Extracting power “from thin air” has a quality of science fiction about it, yet technology trends make it likely that in the near future, small computers in urban areas will use ambient RF signals for both power and communication. Over the past decade, personal computers have been transformed into small, often mobile devices that are rapidly multiplying. Aside from the ever-present smartphone, a growing set of computing devices has become part of our everyday world, from thermostats and wristwatches, to picture frames, personal activity monitors, and even implantable devices such as pacemakers. All of these devices bring us closer to an “Internet of Things,” but supplying power to sustain this future is a growing burden. Technological advances have so far largely failed to improve power delivery to these machines. Power cords tie devices down, prohibiting their free movement, while batteries add weight, bulk, cost, the need for maintenance, and an undesirable environmental footprint.

Fortunately, running small computing devices using only incident RF signals as the power source is increasingly possible. We call such devices RF-powered computers. As might be expected, the amount of power that can be harvested from typical RF signals is small. However, the energy efficiency of the computers themselves has improved exponentially for decades—a lesser-known consequence of Moore’s law. This relentless improvement has recently brought the power requirements of small computational workloads into the microwatt realm, roughly equal to the power available from RF sources in practical settings.

Figure 1 shows the increasing energy efficiency that has accompanied decreasing transistor geometry. Importantly, this trend favors the emergence of RF-powered computing over time: the size of the workload that can be run from a fixed RF power source is increasing exponentially, and the operating range of an RF-powered device from a fixed RF power source is increasing at half the rate of Moore’s law, assuming $1/r^2$ propagation losses.

RF signals are a compelling power source for energy harvesting, even though solar cells can often generate more power. RF signals have three key benefits. First, and most important, they can be reused for communication. Nearly all useful computing devices need to communicate, but conventional communication is very expensive in terms of power—1 μW is a tiny fraction of the order 10 mW power consumption of a low-power transmitter such as Zigbee. While it is possible to duty-cycle transmitters to lower their power requirements, a very low duty cycle makes communications largely unavailable.

Second, RF signals for TV broadcasts, cellular communications, and so on are ubiquitous in most urban environments. Unlike energy sources such as solar or mechanical vibration, RF signals are capable of providing power to devices day and night, inside and outside buildings, regardless of whether the receiving device is stationary or mobile. With existing RF transmission power levels, it is feasible to harvest power several kilometers from TV towers and several hundred meters from cellular base stations. Although Wi-Fi is another obvious source, it has a much lower energy density. Moreover, when devices are powered solely by ambient RF signals, there is zero added energy cost.

Finally, RF signals are attractive from an industrial design perspective. They propagate through plastic housings, while solar energy harvesting requires covering large areas of the device exterior with light-absorbing (and thus dark-colored) glass or plastic. Additionally, most mobile
devices already have antennas for communication. By reusing them, power can be harvested from RF signals without compromising the device aesthetics.

We expect RF-powered computing to move from a research curiosity to consumer products over the next few years. We have developed the necessary technologies over the past five years to build a series of prototypes of increasing functionality. To demonstrate the viability of our vision, we describe two of our latest research prototypes, both of which combine sensing, computing, and communication in ways that highlight the unique advantages of using RF signals for power and communication. The first is a telemetry system that enables collection of data from a dragonfly’s brain and muscle activity while it is in flight.4 This application is not possible using batteries or power cables, because their weight would prevent the insect from flying. The second prototype demonstrates a new communication technique called ambient backscatter that lets nearby battery-free devices exchange messages using ambient TV signals as a communication medium instead of generating their own radio waves.5 Both prototypes demonstrate that RF-powered computing can support rich functionalities and applications that were previously infeasible.

HARVESTING AND BACKSCATTER

The techniques for harvesting power from RF signals and using such signals for backscatter communication are well-established and form the basis of modern RFID systems, such as Electronic Product Code tags that can be placed on objects and identified from a distance. This kind of RFID uses UHF (ultra-high frequency) radio waves and is known in the industry as the EPC Gen 2 standard. RF-powered computing builds on this heritage.

Harvesting power from RF signals

When a propagating radio wave encounters an antenna, its electric field causes electrons to move, creating an alternating current in the antenna. RF power-harvesting circuits convert the antenna’s AC into a more useful DC form by rectifying it to a steady current that charges a storage capacitor. Figure 2 shows a representative energy-harvesting circuit. The harvester is composed of diodes and capacitors, with multiple stages that boost the output voltage. The diodes are the rectifying elements: they pass current in only one direction. The resulting DC is then used to charge a capacitor, storing energy that can be drawn down to supply power at a stable voltage level to run a computer. It is the presence of the RF signal itself that turns on the power-harvesting circuit.

The amount of power arriving at a device depends on the transmission power of the RF source and the distance over which the signal propagates. The initial transmission power of typical RF sources varies greatly, from around 10^6 W for TV stations to order 10 W for cellular and RFID systems to roughly 0.1 W for Wi-Fi systems. Only a very small fraction of this power will arrive at a device in normal usage because the RF signal is spread over a large area. The amount of power that can be captured depends on the design of the harvester, and it is a significant engineering challenge to capture energy efficiently at low power levels and high frequencies.

Figure 1. Computing’s energy efficiency has improved by 12 orders of magnitude between 1950 and 2010.1
Backscatter communication

Conventional wireless communications such as Wi-Fi require each device to generate its own RF carrier. This method has been tremendously successful, but it is less practical for RF-powered computers because typical RF transmitters require orders of magnitude more power for carrier generation than is available.

Backscatter communication works by modulating the reflection of an existing RF signal. When an RF signal is incident on a solid object, the signal is reflected; radar works by tracking these reflections. Conversely, when an RF signal is incident on a well-matched antenna, it is largely absorbed. By changing whether the RF signal is reflected or absorbed in a time-varying pattern, backscatter communication encodes messages at very low power consumption. The change between absorbing and reflecting states can be made simply by switching the load presented to the antenna. The reflected RF signal propagates to a receiver, where it will show up as a small ripple on the more powerful RF signal. As an analogy, imagine conventional communications to be shining a flashlight at a receiver and turning the light on and off with Morse code. For backscatter communications, imagine holding a mirror and changing its orientation to reflect sunlight at a receiver.

Figure 3 shows an example of a backscatter signal. Because it leverages an external power source, backscatter communication can be four orders of magnitude more energy efficient than conventional communications such as Wi-Fi.

BIOTELEMETRY FROM FLYING DRAGONFLIES

We developed an RF-powered computer to gather data from insects while they are in flight. The device’s tiny size and weight demonstrate that smaller and less intrusive wearable and implantable computing devices could be feasible for other species, including humans.4

Scenario

The study of neural activity during animal behavior is of intense interest for advancing neuroscience, but progress is slow due to the difficulty of obtaining data in naturalistic settings. The scenario we target measures the activity of multiple neurons in a dragonfly (or another flying insect) during prey capture flights.

To be feasible, the size and weight of the instrumentation must be so small that it does not interfere with the animal’s behavior. Dragonflies of the species Libellula lydia weigh about 400 mg and can maintain their interception behavior with payloads of up to 33 percent of their body weight. This limits instrumentation to about 130 mg, a severe restriction easily exceeded by today’s batteries. The device we developed is battery-free and weighs only 36 mg.

Another challenge for this scenario is that the biotelemetry must support a relatively high data rate. The dragonfly has 16 target-selective descending neurons that appear to control wing steering for prey interception. At flight temperatures of 35°C, these neurons have action potential spikes of ≈250 microseconds in duration. The action potentials must be sampled at 25 to 40 kHz to have sufficient resolution for accurate identification. The total required data rate is approximately 5 Mbps.

System design

Figure 4a shows the system’s architecture, which comprises a powered base station and a tiny RF-powered
telemetry instrument carried on the dragonfly. Figure 4b shows a close-up of the telemetry package including the antenna mounted on a dragonfly. Conceptually, this arrangement is similar to that of a powered UHF RFID reader and a passive RFID tag, though at a much higher level of capability.

The base station is connected to an antenna near a perch in the insect enclosure. The antenna simultaneously transmits an RF signal from the base station and receives a reflected RF signal from the environment. The transmitted signal is sent in the 902- to 928-MHz Industrial, Scientific and Medical (ISM) bands at +36 dBm (4 W), the maximum radiated power allowed by the US Federal Communications Commission’s (FCC’s) Part 15 regulations, to maximize the power arriving at the telemetry device. The received signal is processed by the base station to separate it from the transmitted signal and decode transmissions from the telemetry chip.

The telemetry device is the more interesting of the two components. It receives the base station signal and uses it to harvest operating power using the circuit in Figure 2. The harvested power runs all functions of the telemetry package, including neural sensor sampling, encoding of measurement data, and backscatter communication, to wirelessly stream data to the base station.

To meet size and power targets, the telemetry device is fabricated as a chip in a commercial 0.35-µm complementary metal-oxide semiconductor (CMOS) process. The die measures 2.36 × 1.88 mm and is wire bonded into a flex circuit assembly measuring 4.6 × 6.8 mm.

When it is in range of the antenna, the device operates as follows. Neural signals are amplified by low-noise biopotential amplifiers that can capture weak signals in the µV range. Each sample is digitized using an 11-bit analog-to-digital converter (ADC). Error coding is then added with an extended Hamming code, bringing the sample to 16 bits. This coding mitigates any data transmission errors by allowing a single-bit error to be corrected, and two bit errors to be detected.

Frames comprising 192 samples are sent as complete messages using backscatter communication as outlined earlier. The frame is delimited by a unique 48-bit marker so that the base station can detect when it starts. We use phase-shift keying for the backscatter, rather than the traditional amplitude shift keying, because it has minimal effect on power harvesting efficiency.

**Results and lessons**

The total weight of the telemetry device is 36 mg, much lighter than state-of-the-art alternatives using batteries. (Existing battery-powered devices described in the literature weigh at least 170 mg.) The total power draw for the package is 1.51 mW, due mostly to the biopotential amplifiers. The backscatter communication scheme consumes less than 2 percent of the total operating power. For the 4-W transmitted power level, this gives the system an operating range of 1.5 m: when the dragonfly enters the range above the perch, the system turns on and continuously streams neural data.

The telemetry system shows that RF-powered computing can deliver significant functionality in a small package. In other work, we have shown that even higher data rates can be supported. By using a 16-state quadrature amplitude modulation (QAM) backscatter signaling scheme and a semi-passive design, we have achieved backscatter communication rates of 96 Mbps with a power consumption of 15.5 pJ/bit and a theoretical maximum operating range of 17 m. This speed is comparable to Wi-Fi, but our device is over 50 times more energy efficient than a Wi-Fi client.
For comparison, the highest data rate of UHF RFID tags is 640 kbps.

**AMBIENT BACKSCATTER COMMUNICATION**

We developed a prototype that has two architectural advances compared to the telemetry system: power is harvested from ambient TV signals, and the RF-powered computers can communicate directly by piggybacking on existing signals. We call this capability ambient backscatter communication.  

**WISP and WARP**

Our ambient backscatter system has two key ancestors: WISP (Wireless Identification and Sensing Platform) and WARP (Wireless Ambient Radio Power).

**WISP.** A flexible platform that lets researchers explore RF-powered programs, sensing, and backscatter communication, WISP was refined over a period of five years at Intel’s former Seattle research lab and the University of Washington. WISP is powered and read by commercial RFID readers that implement the popular EPC Gen 2 standard. To ease experimentation, we also developed a highly flexible reader based on the Universal Software Radio Peripheral (USRP) software-defined radio platform. Unlike ordinary RFID tags, WISP has no batteries. Unlike RFID tags, it is fully programmable, can execute arbitrary code, and is easily augmented with sensors.

WISP harvests power from RF signals in the 902- to 928-MHz band, storing energy in a capacitor and using it to operate an MSP430 microcontroller when there is sufficient energy at a workable voltage. The microcontroller runs software that can be changed on the fly. Downlink signals from an RFID reader are decoded using envelope-detecting amplitude-shift keying demodulation, and uplink backscattered signals to the RFID reader are encoded via the protocol specified in the EPC Gen 2 standard. A small amount of data storage, both volatile and flash, is provided, and the system can be interfaced to low-power external sensors. We have successfully integrated WISP with acceleration, temperature, light, and capacitive touch sensors.

To encourage experimentation, the WISP hardware designs and software systems are open source (http://wisp.wikispaces.com). More than 30 research groups worldwide have experimented with it, producing many papers.

**WARP.** The RF-harvesting circuit found in WISP or the telemetry device can, in principle, be used to harvest ambient, rather than reader-generated, RF signals. The WARP device harvests power from ambient TV signals to operate a temperature sensor with an LCD display, a microcontroller with a short-range radio, and a segmented E Ink display. These experiments were performed several kilometers from a 1-MW TV tower. We have also recently operated WARP sensor nodes 200 m from cellular base stations, using a new and improved harvester.

**Scenario**

The next logical question is whether backscatter communication (as well as power harvesting) can be generalized from planted to wild RF signals. We have shown that it can by developing the ambient backscatter communication primitive to let nearby RF-powered computers exchange messages without dedicated infrastructure. The simple ability to exchange messages is a hallmark of conventional computers that are networked with technologies such as Wi-Fi, yet prior to our work this ability had not been shown for RF-powered computers.

Figure 5 shows the architecture for ambient backscatter, where we use a TV signal as the ambient RF source. One RF-powered computer, Alice, sends a message to another RF-powered computer, Bob, using ambient backscatter. Also shown is a legacy TV receiver as a reminder that the ambient signal exists for a primary purpose—in this case, to broadcast television. Ambient backscatter signals also reach nearby legacy receivers, and they must be designed not to interfere with legacy service.

The device-to-device communication provided by ambient backscatter enables many formerly difficult-to-build applications. We have prototyped two examples: battery-free smart cards that can perform transactions with one another, and “tagged” items that can detect if they are filed in the wrong position on a shelf.

**System design**

We selected digital broadcast TV as the ambient RF source because of its relatively high energy density and
excellent coverage, particularly in urban areas: the top four broadcast TV networks in America reach 97 percent of households, and the average American household receives 17 broadcast TV stations.

To harvest power, we used the WARP energy harvester with a 258-mm dipole antenna to target UHF TV broadcast signals in a 50-MHz band centered at 539 MHz. We work with ATSC-encoded TV broadcasts in the US, though our ideas apply to other widely used standards such as DVB-T and ISDB-T that use different forms of modulation at the physical layer.

Sending an ambient backscatter signal occurs in the same manner as backscatter with a dedicated power signal, but it uses the ambient RF signal instead. Because the antenna is not frequency selective within the TV band, it does not matter which 6-MHz TV channel is broadcast—signals from all channels in the band will be backscattered. Ensuring that the backscatter does not interfere with legacy devices is an important consideration. Fortunately, to a legacy device, a backscatter transmitter is simply another feature of the environment that contributes to multipath distortion. Modern receivers are already built to measure and compensate for multipath, so there will be no degradation, even to nearby receivers, as long as the backscatter device does not modulate faster than the legacy receiver can adapt.

Decoding an ambient backscatter signal at the intended receiver is another matter. The TV broadcast signal has a rapidly varying amplitude (since it has a high information rate), and the backscatter signal is merely a ripple on this signal. This means that a receiver cannot simply subtract a fixed baseline to expose the backscatter signal (as is done on an RFID reader). Instead, we use the insight that the backscatter signal is changing more slowly than the TV signal (because of its much lower rate of information). This insight lets us expose the backscatter signal by time-averaging the received signal: with suitable averaging periods, the variations in the TV signal will be smoothed out, while the variations in the backscatter signal remain. Figure 6 shows this effect with experimental data.

To work in an RF-powered computer, the decoding operation must also consume extremely little energy. This is problematic, as power costs for receiving messages are often high and difficult to reduce for conventional receivers due to the need for power-intensive amplifiers and analog-to-digital converters. Instead, we implement much of the decoding with passive components such as capacitors and resistors that perform the time-averaging operations. Once the signal is time averaged, the information is decoded by sampling at a low rate to distinguish between the zero and one bits.

Finally, we need to sense when a message is received to enable bidirectional communication between devices. Conventional solutions such as energy detection do not apply given the fast-changing TV signal, and correlation with a known preamble is not power efficient. Our insight, once again, is that time averaging reveals the backscattered signal. In the presence of backscatter, the short-term, time-averaged signal smooths out the variations in the TV signal but not the backscatter signals. Hence the short-term and long-term time-averaged signals differ from each other. In the absence of backscatter, these signals are very similar. To perform this check efficiently, we use the analog processing of a comparator to sample message bits; the comparator requires a small voltage to turn on, with the added benefit that it only activates in the presence of an incoming message.

Figure 6. Revealing the ambient backscatter signal. The combined TV and backscatter signal is shown in the top subplot and appears to be random. After time averaging, the structure of the hidden backscatter signal is exposed in the bottom subplot.
Combining these techniques, we have a complete ambient backscatter communication system. The prototype illustrated in Figure 7 is similar to WISP and includes a capacitive touch sensor for input and LED for output.

Results and lessons

Our prototype achieved ambient backscatter communication at rates of up to 1 kbps with bit-error rates below $10^{-2}$ at distances of 0.75 m outdoors and 0.5 m indoors, all with the TV tower up to 4 km from the devices. Although this performance level is modest, the result is significant because it represents a new capability. We expect that the performance of these devices will improve quickly over time with better designs.

It is also significant that we have demonstrated all the key components—including carrier sense—needed to enable a network based on ambient backscatter, in which multiple devices communicate with one another and can ultimately connect to the Internet. This technology could be used to construct wireless sensor networks in which nodes sense, compute, and communicate with each other, all without the need to replace batteries.

RESEARCH DIRECTIONS

RF-powered computing is an emerging technology, so there are many opportunities for it to advance. As its capability increases, we expect that RF-powered computing will push the boundaries of ubiquitous computing, sensor networks, mobile apps, embedded computing, and the Internet of Things.

Power

Gregory Durgin and his colleagues have shown that some signal waveforms can be harvested more efficiently than others: for a fixed-transmit power source, a “peaky” waveform will deliver more harvested power than a signal with constant amplitude. This is because the diode used as a component in the harvester does not “turn on” until a sufficiently large voltage is applied. This observation suggests the notion of coding for the “power channel.” In conventional channel coding, sets of waveforms are chosen to maximize information delivered per channel use or per time; in power coding, the goal is to maximize energy delivered per channel use or per time. Power coding is an interesting challenge because of the inherent nonlinearity of the diodes in the energy harvester.

A complementary technique is to focus the power of RF signals in the spatial region of a device. Depending on the device’s ability to provide feedback to the transmitter, this can be accomplished with extensions to well-known multiple-input and multiple-output (MIMO) techniques. In preliminary indoor experiments exploring this concept, Matthew Reynolds and his colleagues increased the incident RF signal power by over 8 dB, nearly an order of magnitude, using an 8 x 8 element MIMO setup.

Both of these concepts rely on the ability to customize the transmission of RF signals. To increase power efficiency when using ambient RF signals, it is likely that we will need harvesters that adapt themselves to characteristics of existing ambient signals.

Communications

The range of ambient backscatter communication we have demonstrated to date is small compared to Wi-Fi or cellular ranges. Larger ranges can be obtained when one endpoint is powered, as is the case for infrastructure with connectivity to the Internet. This is because the powered endpoint can transmit at a higher power level and use sophisticated signal-processing techniques to better decode weak received signals.

A key powered endpoint for RF-powered computers is the cellular base station. The ability to communicate with this endpoint at moderate distances (of 50 m, say) would greatly enhance the value of RF-powered computers. Thus we plan to explore ambient backscatter communication using cellular signals and with a cellular base station. Cellular base stations employ multiple antennas and sophisticated signal processing that can be used to recover weak signals. It should be noted, however, that cellular protocols are heavily tailored to powered devices—mobile phones—and they require prolonged interactions to send a message. Continued evolution of the cellular protocols may lead to better support for RF-powered clients.

Tradeoffs

RF-powered computers inextricably link energy and information because both quantities are carried by a single RF signal. This introduces interesting tradeoffs, such as the act of backscattering reducing the power that can be harvested. As yet, there is no result extending
Shannon’s capacity theorem to quantify energy delivery alongside information delivery. Thus an important theoretical problem in RF-powered computing is to characterize the maximum rates at which energy and information can be simultaneously transferred over a channel given some constraints. In more practical terms, it is natural to design waveforms that optimize delivery of either energy or information, or trade them off in a controlled fashion to best suit the needs.

Extracting power “from thin air” has a science-fiction-like quality about it, yet technology trends make it likely that in the near future small computers in urban areas will indeed use ambient RF signals for both power and communication. It is natural to wonder if this is simply the next generation of RFID, the only widely used technology that harvests power from RF signals. Yet the capabilities we have demonstrated—running programs, rich sensing, high-rate data streaming, harvesting from ambient RF sources, and device-to-device communication—go far beyond the vision and abilities of modern RFID. They are more akin to a new form of computing. As this technology advances, it promises to embed computing into the everyday world in ways that were previously infeasible.

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