Ambient RF Energy Harvesting Technology and its Applications

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Abstract—This paper is focused on equipping wireless devices (including sensors) with novel, high efficiency circuitry to harvest and convert ambient RF power to direct current (dc). Key components of this technology are (a) miniaturized antenna and (b) high efficiency rectifying circuit. The first is responsible for capturing the RF waves, and the latter converts the RF energy to dc. A major challenge is the design of novel circuitry to generate a battery-like voltage from very low incoming RF energy. Under this study, we designed a novel RF power harvesting front-end whose conversion efficiency is significantly improved at low RF power levels (<-20 dBm) as compared to existing technologies. Thus, the new circuitry can harvest ambient and widely available RF energy, making a game changing technology for powering mobile devices. In this study, we demonstrate this technology by using it to power a commercially available temperature and humidity meter with an LCD display. The latter is powered using nothing more than ambient WiFi signals in an office environment.

Index Terms—antenna, DC–DC conversion, rectenna array, rectifier, RF energy harvesting, sensing, zero-bias diode

I. INTRODUCTION

RF energy is currently broadcasted from billions of radio transmitters around the world, including mobile telephones, handheld radios, mobile base stations, and television/radio broadcast stations [1]. The ability to harvest RF energy, from ambient or dedicated sources, will enable continuous charging of low-power devices, and could eliminate the need for a battery altogether [2]. Further, battery-based devices can
be charged to extend the operating life of rechargeable and disposable batteries. Battery-free devices can be
designed to operate on demand or whenever sufficient charge is accumulated. In both cases, these devices
can be free of connectors, cables, and battery access panels with significant mobile freedom while charging
and in use.

The obvious appeal of harvesting ambient RF energy over dedicated wireless power transmission is
the utilization of “free” energy generated by radio transmitters, such as those for mobile base stations and
handsets. These RF transmitters will continue to increase as the number of mobile subscriptions also
increases [3]. Of particular interest is the increase of broadband mobile subscriptions, already reaching 1
billion [4]. Mobile phones represent a large source of transmitters from which to harvest RF energy, and
will potentially enable users to provide on-demand power for a variety of close range sensing applications.
Also, consider the number of WiFi routers and wireless end devices such as laptops. Already, in some urban
environments, one can detect tens of WiFi transmitters from a single location [5]. At close range, as is the
case with indoor WiFi access points, it is possible to harvest energy from a typical WiFi router transmitting
at a power level of 100 mW. Of course, for long distance harvesting, higher gains are needed for practical
harvesting of RF energy from mobile base stations and broadcast radio towers.

Ambient RF energy can be used to charge or operate a wide range of low-power devices. At close
range (to the RF transmitter), this energy can be used to charge a number of devices including GPS or RLTS
tracking tags, wearable medical sensors, and consumer electronics such as e-book readers and headsets.
Mobile phones can also be used as portable RF power sources for a number of battery-free wireless devices.
That is, while using the cell phone, body-worn sensors can be powered to enable data transfers via
commonly used protocols such as Wi-Fi, Bluetooth or ZigBee. The transferred data can be displayed locally
on the handset or transmitted by the phone to a distant monitoring service at a hospital or point-of-care
service provider.
Research efforts to harvest ambient RF energy gained impetus since the late 90s. A major reason for this momentum is the growth of RF transmitting devices and availability of low-power consumer electronics. Among previous works, Hagerty et al. [6] presented a broad-band rectenna array that attempts
to harvest ambient RF power over a frequency range of 2–18 GHz. Also, in 2009, Intel Research Seattle demonstrated ambient RF energy harvesting from 2.55 miles (~4.1 km) away using a 960-kW TV broadcast station [7]. Powercast did a similar demonstration in 2005 at 1.5 miles (~2.4 km) away using a smaller power (5-kW AM) radio station [8]. However, these systems are typically operational only in the presence of physically large, very high gain antennas with line of sight transmission, which significantly limited their mobility.

In this study, we propose a novel, compact, and efficient design that can harvest very low level ambient energy to power a sensor system (and its display) from a typical WiFi router (transmitting only 100 mW) at short range (see Fig. 1a). The ubiquity of WiFi and the fact that it operates in the crowded 2.45 GHz band (the same as Bluetooth, ZigBee, RFID, cordless phone, etc.) makes it the perfect candidate for ambient RF energy harvesting. In the following, we start our discussion with characterization of the ambient WiFi signal strength in an ordinary office environment. Then, we present an improved rectification circuit using a miniaturized rectenna that improves the harvesting low-level ambient RF energy performance. Subsequently, a very efficient power management system is presented to minimize leakage and to provide uninterrupted regulated energy to the sensor. These new components are integrated in a complete RF power harvesting system used to drive low-power consumer electronics.

II. ASSESSMENT OF AMBIENT RF SIGNAL STRENGTH OF WLAN

Making a realistic assessment of available ambient RF energy is essential in maximizing the performance of the harvesting circuitry. Of course, the received power by the mobile device is heavily influenced by the propagation characteristics, which vary significantly from location to location. In this study, the interest is in RF harvesting while indoors. Therefore we begin by conducting an RF characterization (for WLAN) of the typical office environment depicted in Fig. 1.
Prior to presenting the details of our characterization, a basic understanding of WLAN (specifically, IEEE 802.11) is appropriate. The IEEE 802.11 standard specifies parameters for both the physical and medium access control (MAC) layers of a WLAN [9]. By combining existing measurement methods from other communication systems (such as GSM or UMTS) with the knowledge of the physical layers of WLAN system, a spectral characterization method can be developed. Focusing on the modulation scheme used for 802.11b, we note that it relies on a Direct Sequence Spread Spectrum with a chipping rate of 11 MHz [10]. However, other 802.11 schemes, such as 802.11g, use the hybrid complementary code keying OFDM modulation [11]. In any case, data transmission via the 802.11 protocol does not take place at a single frequency. We also note that the 802.11 protocol employs 11 transmission channels (13 in Europe, 14 in Japan), with the modulation spreading the data transmission over multiple channels for effective use of the frequency spectrum.

In the far field, traditional RF equipment such as an antenna with a spectrum analyzer as the receiver can be used for characterization. For our study, we measured the WiFi signal from 3 orthogonal directions and at several positions within the office depicted in Fig. 1 to observe and compensate for the fast fading. With these in mind, we employed a quarter-wavelength monopole (operating from 2.3 GHz to 2.5 GHz) antenna and an Agilent E4407B spectrum analyzer as the receiver (see Fig. 1b). We should note the room in Fig. 1a is next to several other rooms of the same type. Therefore, the WiFi spectrum was fully used by the traffic between the access points on the ceiling and numerous laptops and smartphones. The monopole antenna listened to this environment and the spectrum analyzer recorded the power level of the captured RF signal. As would be expected, the data are sent in packages with no RF signal between these packets. Thus, there are gaps between frequencies, implying that full channel bandwidth will not be captured in one sweep. A way to circumvent this issue is to use “max hold mode” option of the spectrum analyzer and record the received RF signal over several sweeps. This approach provided a fair measure of the ambient RF power during transmission of the data packets. Fig. 2 presents the measured WiFi signal strength taken over two
minutes using this measurement approach. As can be seen, in presence of heavy wireless traffic, considerable amount of ambient RF power is available for harvesting.

![Ambient RF Power Signal Strength](image)

Figure 2: Ambient RF signal strength measured on one of the desks in the office environment depicted in Fig. 1a with a standard monopole antenna.

### III. INTEGRATED RECTENNA DESIGN

A typical WiFi router transmits only 100 mW, almost ten million times less power than day-time TV broadcast. Hence, efficient, low leakage, and compact RF harvesting at low power levels (<-20 dBm) is of utmost importance. Fig. 3 illustrates the block diagram of our method for harvesting ambient RF energy in the 2.45 GHz ISM band while in the office space depicted in Fig.1.

The first component of the RF to dc energy conversion system is the antenna. As seen in Fig. 3, we employ an antenna array, which is essential, as the incident WiFi power level is so low that a single antenna does not suffice. However, the array must still be small in size to make it practical. In this regard, the antenna element design and its miniaturization play an important role.
Figure 3: Block diagram of a rectenna array for ambient energy harvesting. Each element in the array is integrated with its own rectifier. The resulting dc outputs are combined and fed to power management electronics.

The next component of the RF harvesting circuitry is the rectifier. That is, once the RF signal is received it must then be rectified to generate dc power. This must be done in the most efficient possible manner. Since the received WiFi signal is very low, to rectify the received RF signal, each antenna element in the array is integrated with its own rectifier. In the following, we will present a modified version of the Greinacher rectifier using zero-bias Schottky diodes. The latter are important since the incoming signal is expected to be small. Therefore, we like to turn-on the rectifier circuit at the lowest possible power levels. Matching of the diodes to the rest of the circuitry and to the antenna is also critical to minimize reflections and therefore increase harvesting efficiency. Doing so for the non-linear diode load is challenging. Therefore, we carried out the matching using a pre-specified range of input power levels for several diode candidates.

Once the dc power is collected from all array elements, the overall (harvested) dc voltage must be regulated by a power management block to ensure delivery of a constant and on-demand dc voltage supply. A low-leakage capacitor was used as the storage element in the management block, and a dc-to-dc converter start-up IC was employed for stepping up low voltage levels. Below, we discuss the details of these components.
A. Antenna Element Design

Use of compact antenna is critical in any mobile device. Planar patch antennas are low-profile, conformal, lightweight, and easy to fabricate. However, they are not essentially small in aperture size. A popular solution for size reduction is to fabricate the patch antenna on high permittivity material (Rogers RO6010, $\varepsilon_r = 10.2$, $d = 100$ mil has been chosen in this study). However, additional miniaturization can be achieved by adopting a modified version of the Koch geometry to form the patch shape. The patch antenna design is shown in Fig. 4a and discussed in [12].

We remark that small size patches on high index materials are often associated with degraded performance. This is likely due to the excitation of surface waves [13-14]. Thus, patched on high dielectric substrates exhibit reduced efficiency, degraded radiation patterns, and undesired coupling between the various elements in array configurations. An approach to overcome these issues is to employ both a substrate and a superstrate [15]. With this in mind, we added a superstrate layer (Rogers RO6002, $\varepsilon_r = 2.94$, $d = 20$ mil) to our Koch-shaped patch. This superstrate layer also provides protection for the antenna.

The employed antenna size was only $0.164\lambda_0 \times 0.162\lambda_0$. Concurrently, the bandwidth was improved over a standard patch antenna by employing a capacitively coupled probe feed. Making it circularly polarized also allowed for reliable energy harvesting of the ambient RF signals. Fig. 4b shows the magnitude of the measured $|S11|$ and realized gain of the designed antenna element operating at 2.45 GHz ISM band. As seen, the proposed antenna has 6% bandwidth and greater than 4.5 dBi realized gain at boresight.
(a) Fabricated prototype unit without the superstrate.

(b) Measured $|S_{11}|$ and total realized gain (at boresight) of the proposed antenna element.

Figure 4: Details of the antenna element design.

B. Rectifier Circuit Design

A typical WiFi router transmits only 100 mW, almost ten million times less power than day-time TV broadcast. Because of this low power transmission, power harvesting of ambient WiFi signals requires high efficient circuitry. Towards this goal, we adopted a modified version (shown in Fig. 5) of the single-stage full-wave Greinacher rectifier (from [16]) and employed herewith. As shown in Fig. 5, D1, D2, D3, and D4 are four zero-bias low barrier Schottky diodes of the rectifier, implying higher output voltage even though the ambient RF power is at low levels. These diodes also feature high-saturation current, therefore, do not require additional biasing. This is important as a few microamperes of bias current effects the conversion efficiency. The only drawback of the proposed rectifier configuration in Fig. 5 is the resulting higher series
resistance. This implies that 100% conversion efficiency can never be achieved. It should be noted that other rectifier configurations that can also operate near theoretical performance bounds of power extraction are available in the literature [17, 18]. Nevertheless, we utilized a modified version of Greinacher rectifier as it can be built by discrete off-the-shelf components; viz. does not require integrated circuit design.

The operation of the single stage modified Greinacher rectifier is as follows. First, the induced voltage at the output of the matching circuit passes through the DC blocking capacitors (C1 and C3). The rectified current output is then pumped to the storage capacitors (C2 and C4). The energy stored on these capacitors supply the DC power to the load once the rectifier reaches its steady-state mode. As opposed to other rectifier circuits (such as Dickson or Villard), the proposed Greinacher rectifier is RF symmetric. As such, every rectifying diode is excited with the same input power. In addition, this symmetry helps us reduce harmonic content generated by the diodes (as even harmonics cancel each other).

Figure 5: Schematic and the layout of the rectifier prototype, etched on Rogers RO3206. \( w_1 = 72 \text{ mil} \),
w₂ = 12 mil, L₁ = 225 mil, and A₁ = 75°. Diodes: SMS7630, Capacitors: 100 nF.

----- : Matching network, — — : Zero-bias diodes,
● : Shorting vias, ◙ : Antenna excitation

The impedance matching stage of the RF harvesting circuit is critical in providing maximum power transfer from the antenna to the rectifier circuit. However, matching network design is challenging since the rectifier diodes are nonlinear devices with complex impedances that vary with frequency, input power level, and load resistance. Understandably, for optimal matching performance, these parameters must be determined prior to designing the matching network. For our RF energy harvester, the frequency of operation is from 2.4 GHz to 2.48 GHz, same as WiFi. Also, as indicated in Fig. 2, the anticipated input power is between -40 dBm and -20 dBm and these values effect our design of the matching network. Further, the load resistance for this design was chosen to be 10 kΩ, a decision to be justified in the next subsection.

With the above in mind, a rectifier prototype was fabricated, and Fig. 6 shows the measured reflection coefficient (S₁₁) of this rectifier as a function of frequency and input RF power level. As seen, and by choice, the rectifier is well matched when the input power is between -40 dBm and -20 dBm with the operating frequency between 2.4 GHz and 2.48 GHz. The power harvesting capabilities of the fabricated rectifier are depicted on Fig. 7. We note that, for the same load resistance, our newly designed RF power harvester generates approximately three times more voltage as compared to the state-of-the-art technology. More specifically, at low power levels, the proposed rectifier circuit has better conversion efficiency than any power harvester in the market.
Figure 6: $S_{11}$ of the rectifier circuit and the VSWR = 1.5 circle.

$$2.4 \text{GHz} < f < 2.48 \text{GHz} \quad \& \quad -40 \text{ dBm} < \text{Power} < -20 \text{ dBm}$$

Figure 7: Input RF power vs. harvested dc voltage for various power harvesters. A picture of OSU-ESL power harvester is given on top left. P2110* performance is evaluated by connecting the load resistor in parallel to its supercapacitor terminal.

*: operating this device below -11.5 dBm power is not recommended.

C. Array Design

Typically, a single rectenna does not harvest sufficient energy to power a device reliably. Instead, multiple antennas can be arranged to capture a greater percentage of ambient RF energy and channel it to a
single rectifier [19]. In a point-to-point RF system (pencil beam), this configuration offers the most efficient power transfer scheme. Alternatively, each antenna can incorporate its own rectifier to harvest dc power [20]. The harvested dc power from all rectifiers can then be summed in parallel (current summing), series (voltage summing) or hybrid manner. These configurations are most suitable when dealing with large rectenna arrays (as they avoid complex feeds) or harvesting ambient RF power (as they eliminate nulling effects). Since our goal is to harvest the ambient RF power, here, we adapted the second configuration (voltage summing) as at least 1.5V to 3V is needed to turn on a device.

To generate sufficient dc power for the range of input power levels considered in this study, a 3×3 planar array of simple Koch-type patch antennas was designed. The interelement spacing for this array was chosen such that mutual coupling between the antennas is low (i.e., |S_{21}| < -10 dB). Further, each antenna feed location was optimized individually to preserve its bandwidth performance (see Fig. 4b) of the single element. Fig. 8a shows a photograph of the fabricated antenna array (superstrate layer is omitted). We note that the resulting physical size of the final antenna array design is 9cm×9cm. The ambient WiFi harvester has a layered design in which the rectifiers are built in the lower layer and ground plane is shared with the antenna. Fig. 8b shows a picture of the fabricated rectifiers and Fig. 9 provides details regarding the layered design. Shared ground plane is marked with red dashed lines on Fig. 9.

A crucial design aspect of the rectifier array is to achieve optimal dc combining efficiency. Previous work [21] showed that predominantly parallel connections lead to smaller matched loads for the rectenna. However, for a series-connected array, as is our case, the matched load value is much higher. This can be seen by reducing the array to a combination of dc Thévenin sources with the matched load corresponding to the total source resistance. Regardless, the impedance of our energy management unit is needed for matching with the rectenna array. It turns out that our developed energy management unit (details given in the next subsection) has a resistance that varies between 85kΩ and 105kΩ when operational. Therefore, the
series connected rectenna is the best choice since it performs best with these large loads. The dc combining lines used in the presented design are depicted in Fig. 8b.

As noted, the nonlinear performance of the diodes must be accounted for when considering the dc connections. The single rectifier properties may not be valid in an array setting without proper care. That is the load impedance used in the single rectifier might be different than the load impedance within the array setting. In addition, the newly added dc lines may create unforeseen inductances, a potential design flaw. Here, the single rectifier was optimized for the $10k\Omega$ load, a reasonable assumption, as there are nine elements in the array and the total load varies between $85k\Omega$ and $105k\Omega$. Further, the dc lines were designed to be very thin and placed strategically to yield minimal inductance to the load. With these precautions, we proceeded to employ the single element impedances.

Figure 8: Pictures of the fabricated RF power harvester.

(a) The antenna array.  
(b) The rectifier array.

Figure 9: A layered view of the ambient WiFi energy harvester. The antenna and the rectifier share the
D. Energy Storage and Management

Mobile devices operate in a variety of unknown conditions, with large variations in the available ambient RF field and rectenna characteristics. These variable conditions create significant challenges in maximizing the harvested RF energy and motivate the need for power management circuitry. The power management circuit is to optimize the harvested power over a wide range of operating conditions independent of the load behavior. That is, power management circuitry delivers steady-state power to the load during harvesting. However, one important concern is the duty cycle. As many sensors monitor physical quantities infrequently, their duty cycle of operation and average power requirement are low. For example, if a sensor system requires 3.3V at 30mA (100mW) while awake, but is only active for 1/100th of a second, the average power requirement is only 1mW. Further, if the same sensor only samples and transmits/displays once a minute instead of once a second, the average power plummets under 20µW. Hence, with the help of a very low leakage, high capacity capacitor with a suitable energy management circuit, many sensor systems can be operational by harvesting ambient WiFi signals.

To realize the energy management circuit block, we used the integrated circuits called S882 and AS1310. AS1310 is a hysteretic step-up dc-dc converter from Austria Microsystems that has ultra low quiescent current (<1 µA) and can be operational even when the harvested dc voltage is as small as 0.7V [22]. On the other hand, S882Z from Seiko Instruments is a charge pump IC that improves the performance of any step-up dc-dc converter [23]. It is capable of stepping up voltages up to a level that allows AS1310 to start up. The operation of the energy management unit is as follows. When a voltage of 0.3 V or higher is harvested, the oscillation circuit inside S882 starts itself and creates a clock signal. Subsequently, the CLK signal drives a charge pump circuit that steps up the harvested voltage and stores it in the C_{CPOUT} capacitor.
depicted on Fig. 10. When the voltage on \( C_{\text{CPOUT}} \) reaches a certain prespecified level, the power begins to flow to AS1310. Ultimately, AS1310 converts the low input voltage to usable regulated output voltage (\( V_{\text{OUT}} = 1.8\text{V} \) in this study) and powers the sensor. It should be noted that the \( C_{\text{CPOUT}} \) is a low leakage capacitor to assure that enough energy is stored before AS1310 becomes operational and feeds the sensor.

Figure 10: Circuit diagram of the power management unit. A picture of the fabricated prototype (size: 1cm × 1cm × 50 mil) is also given.

IV. AMBIENT WiFi ENERGY HARVESTER

The aforementioned antenna array, rectifier array, and energy management units were combined (see Fig. 9) to form the ambient WiFi energy harvester. This harvester was tested under a variety of operating conditions. To measure the performance, a monopole antenna and a spectrum analyzer were placed next to the power harvester to monitor the RF power sensitivity of the harvester. Table 1 summarizes the test results and as seen, the device can supply battery-like regulated voltage to the load.

The current generation capabilities of the device were evaluated by connecting a variable resistor and measuring the voltage across the resistor terminals. In a typical office environment and under the conditions depicted in Fig. 1a-b, the device is able to supply a continuous current of 10 mA to the load. The maximum output current measured under typical ambient WiFi conditions was 50 mA (when ten WiFi devices were used to create wireless traffic). Although it is not the focus of this paper, the device was also
tested with dedicated RF power where an RFID interrogator was used as the energy source (5 meters away from the harvesting device). Under this scenario, the harvester generated 780 μA.

One important parameter in Table 1 is the initialization time. It refers to the time needed for the storage capacitor to reach a certain voltage, at which point the management circuit allows the powering of the load. Typically, it takes five minutes for the harvesting device to initialize. Further as the WiFi traffic declines, the initialization time increases, reaching 20 minutes when only two WiFi devices were communicating with the WLAN access point. The shortest initialization time was observed when the RFID interrogator is used as the energy source, ten seconds. Of course, an increase in the wireless traffic in the 2.45 GHz band yields a reduction in the initialization time.

<table>
<thead>
<tr>
<th></th>
<th>Minimum</th>
<th>Typical</th>
<th>Maximum</th>
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</thead>
<tbody>
<tr>
<td>Output Voltage</td>
<td>1.764 V</td>
<td>1.8 V</td>
<td>1.836 V</td>
</tr>
<tr>
<td>Output Current</td>
<td>n/a</td>
<td>10 μA</td>
<td>50 μA / 780 μA</td>
</tr>
<tr>
<td>Time to Initialize</td>
<td>10 sec. / 3 min.</td>
<td>5 min.</td>
<td>20 min.</td>
</tr>
<tr>
<td>RF Power Sensitivity</td>
<td>-40 dBm</td>
<td>-30 dBm</td>
<td>0 dBm</td>
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Table 1: Performance ratings of the OSU-ESL RF energy harvester.
The ambient RF harvesting system is tested in a practical setting by powering a commercially available indoor-outdoor temperature and humidity meter (thermometer-hygrometer) with an LCD display [24]. By design, one 1.5V AAA battery is enough to power this device and the thermometer-hygrometer is measured to consume around $10\mu\text{A}$ at 1.5V (on average) from a laboratory power supply. Notably, about once every 30 seconds, its current consumption spikes up to around $25\mu\text{A}$, presumably when sensor takes an actual measurement.

The thermometer-hygrometer functioned when the battery was removed and the power was supplied by power harvesting circuit. We found that the display reads well and temperature/humidity measurements are accurate. Fig. 11 depicts such an accurate measurement. In that scenario, 4 WiFi enabled devices were communicating (downloading files) with the access point mounted on the ceiling of a typical office. After the initialization period, the device operated continuously. In another scenario, the number of WiFi communicating devices was reduced to two. After a 20 min. initialization period, the device started operation but stopped working after 10 minutes. When there was no wireless traffic, (i.e., router transmits the beacon signal only, no WLAN enabled devices are present), the device stopped operating altogether.

![Figure 11: OSU-ESL RF energy harvester drives a temperature/humidity meter (including display) with harvested ambient WiFi power.](image)

V. CONCLUSION
A highly efficient rectenna system that can generate battery-like voltage to run a variety of low-power consumer electronics is demonstrated. The RF harvesting module consisted of (a) 3×3 miniaturized antenna array, (b) novel rectifier circuitry efficient even at low power levels, and (c) the power management circuitry. The final design was found to generate dc voltage even when the received power is as low as -40 dBm. Thus, it could operate even when very small amounts of RF energy are available. A 9cm×9cm×1cm prototype was built and used to demonstrate that the RF harvesting design can deliver enough energy to drive an off-the-shelf temperature and humidity meter with an LCD display. It was powered using nothing more than ambient WiFi signals in an office environment.

REFERENCES


[23] Seiko Instruments Inc., S882Z-MP005-A,