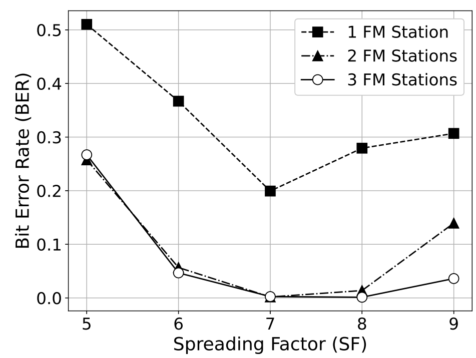

Fig. 6. Bit error rate versus spreading factor for receiver tuned to one, two, and three ambient FM stations, measured indoors with the receiver placed 8 m from the tag.

signal shown in Fig. 3 (right). This waveform toggles the ADG919 between two impedance states, $Z_0 \approx 5.7 + j5.03$ and $Z_1 \approx 27.97 - j504.12$, resulting in a reflection-coefficient distance of $\Delta\Gamma \approx 1.785$, as shown in Fig. 3 (left). The transitions between these two impedances reflect the CSS modulated signal on the carrier, leading to valid packets that can be recovered at the receiver, as shown in Fig. 4.

On the receiver side, an Airspy Mini SDR with cost around $\$100$ is used due to its small form factor, high sensitivity, and capability for sampling up to 6 MHz of instantaneous bandwidth. Since commercial FM broadcasts occupy 88 MHz to 108 MHz with typical spacing of 200 kHz, this bandwidth theoretically allows simultaneous reception of up to 30 stations. Practically, due to the relatively low number of active FM broadcasters, at most four FM stations can be captured within a 6 MHz bandwidth. Cheaper SDRs, such as RTL-SDR (2.4 MHz), can capture one or two FM stations, while high-end SDRs like HackRF (20 MHz) or USRP B200 (56 MHz) can capture the entire FM broadcast band, which is 20 MHz wide. This is beneficial since the backscattered CSS signal resides within the FM stereo area, and using multiple stations increases the sensitivity of the system as it reduces localized interference, and in-band noise variability. In this work, the full 6 MHz spectrum is captured in GNU Radio, where frequency-isolating filters extract individual FM channels. Each channel is demodulated using FM-stereo receiver blocks, and the recovered real samples are passed to a custom CSS decoder, initially developed in MATLAB and later ported to Python for planned open-source receiver release and real-time operation.

III. Power consumption and results

The energy efficiency of the proposed digital ambient backscatter system was evaluated by measuring the current drawn by the tag using an nRF Power Profiler II at 1.8 V. Operating the system at a fixed duty cycle of 1% active transmission time following official LoRa guidelines [12], the system achieves average current consumption of around 9.8 μA (17.6 μW) regardless of the SF. By limiting active airtime to 1%, the system becomes scalable and energy-efficient, enabling dense ambient-backscatter by allowing multiple nodes to transmit simultaneously with minimal channel congestion.

Fig. 5 breaks down the energy consumption characteristics further, with the energy consumption of a 4-byte packet (with 8 preamble symbols), plotted against different values of SF. Since on-air time is directly proportional to SF, increasing the value of SF results in longer transmission times and greater energy consumption. This can be clearly seen as SF 9 has an energy consumption of 1.41 mJ, while SF 5 is 124.99 μJ. These results show a range of energy costs for different modulation configurations and indicate the importance of choosing the best configuration based on system needs. Although conventional LoRa systems typically operate in a range between SF 7 and SF 12, we narrow our investigation to the spreading factors SF 5 and SF 9, as our system targets higher data rates, while still keeping acceptable range. Furthermore, due to the fact that the nRF52 platform supports only 128 kB of Random Access Memory (RAM) and our design stores full lookup tables for both upchirp and downchirp, generating chirps above SF 9 consumes high memory and is not practical for real-time operation.

Error performance was measured indoors in terms of bit error rate (BER) when the SDR was tuned to one, two, and three ambient FM stations, as shown in Fig. 6. The tag was placed 8 meters away from the receiver and the FM stations were more than 30 km way from the experimental setup.

While conventional LoRa systems typically show monotonically decreasing BER as SF increasing, our measured BER versus SF curve shows a clear minimum at SF 7 before increasing again. The cause of this behaviour is still under investigation, with potential contributing factors including clock inaccuracy at longer chirp durations or increased susceptibility to ambient FM interference. Therefore, SF 7 and SF 8 offer the best in-band performance for ambient FM backscatter. It was also observed that tuning to more than one FM station significantly reduces BER. The probability of two or three FM stations transmitting in stereo lines simultaneously is significantly lower. Hence, there is a sharp decline in BER when tuning to more than one station. It was also observed that the BER vs SF difference is not much in the case of two and three FM stations. Hence, it is recommended to optimize the system based on BER performance to reduce computation overhead.

Preliminary outdoor experiments also showed long-range capability as SF 7 packets with coding rate (CR) $4/8$ could be successfully decoded with signal-to-noise ratio (SNR) of -10.83 dB at a distance of 121 m.

IV. Conclusion And Future Work

In this work, we present LoRAB 2.0, a novel CSS-based ambient backscatter tag using the digital peripherals of a low-power nRF52833 MCU that achieves outdoor communication ranges above 100 m while operating at 17.6 μW. The minimal two-component architecture (MCU+RF switch) and fully software based waveform generation substantially reduce hardware complexity, system cost, and development overhead compared to prior CSS backscatter approaches. A practical MISO receiver configuration was also shown that noticeably lowers BER.

Future work includes properly time-synchronizing and phase-synchronizing the MISO channels at the receiver to achieve additional gain and better ranges. The receiver is also being ported to Python for planned open-source release, real-time decoding, and development of a mobile Application. A custom test PCB is under development, with an integrated tiny solar-cell harvesting circuit for battery-free operation. This will lead to a custom proof-of-concept design board with an estimated final cost below $10.

References

[1] K. Xu, W. Gong, Y. Li, J. M. Purushothama, G. Goussetis, S. McLaughlin, J. S. Thompson, C. Song, and Y. Ding, "FM Rider: Two-FSK Modulation-Based Ambient FM Backscatter Over 100 m Distance," *IEEE Trans. Microw. Theory Techn.*, vol. 72, no. 9, pp. 5563–5575, Feb. 2024.

[2] S. N. Daskalakis, R. Correia, G. Goussetis, M. M. Tentzeris, N. B. Carvalho, and A. Georgiadis, "Spectrally Efficient 4-PAM Ambient FM Backscattering for Wireless Sensing and RFID Applications," in *Proc. IEEE MTT-S Int. Microw. Symp. (IMS)*, Philadelphia, Pennsylvania, USA, Jun. 2018.

[3] V. Talla, M. Hessar, B. Kellogg, A. Najafi, J. R. Smith, and S. Gollakota, "LoRa Backscatter: Enabling The Vision of Ubiquitous Connectivity," in *Proc. ACM Int. joint Conf. on Pervasive and Ubiq. Comp.*, Orlando, Florida, USA, Sep. 2017.

[4] F. Zhu, J. He, J. Lin, Y. Qin, B. Wang, Q. Di, M. Jin, and X. Tian, "Inductor-Free LoRa Backscatter," *IEEE Transactions on Networking*, vol. 33, no. 4, pp. 1514–1527, Feb. 2025.

[5] C. Lohr, "LoLRa: Transmit LoRa Frames Without a Radio," https://github.com/cnlohr/lolra, 2025, accessed: 2025-10-12.

[6] S. N. Daskalakis, J. Kimionis, A. Collado, G. Goussetis, M. M. Tentzeris, and A. Georgiadis, "Ambient Backscatterers using FM Broadcasting for Low Cost and Low Power Wireless Applications," *IEEE Trans. Microw. Theory Techn.*, vol. PP, no. 99, pp. 1–12, Nov. 2017.

[7] A. Wang, V. Iyer, V. Talla, J. R. Smith, and S. Gollakota, "FM Backscatter: Enabling Connected Cities and Smart Fabrics," in *Proc. USENIX Symp. on Networked Sys. Design and Impl. (NSDI)*, Boston, MA, Mar. 2017, pp. 243–258.

[8] G. Vougioukas and A. Bletsas, "Switching Frequency Techniques for Universal Ambient Backscatter Networking," *IEEE Journal on Selected Areas in Communications*, vol. 37, no. 2, pp. 464–477, Sep. 2018.

[9] S. N. Daskalakis, A. Georgiadis, M. M. Tentzeris, G. Goussetis, and G. Deligeorgis, "The New Era of Long-Range "Zero-Interception" Ambient Backscattering Systems: 130 m with 130 nA Front-End Consumption," *MDPI Sensors*, vol. 22, no. 11, May 2022.

[10] *NI myDAQ, Student Data Acquisition Device, User quide and Specs*, National Instruments, 2024. [Online]. Available: https://www.ni.com/docs/en-US/bundle/mydaq-specs/page/specs.html

[11] V. Liu, A. Parks, V. Talla, S. Gollakota, D. Wetherall, and J. R. Smith, "Ambient Backscatter: Wireless Communication Out of Thin Air," *ACM SIGCOMM Comput. Commun. Rev.*, vol. 43, no. 4, pp. 39–50, Oct. 2013.

[12] LoRa Alliance Technical Committee, "LoRaWAN™ 1.0.3 Regional Parameters," LoRa Alliance, Inc., Tech. Rep. V1.0.3, Jul. 2018.