Ambient Backscatter- Harvesting Power out of Thin Air

Ritika Tandon
Assistant Professor, EC Department
MIT, Moradabad, U.P. India

Alpana Singh
Assistant Professor, EC Department
MIT, Moradabad, U.P. India

Saurabh Khanna
Assistant Professor, EN Department
NIT, Meerut, U.P. India

Abstract: **As computing devices become smaller and more numerous, powering them becomes more difficult; wires are often not feasible, and batteries add weight, bulk, cost, and require recharging/replacement that is impractical at large scales. Ambient backscatter communication solves this problem by leveraging existing TV and cellular transmissions, rather than generating their own radio waves. This novel technique enables ubiquitous communication where devices can communicate among themselves at unprecedented scales and in locations that were previously inaccessible.**

Ambient Backscatter transforms existing wireless signals into both a source of power and a communication medium. It enables two battery-free devices to communicate by backscattering existing wireless signals. Backscatter communication is orders of magnitude more power-efficient than traditional radio communication. Further, since it leverages the ambient RF signals that are already around us, it does not require a dedicated power infrastructure as in RFID.

Keywords: -Backscatter; Internet of Things; Energy harvesting; Wireless

I. INTRODUCTION

Ambient backscatter, a new communication mechanism that enables devices to communicate by backscattering ambient RF. In traditional backscatter communication, a device communicates by modulating its reflections of an incident RF signal. Hence, it is orders of magnitude more energy-efficient than conventional radio communication. Ambient backscatter differs from **RFID**-style backscatter in three key respects.

Firstly, it takes advantage of existing RF signals so it does not require the deployment of a special-purpose power infrastructure—like an RFID reader—to transmit a high-power (1W) signal to nearby devices. This avoids installation and maintenance costs that may make such a system impractical, especially if the environment is outdoors or spans a large area. Second, it has a very small environmental footprint because no additional energy is consumed beyond that which is already in the air. Finally, ambient backscatter provides device-to-device communication. This is unlike traditional RFID systems in which tags must talk exclusively to an RFID reader and are unable to even sense the transmissions of other nearby tags.

- *Radio Frequency Identification (RFID)*

Radio-frequency identification (RFID) is the wireless non-contact use of radio-frequency electromagnetic fields to transfer data, for the purposes of automatically identifying and tracking tags attached to objects. A radio-frequency identification system uses tags, or labels attached to the objects to be identified. Two-way radio transmitter-receivers called interrogators or readers send a signal to the tag and read its response.

The RFID tag can be affixed to an object and used to track and manage inventory, assets, people, etc. For example, it can be affixed to cars, computer equipment, books, mobile phones, etc.

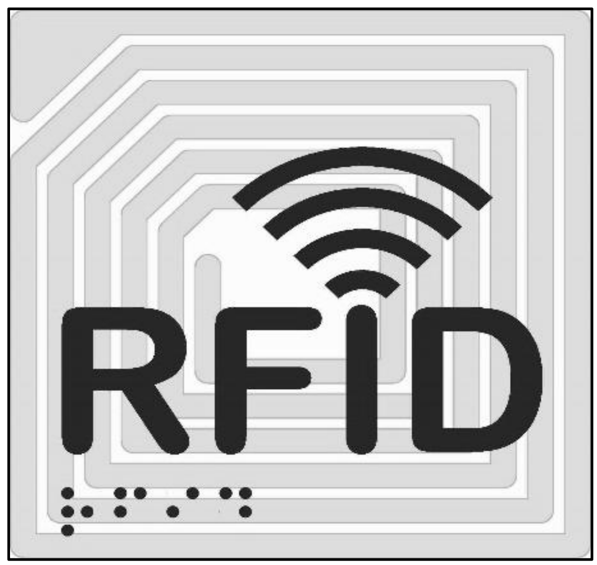


Fig. (c): Radio Frequency Identification Tag

RFID offers advantages over manual systems or use of bar codes. The tag can be read if passed near a reader, even if it is covered by the object or not visible. The tag can be read inside a case, carton, box or other container, and unlike barcodes, RFID tags can be read hundreds at a time. Bar codes can only be read one at a time using current devices.

Now, to understand ambient backscatter in more detail, consider two nearby battery-free devices, Alice and Bob, and a TV tower in a metropolitan area as the ambient source, as shown in Fig.(1)

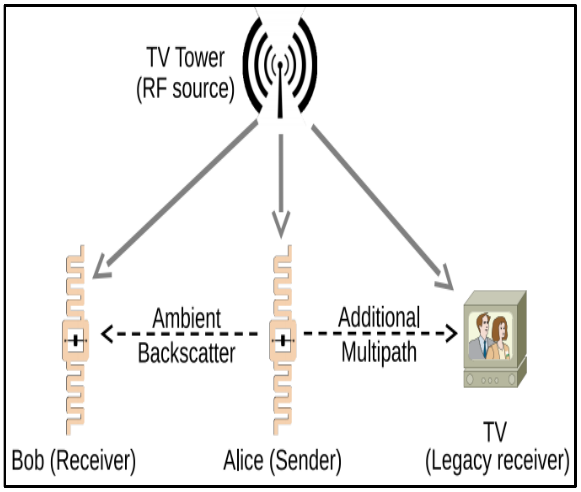
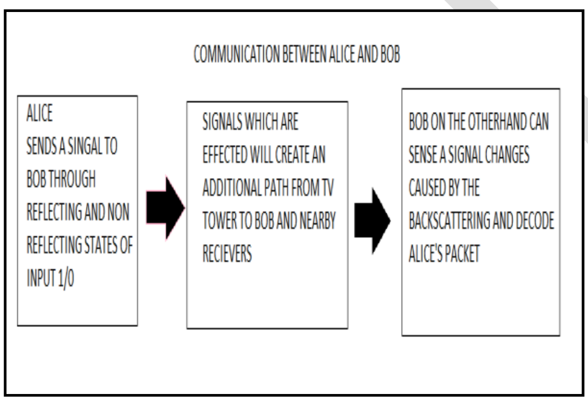


Fig.(1) Backscatter: Communication between two battery-free devices.

Suppose Alice wants to send a packet to Bob. To do so, Alice backscatters the ambient signals to convey the bits in the packet—he can indicate either a '0' or a '1' bit by switching his antenna between reflecting and non-reflecting states. The signals that are reflected by Alice effectively create an additional path from the TV tower to Bob and other nearby receivers. Wideband receivers for TV and cellular applications are designed to compensate for multi-path wireless channels, and can potentially account for the additional path. Bob, on the other hand, can sense the signal changes caused by the backscattering, and decode Alice's packet.



II. BACKGROUND ON TV TRANSMISSIONS

In principle, ambient backscatter is a general technique that can leverage RF signals including TV, radio and cellular transmissions. In this section we have chosen to focus on demonstrating the feasibility of ambient backscatter of signals from TV broadcast sources. TV towers transmit up to 1 MW effective radiated power (ERP) and can serve locations more than 100 miles away from the tower in very flat terrain and up to 45 miles in denser terrain. The coverage of these signals is excellent, particularly in urban areas.

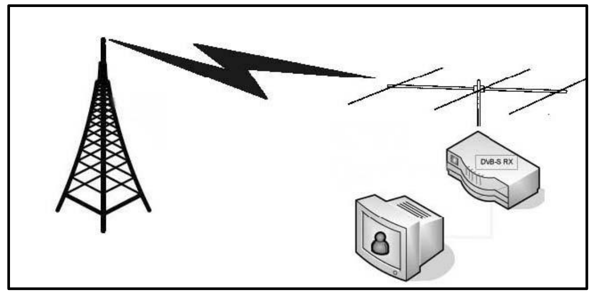


Fig. (2): Signals transmitted from TV towers

There are currently three main TV standards that are used around the world: ATSC (N. America and S. Korea), DVB-T (Europe, Australia, New Zealand, etc.) and ISDB-T (Japan, most of S. America). Methods for communicating using ambient signals leverages the following properties of TV signals that hold across all standards:

Firstly, TV towers broadcast uninterrupted, continuous signals at all hours of the day and night. Thus, they provide a reliable source of both power and signal for use in ambient backscatter. Secondly, TV transmissions are amplitude-varying signals that change at a fast rate. For example, in ATSC, which uses an 8-level vestigial sideband (8VSB) modulation to transmit one of eight amplitude values per symbol, symbols are sent over a 6 MHz wideband channel, resulting in a very fast fluctuation in the signal. Lastly, TV transmissions periodically encode special synchronization symbols that are used by the receiver to compute the multipath channel characteristics. Since ambient backscatter effectively creates additional paths from the transmitter to the TV receiver, the existing ability of TV receivers to account for multipath distortion make them resistant to interference from backscattering devices that operate at a lower rate than these sync segments.

III. AMBIENT BACKSCATTER DESIGN

Ambient backscatter is a new form of communication in which devices can by reflecting existing RF signals such as broadcast TV or cellular transmissions to communicate. An ambient backscattering device reflects existing RF signals such as broadcast TV or cellular transmissions to communicate. Since the ambient signals are preexisting, the added cost of such communication is negligible. Designing such devices, however, is challenging for three main reasons:

- The ambient signals are random and uncontrollable. Thus, we need a mechanism to extract the backscattered information from these random ambient signals.
- The receiver has to decode these signals on a battery-free device which significantly limits the design space by placing a severe constraint on the power requirements of the device.
- Since there is no centralized controller to coordinate communications, these devices need to

operate a distributed multiple access protocol and develop functionalities like carrier sense.

In the rest of this section, we describe how our design addresses the above challenges.

A. Overview of Ambient Backscattering design

Figure (3) shows a block diagram of our ambient backscattering device design. It consists of a transmitter, a receiver and a harvester that all use the same ambient RF signals and thus are all connected to the same antenna.

The transmitter, receiver, and the harvester are all connected to a single antenna and use the same RF signals. The transmitter and receiver communicate by backscattering the ambient signals. The harvester collects energy from the ambient signals and uses it to provide the small amount of power required for communication and to operate the sensors and the digital logic unit.

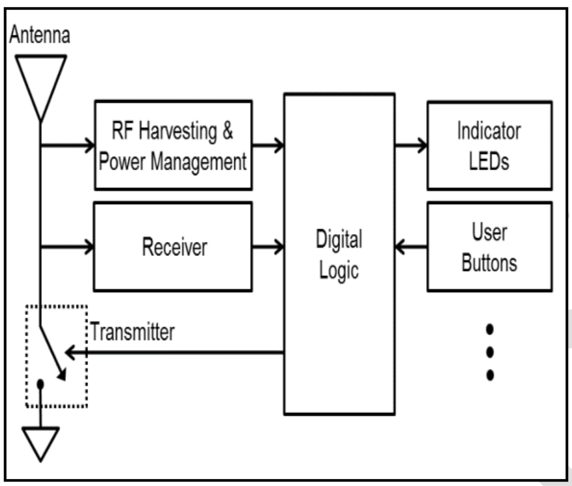


Fig. (3): Block diagram of Ambient Backscattering device

The transmitter and receiver use modulated backscattering of ambient signals to communicate, and the harvester extracts energy from those same ambient signals to provide power for the device. Further, they operate independent of each other. However, while the transmitter is active and backscattering signals, the receiver and harvester cannot capture much signal/power. The harvested energy is used to provide the small amounts of power required for ambient backscatter communication and to power the sensors and the digital logic units (e.g., microcontroller).We reproduce the harvester circuit in and use it as a black box. The main difference from is that we operate the harvester using a small dipole antenna, instead of a large horn antenna.

B. Ambient Backscattering Transmitter

The design of our ambient backscattering transmitter builds on conventional backscatter communication techniques. At a high level, backscattering is achieved by changing the impedance of an antenna in the presence of an incident signal. Intuitively, when a wave encounters a boundary between two media that have different impedances/densities, the wave is reflected back. The amount of reflection is typically determined by the difference in the impedance/density values. This holds whether the wave is a mechanical wave that travels through a rope fixed to a point on a wall or an electromagnetic wave encountering an antenna. By modulating the electrical impedance at the port of the antenna one can modulate the amount of incident RF energy that is scattered, hence enabling information to be transmitted.

To achieve this, the backscatter transmitter includes a switch that modulates the impedance of the antenna and causes a change in the amount of energy reflected by the antenna. The switch consists of a transistor connected across the two branches of the dipole antenna. The input signal of the switch is a sequence of one and zero bits. When the input is zero, the transistor is off and the impedances are matched, with very little of the signal reflected. When the switch input signal is one, the transistor is in a conducting stage which shorts the two branches of the antenna and results in a larger scattered signal amplitude. Thus, the switch toggles between the backscatter (reflective) and non-backscatter (absorptive) states to convey bits to the receiver.

C. Ambient Backscattering Receiver

Designing an ambient backscatter receiver is challenging for two main reasons: First, ambient signals already encode information and hence backscattering additional information over these signals can be difficult. Second, the backscattered information should be decodable on an ultra-low-power device without using power hungry hardware components such as ADCs and oscillators.

For each device, the researchers built antennas into ordinary circuit boards that flash an LED light when receiving a communication signal from another device. Groups of the devices were tested in a variety of settings in the Seattle area, including inside an apartment building, on a street corner and on the top level of a parking garage. These locations ranged from less than half a mile away from a TV tower to about 6.5 miles away.

It was found that the devices were able to communicate with each other, even the ones farthest from a TV tower. The receiving devices picked up a signal from their transmitting counterparts at a rate of 1 kilobit per second when up to 2.5 feet apart outdoors and 1.5 feet apart indoors. This is enough to send information such as a sensor reading, text messages and contact information.

D. Prototype Implementation

We implement our prototype on a 4-layer printed circuit board (PCB) using off-the-shelf circuit components. The PCB was designed using Altium design software and was manufactured by Sunstone Circuits. The circuit components were hand-soldered on the PCBs and individually tested which required a total of 50 man-hours.

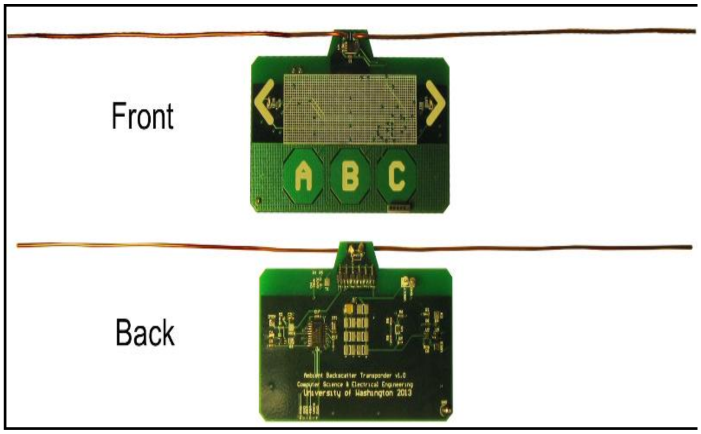


Fig. (4): Ambient Backscatter Prototype

As shown in Fig. (4), the prototype uses a dipole antenna that consists of two 2 sections of 5.08 in long 16 AWG magnetic copper wire. The prototype's harvesting and communication components are tuned to use UHF TV signals in the 50 MHz band centered at 539 MHz4. The transmitter is implemented using the ADG902 RF switch connected directly to the antenna. The packets sent by the transmitter follow the format shown in Fig. (5).

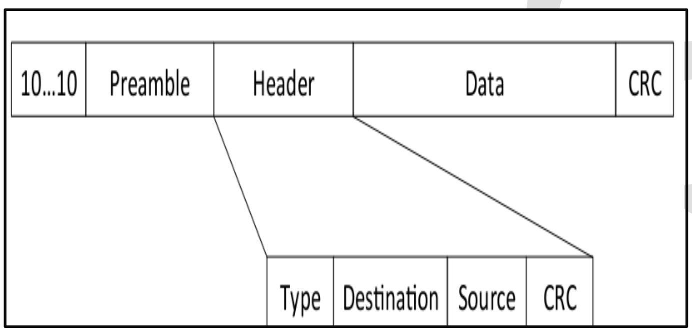


Fig. (5): Packet Format

Further, it is capable of transmitting packets at three different rates: 100 bps, 1 kbps, and 10 kbps. We also implement both preamble correlation and energy detection in digital logic to perform carrier sense at the transmitter. Our implementation currently does not use error correction codes and has a fixed 96-bit data payload with a 64-bit preamble. The output of the comparator is fed to the MSP430 microcontroller which performs preamble correlation, decodes the header/data and verifies the validity of the packet using CRC.

Our prototype also includes two sensing and I/O capabilities for our proof-of-concept applications that are controlled by the microcontroller: low-power flashing LEDs and capacitive touch buttons implemented on the PCB using a copper layer. However, these sensors as well as the microcontroller that drives them can significantly add to the power drain In hardware, the duty cycle is implemented by a voltage supervisor that outputs a high digital value (indicating active mode) when the voltage on the storage capacitor is greater than 1.8 V.

E. Hardware Prototype

Prototype, approximately the size of a credit card, includes a power harvester for TV signals, as well as the ambient backscatter hardware that is tuned to communicate by using UHF TV signals in a 50 MHz wide frequency band centered at 539 MHz. The harvested energy is used to provide the small amounts of power required for ambient backscatter and to run the microcontroller and the on-board sensors.

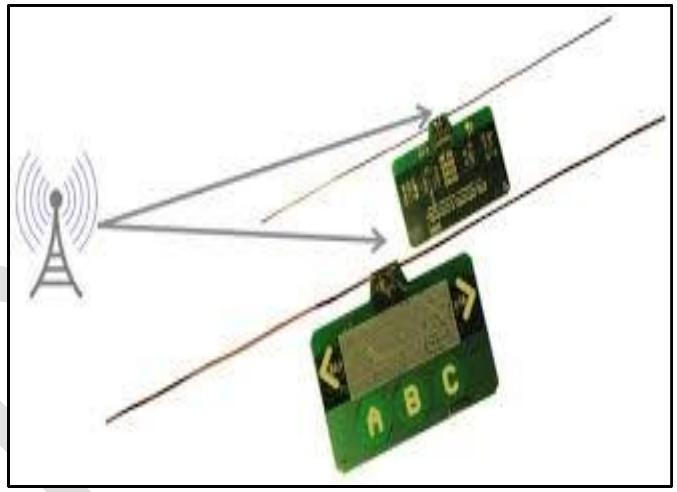


Fig. (6): Hardware Prototype

Prototype also includes a low-power flashing LED and capacitive touch sensor for use by applications. The sensing elements senses the existing RF current from the atmosphere that can radiate off a conductor into space as electromagnetic waves (radio waves) and does not penetrate deeply into electrical conductors but tends to flow along their surfaces.

Thus, using backscattered radio frequency signals, it allows to transmit the data from one end to the other end.

F. Effectiveness of Ambient Backscattering

The effectiveness of a backscattering transmitter is determined by the extent to which it affects the received signal. To quantify this, we compute the ratio of the received power, after averaging, between the non-reflecting and reflecting states of the transmitter. Specifically, if $P1$ and $P2$, $P1 \geq P2$, are the two average power levels at the receiver, we compute the ratio, $P1/P2$. A ratio close to one means that the receiver cannot distinguish between the two power levels; while a higher ratio increases the ability of the receiver to distinguish between them.

IV. APPLICATIONS OF AMBIENT BACKSCATTER

Ambient backscatter enables devices to communicate using only ambient RF as the source of power. In this section, we demonstrate proof-of-concepts for two applications that are enabled by ambient backscatter: a bus card that can transfer money to other cards anywhere and a grocery store application where item tags can tell when an item is placed in a wrong shelf. These proof-of-concepts are similar to existing RFID applications, but differ in ways that were previously impossible—they are able to function anywhere and with no maintenance. They are only a glimpse into the possibilities opened by this technique.

A. Smart Card Application

We use our prototype design to evaluate a smart card application where passive cards can communicate with each other anywhere, anytime, without the need for a powered reader. Such an application can be used in multiple scenarios, such as money transfer between credit cards, paying bills in a restaurant by swiping the credit card on the bill or to implement a digital paper technology which can display digital information using e-ink and transfer content to other digital paper using ambient backscatter. In this section, we implement and evaluate a simple proof-of concept of the smart card application. We leverage our prototype that comes complete with an ambient backscattering transmitter/receiver, MSP430 microcontroller, capacitive touch sensor, and LEDs. When a user swipes the touch sensors (marked by A, B, C in Fig. (3)), in the presence of another card, it transmits the phrase "Hello World". The receiver on the other card decodes the transmission, checks the CRC, and confirms a successful packet decoding by flashing the LED.

B. Grocery Store Application

Ambient backscatter can also be used to tell when an item is missing or out of place on a shelf in a grocery store. In this section, we use our prototype to evaluate a proof-of-concept for this application. The algorithm we use is simple: each device broadcasts its ID periodically (every 5 sec). Neighboring tags listen to these transmissions and store the successfully decoded IDs. Each tag determines on its own if it is out-of-place by computing the difference between its ID and that of the overheard IDs. If the tag has at least two different stored IDs that have this distance to be greater than a threshold, it concludes that it is out-of-place and flashes the LED.

V. FUTURE APPLICATIONS

Smart sensors could be built and placed permanently inside nearly any structure, then set to communicate with each other. For example, sensors placed in a bridge could monitor the health of the concrete and steel, then send an alert if one of the sensors picks up a hairline crack. The technology can also be used for communication – text messages and emails, for example – in wearable devices, without requiring battery consumption.

Fig. (6): Text Message Servic

VI. PROS OF AMBIENT BACKSCATTER

- It takes advantage of existing RF signals so it does not require the development of a special-purpose power infrastructure.
- It has a very small environmental footprint because no additional energy is consumed beyond that which is already in the air.
- Ambient backscatter provides device-to-device communication.
- No Additional Battery or Power outlet required.
- Can be used for Home Monitoring: The tech could also be used to allow smartphones to send text messages even if their battery is dead, or to tag various items such as keys, wallet or phone to transmit their location if they are lost.
- It creates no pollutions and is compact in size.

VII. CONS OF AMBIENT BACKSCATTER

- The ambient signals are random and uncontrollable. Thus, we need a mechanism to extract the backscattered information from these random ambient signals.
- The receiver has to decode these signals on a battery-free device which significantly limits the design space by placing a severe constraint on the power requirements of the device.
- Since there is no centralized controller to coordinate communications, these devices need to operate a distributed multiple access protocol and develop functionalities like carrier sense.

VIII. CONCLUSION

For the first few decades of their existence, computers were fundamentally limited by the infrastructure on which they rely. Computers were tethered by their power cords and were rendered useless without a nearby power outlet. Wireless communication combined with battery packs liberated these devices for short periods of time so that they could compute and communicate, untethered, as long as their batteries were occasionally recharged or replaced.

In this report, we introduce ambient backscatter, a new form of communication that provides connectivity between computers out of what is essentially thin air. In this technique, TV signals and other source of RF signals serve as both the source of power and the means of communication. Because ambient backscatter avoids the maintenance-heavy batteries and dedicated power infrastructure of other forms of low-power communication (e.g., RFID and NFC), it enables a bevy of new applications that were previously impossible or at least impractical. We believe that ambient backscatter provides a key building block that enables ubiquitous communication (with no restrictions except the existence of ambient RF signals) among pervasive devices which are cheap and have near-zero maintenance.

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