AmbientSense: Ambient Backscatter Communication for Air Quality Sensing

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Background

Ambient backscatter communication (ABC) offers a path to batteryless, city-scale environmental sensing by letting devices communicate through reflection of existing radio waves rather than by generating their own. This technology can be applied for continuous air-quality monitoring. Currently, the U.S. regulatory network remains sparse and unreliable due to maintenance gaps and regular need for repair. ABC based communication with low-cost sensors would fill those gaps and require roughly 100 mW of continuous power and regular maintenance. The background below first introduces the technology of ABC, then illustrates the gaps in current air-quality monitoring, and finally details the design prototype of AmbientSense.

Ambient Backscatter Overview

Conventional wireless communication nodes generate their own radio-frequency (RF) carriers using oscillators, mixers, and amplifiers. These components make signal generation among the most energy intensive modules of a wireless system. Backscatter communication inverts this model, wherein a tag modulates how it reflects an incident RF wave by switching its antenna between two (or more) impedance states, so that a matched load absorbs the wave while a mismatched load reflects it [1], [5], [6]. Traditional passive RFID requires a dedicated reader emitting a continuous source signal. Ambient backscatter, introduced by Liu et al. at ACM SIGCOMM 2013, eliminates the need for a dedicated emitter by scavenging signals already present in the environment such as broadcast television, FM radio, Wi-Fi, and cellular [1]. As shown in Figure 1 from the Liu et al. paper, a common RF source is received by both the Receiver and Sender. The Sender then reflects a modulated version of the signal to the Receiver. The pattern of modulation encodes data into the reflected signal. By comparing the modulated and source signals, the Receiver can then decode data.

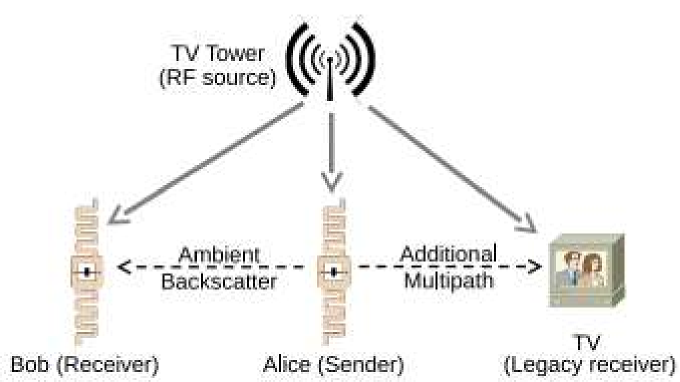

Figure 1: Ambient Backscatter: Communication between two battery-free devices. One such device, Alice, can backscatter ambient signals that can be decoded by other ambient backscatter

devices. To legacy receivers, this signal is simply an additional source of multi-path, and they can still decode the original transmission [1]

In the original Washington prototype, a transistor across the branches of a 258 mm UHF dipole toggled between reflective and non-reflective states at 539 MHz, mapping input bits to reflection amplitude via on-off keying (OOK). They found that incident 8VSB TV signals vary at megahertz and backscattered bits arrive at about 1 kbps. Researchers designed a 4 part module to decode the signal. It begins with an envelope detector module. An envelope signal smoothly traces the peak amplitudes of successive cycles, capturing how the signal's overall strength varies over time. This envelope then serves as the input from which an adaptive threshold is derived for bit decoding. It is fed into an RC averaging circuit to further smooth variation from the TV signal and extract a slower reflection-induced envelope. The threshold for separation between the two signals is not constant since the source signal varies in strength and clarity. Therefore, a second RC averaging circuit, long-time-constant RC average, serves as an adaptive threshold. Finally, a comparator uses this moving threshold to convert the signal into a bit line. This is shown in Figure 2, taken from the Liu et al. paper. Notably, this is accomplished without ADCs or oscillators [1]. The device communicated at 1 kbps over 0.76 m outdoors and 0.46 m indoors while harvesting power from the same TV signal up to 10.5 km from the transmitter [1], establishing that information transport and energy harvesting can share a single ambient carrier.

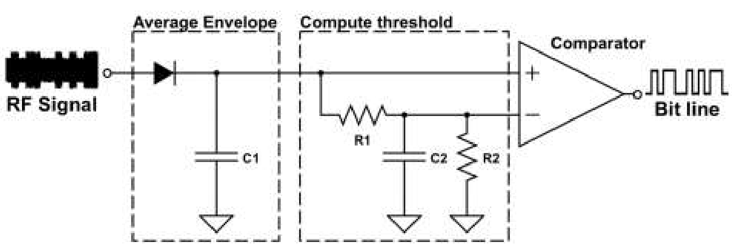

Figure 2: Circuit Diagram for the Demodulator [1]

Improvements and Variations of ABC

As described in the Ambient Backscatter Overview section, the original ABC modulation technique is two-state OOK, in which the receiver detects small amplitude variations in the combined ambient plus backscattered signal using an adaptive threshold derived from that same signal. However, since the weak backscattered reflection occupies the same frequency as the much stronger ambient source, self-interference severely limits data rate and range. Frequency-shifted backscatter addresses this by toggling the tag's antenna impedance at a fixed offset rate, shifting it to an adjacent band. The receiver then tunes to that known band and demodulates the backscattered signal directly, removing self-interference entirely.

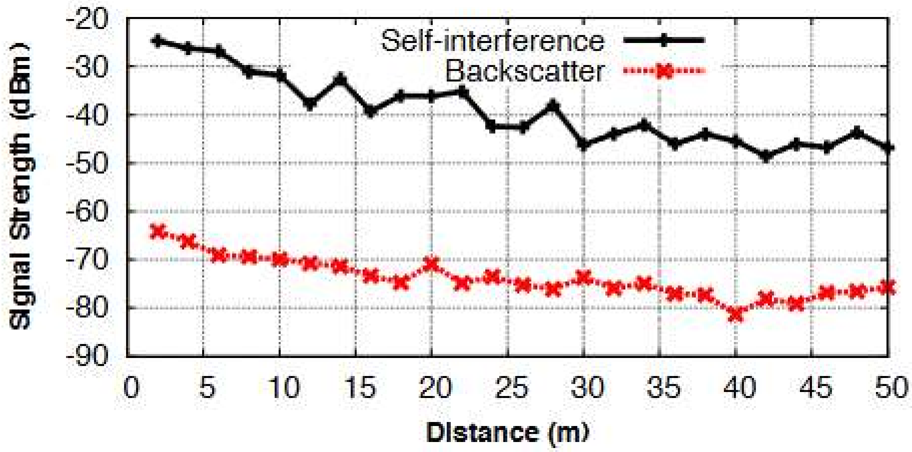

Figure 3: Signal Strength of Self-Interference and Backscattered Signal [4]

Using this technique, Bharadia et al. developed BackFi. Comparable to RFID communication, their WiFi access point also acts as a backscatter receiver, allowing for full duplex cancellation. Using BPSK, QPSK, and 16-QAM data encoding at the sender tag and full duplex cancellation at the access point, they achieved a data transmission rate of 5 Mbps at 1 meter and 1 Mbps at 5 meters over Wi-Fi. [4].

BackFi requires a modified access point with full-duplex self-interference cancellation hardware. In contrast, Zhang et al created the HitchHike system, which allows any 802.11b (WiFi standard by IEEE) receiver to decode their backscattered packet. Their custom tag uses frequency-shifts ABC to an adjacent Wi-Fi channel to avoid self-interference. The 802.11b system encodes data using a finite set of binary sequences, codewords, from a codebook. In the 1 Mbps 802.11b mode used by HitchHike, the codebook contains only two codewords. Since the source WiFi signal already follows the 802.11b protocol, the HitchHike tag translates incoming codewords into other valid codewords within the same codebook to produce standards-compliant 802.11b packets. It does so by selectively phase-flipping the incoming Barker-coded signal. As shown in Figure 4, the tag would relay the first codeword by reflecting the signal unchanged, the second would be phase shifted by 90 degrees, the next 180 degrees, and the next 270 degrees. The receiver recovers the tag's data by XORing the decoded backscattered packet with the known original Wi-Fi packet. For a 2 codeword system, this is shown in Figure 5. This enable ABC across a distance of 54m in line-of-sight, which is 1.5 times the distance of passive WiFi. [3]

$$code_0 = \text{barker}$$
$$code_1 = \text{barker} \times e^{j\frac{\pi}{2}}$$
$$code_2 = \text{barker} \times e^{j\pi}$$
$$code_3 = \text{barker} \times e^{j\frac{3\pi}{2}}$$

Figure 4: Barker Codeword Encoding [3]

decoded data	802.11b data	backscatter bits
1	1	0
1	0	1
0	1	1
0	0	0

Figure 5: Barker Codeword Decoding [3]

In CSS, each symbol is encoded as a chirp — a frequency sweep that rises or falls across a wide bandwidth over a relatively long time period. The receiver decodes by correlating the incoming signal against a known chirp pattern, concentrating the spread energy into a detectable peak even under noisy conditions. Talla et al. applied this to backscatter by building a tag that produces LoRa-compatible chirps through its impedance switching pattern instead of the aforementioned Wi-Fi-compatible reflections, achieving ranges of 475 m in bistatic configurations and 2.8 km with a co-located source and receiver [2].

For longer range applications, which would be relevant for air-quality sensor communication, chirp-spread-spectrum (CSS) modulation is an alternative technique. Although slower at transferring data, it is more resilient to the low signal-to-noise ratio (SNR) quality common in outdoor radio. A “chirp” is a frequency sweep that gradually rises and falls across a wide bandwidth over a relatively long time period. The receiver decodes the gradual rise and fall of the chirps by correlating the incoming signal against a known chirp pattern. Talla et al. applied this to backscatter by building a tag that produces LoRa-compatible chirps through its impedance switching pattern instead of the aforementioned Wi-Fi-compatible reflections, achieving ranges of 475. Talla et al. further demonstrates using this technology to send epidermal patch sensor data over LoRa. The patch reliably transmitted sensor data across 309 meters indoors. [2] AmbientSense similarly must collect sensor data and transmit the information through an ABC tag. LoRa may be a useful implementation since the tags must be placed outdoors and must send data across large distances.

Limits of Today's Air-Quality Monitoring Networks
The United States monitors outdoor air quality through a network of regulatory-grade stations. These stations use instruments such as gravimetric filter samplers, beta-attenuation monitors, and nephelometers for particulate matter. While highly accurate, these instruments are expensive (a single $PM_{2.5}$ analyzer costs upward of $10,000 and a fully equipped multi-pollutant station ranges from $50,000 to $250,000) and require regular maintenance during which data collection must be halted [7]. This cost barrier directly limits how many stations can be deployed. As of the most recent MassDEP Network Assessment, the state operates 26 ambient monitoring stations [8]. For a state of nearly seven million residents spanning urban, suburban, and rural environments. As shown in Figure 6, this means less coverage for rural and towns farther from Boston. The state, in collaboration with the CDC's Environmental Public Health Tracking Network, has recognized the need for higher-resolution monitoring, but the cost and infrastructure demands of regulatory-grade stations make rapid expansion impractical [12].

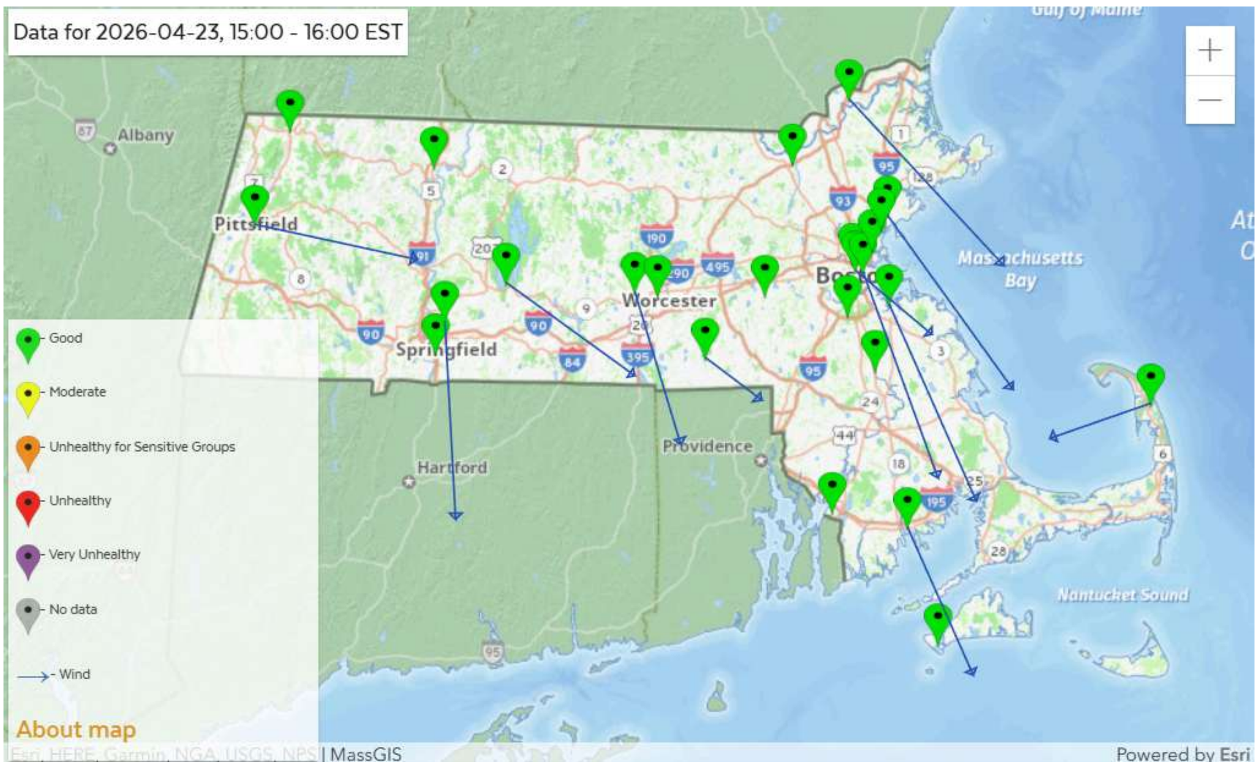

Figure 6: Map of Current Air Quality Sensing Stations: Notice that the points are most concentrated around the city of Boston and highways, with fewer in rural areas.

Low-cost sensor networks can be part of the solution, but they have their own limitations. The initially proposed batteryless operations may be far-fetched when considering that Optical PM sensors require 80–200 mW of continuous power for their fan and laser components, and a complete node with microcontroller, ABC module, and gas sensors typically draws 0.5-2 W [9]. Additionally, cheaper alternatives to the current stations may impose accuracy drops. Electrochemical gas sensors become less accurate with temperature and aging, typically requiring recalibration every six months [10]. Also, long-term field evaluations by S. Diez et al. confirm that no low-cost sensor currently meets Federal Reference or Federal Equivalent Method standards [11].

AmbientSense targets to leverage ambient backscatter communication to enable low-power, continuous sensor nodes. The system could provide dense, low-maintenance monitoring in the undercovered areas that current sensors do not reach. Future iterations may improve accuracy and precision to comply with Mass law.

Design of Ambient Sense

The goal for this project was to send a packet of sample air quality data from a custom ABC based tag to a receiver that will decode. The system demonstrates the feasibility of low-power wireless communication by modulating and reflecting an RF source generated by a Software Defined Radio (SDR), rather than actively transmitting a signal from the tag.

The design has 3 main components: the SDR Receiver, SDR Transmitter, and a semi-passive backscatter tag. They are placed in the following configuration shown in Figure 7.

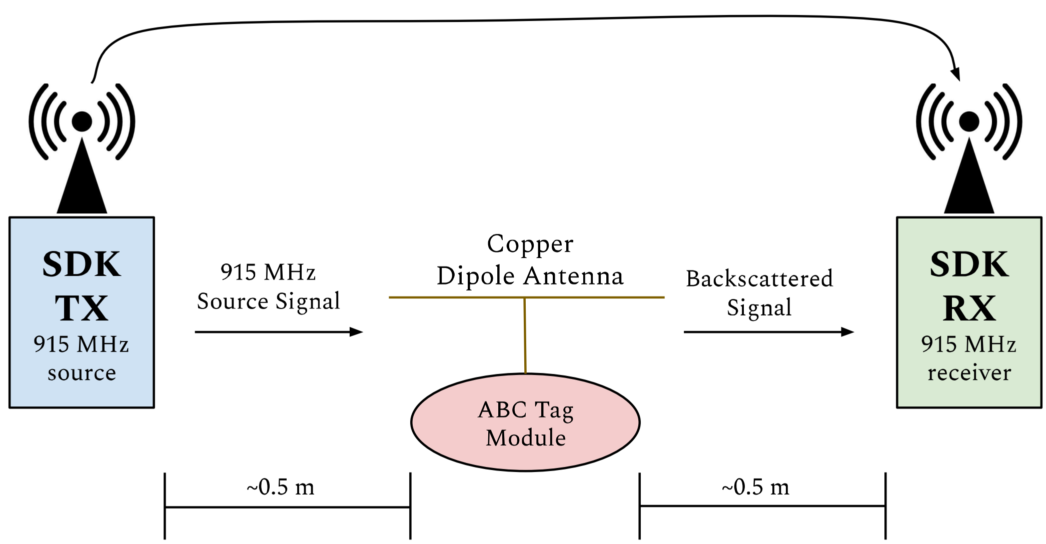

Figure 7: Testing Configuration

The transmitter consists of a software-defined radio configured to generate an unmodulated continuous-wave signal at 915 MHz within the ISM band. This source signal serves as the ambient RF source upon which the backscatter tag operates.

The backscatter tag is the core component of the system. It communicates using OOK by modulating the radar cross-section (RCS) of its antenna, alternating between two discrete impedance states to encode binary data onto the reflected carrier signal.

This design mirrors the paper by Liu et al. Their original 2013 prototype toggled a transistor across a dipole antenna between reflective and non-reflective states to encode bits. [1] The ADG919 switching between an open circuit (reflect) and a 50Ω load (absorb) is the same principle.

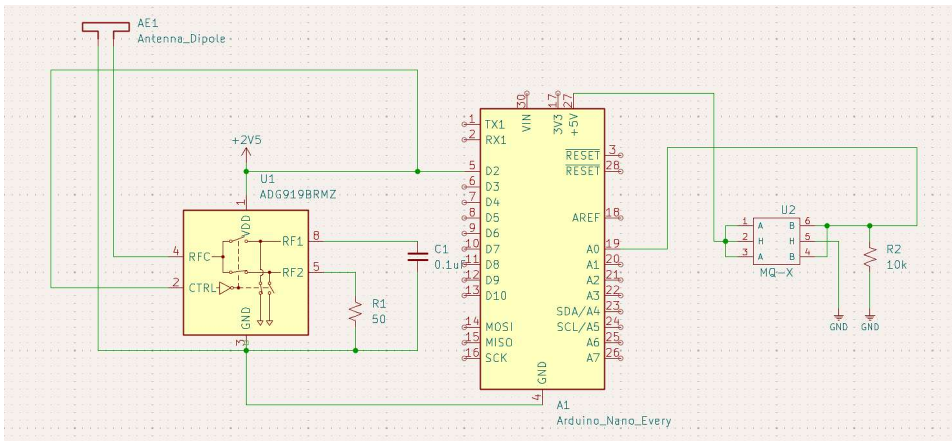

Figure 8: Version 1 Schematic Representation of Backscatter Tag Made on KiCAD

As shown in Figure 8, the backscatter tag consists of a microcontroller (middle), dipole antenna (top left), the ADG919 RF switch (left), and the MQ-135 gas sensor (right). The gas sensor module senses air quality and sends this analog data to the microcontroller, which maps it to an Air Quality Index (AQI) value between 0 and 600. This is then converted to binary and sent through control pin 5 to the RF switch. When the control signal given by the microcontroller is high, it connects to RF1, which is an open circuit. This is the reflected state, and the signal reflects back off the antenna. When the control signal is low, the signal goes to RF2, which connects to a 50 ohm resistor. This is the absorb state, and incoming signal gets dumped into the resistor.

However, this system requires power for a full microcontroller, even though its primary job is to sense data from the air quality sensor and send a corresponding control signal to the RF switch. The MQ-135 has a digital output pin where it sends HIGH above a set threshold and LOW otherwise. Microcontroller can be used to initially program the threshold to be 400 AQI and then connect the digital pin directly to the RF switch, eliminating the need for the microcontroller on the tag as shown in Figure 9.

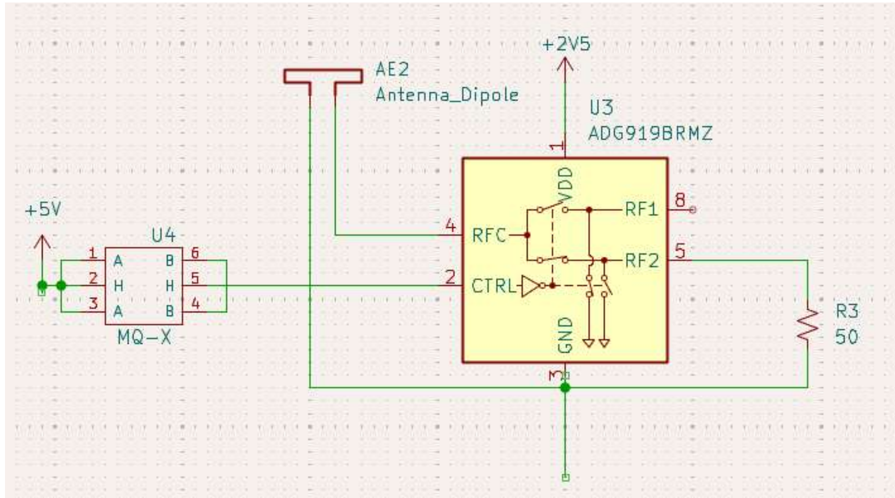

Figure 9: Version 2 Schematic Representation of Backscatter Tag Made on KiCad

This proof of concept experiment demonstrates the full sensing-to-transmission pipeline. Air quality data is received through the air quality sensor, sent to an alternating modulator, and transmitted using OOK.

The third component is the software-defined radio receiver, which extracts the low-rate OOK backscattered signal. The SDR tunes to the 915 MHz carrier and downconverts the received signal to baseband. Since the tag's impedance switching modulates the amplitude of the reflected signal, the backscattered data appears as low-frequency envelope variations as described in section Ambient Backscatter Overview. The receiver computes the signal envelope from the in-phase and quadrature samples, applies a threshold to distinguish between the reflect and absorb states, and recovers the OOK bit sequence to reconstruct the original AQI sensor value. Since we use an SDR, this entire process is performed in software.

Together, these three components form a complete end-to-end ambient backscatter communication link for air quality data. The tag's two-state impedance switching via the ADG919 implements the same OOK modulation principle demonstrated by Liu et al. [1], and the SDR receiver replaces their analog demodulator with software-based envelope detection. The integration of the MQ-135 gas sensor validates that standard air quality sensing hardware is compatible with the backscatter transmission pipeline. Although this prototype uses a controlled continuous source rather than a truly ambient signal, it proves the modulation and decoding techniques that a future AmbientSense system would require. Subsequent work should transition from the dedicated 915 MHz carrier to ambient Wi-Fi or LoRa signals so that it can work outdoors over greater distances and further optimize the power sensing elements to move closer to the goal of batteryless operation.

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