

Wireless Power Harvesting Skin [†]

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Abstract

Contributing to the quest for renewable energy harvesting, we present, in the work at hand, a conceptual model of a large-scale wireless microwave power harvester that takes the structure of a smart reconfigurable harvesting surface. This structure is assembled by numerous elementary harvesters that, as a whole, present both wide solid angle coverage and high receiving antenna gain. This is achieved by employing two levels of organization, both in the horizontal and in the vertical planes. The horizontal plane, which is the host receiving surface, is tiled by employing square radiators and forms hierarchical subarray structures. At the same time, hierarchical structures are also employed in the vertical plane where the beamforming network collects the received power in a drainage-basin fashion (one receiving port is fed by its assigned and also its neighboring antenna elements) achieving, in this way, increased efficiency. The presented results verify the contributed design.

Keywords: wireless power harvesting; rectenna skin; drainage-basin-like microwave-power-collecting network

1. Introduction

Power harvesting is the collection of energy from renewable ambient sources like the wind, the sun, geothermal energy, and ambient RF and microwave energy. The last being the focus of this paper. Electromagnetic power harvesting is a form of wireless power transfer achieved first by Tesla, but here, the receiver is designed for the maximum-efficiency reception of electromagnetic power from various ambient transmitters that could be WiFi access points, 4–5 or 6G base stations, or even microwave ovens. In fact, typical sources of ambient RF energy include a wide range of communication technologies such as FM radio, digital television (DTV), GSM, GPS, LTE, UMTS, Wi-Fi, WiMAX, 5G, and emerging 6G networks [1]. Focusing here on the microwave frequency range, the receiver is called a rectenna (rectifying antenna), where an antenna followed by a rectifier is employed [2].

Possible applications for wireless power harvesting include all potential uses of IoT devices, wearable devices, transportation, automotive-industry applications, smart home applications and appliances, and smart factories, as shown in Figure 1 [3].



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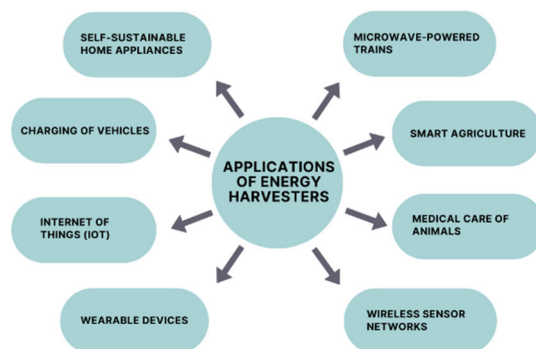


Figure 1. Applications of wireless power harvesting.

Currently, state-of-the-art design includes cube-shaped multiband fractal rectennas for ambient power harvesting [4], but also stretchable wideband dipole rectennas [5], to name few notable example implementations.

Here, we contribute a solution to the directivity problem of harvesting antenna systems. A study of electromagnetic power harvesting by electrically small, resonant, parasitic, superdirective arrays designed via the characteristic mode theory was contributed by the authors of [6]. Such systems are envisioned to form 2D surfaces that receive (collect) EM power mainly from the normal direction of the tangent plane. Indeed, the next major step is to expand to a two-dimensional surface array of harvesting rectenna array particles, which is contributed here. Planar, cylindrical, paraboloidal, or even conical [7,8] host surfaces can be employed for wide angular coverage of the incoming radiation.

This paper is organized as follows: In the current section, a typical wireless power-harvesting system is reviewed to set the stage. Next, we focus on antenna radiators and antenna arrays and beamforming to understand the relative potential and challenges. The contributed system is presented and evaluated in Sections 2 and 3, respectively. This paper concludes with relative discussion.

1.1. Typical Wireless Power-Harvesting System

A typical radio-frequency harvesting system is shown in Figure 2.

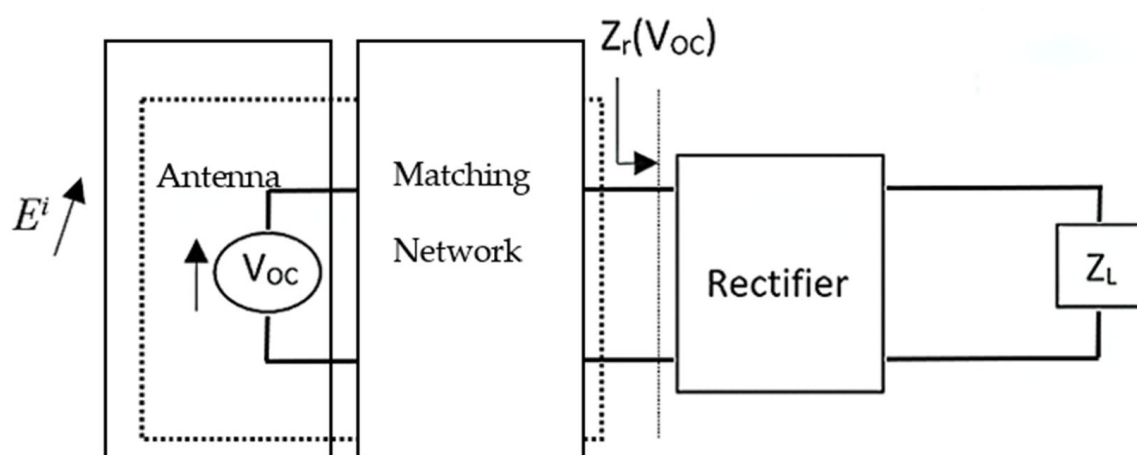


Figure 2. Example of a radio-frequency harvesting system.

The key characteristics of an ideal antenna include an omnidirectional radiation pattern (when there is no dedicated transmitter to be harvested), a small physical size antenna, an easily attached feeding point (very good matching) to the rest of the harvester circuitry,

good wideband—multiband performance and high efficiency. Various rectenna examples can be found in [9–16].

Let us elaborate more on the antenna prescriptions. While a nearly omnidirectional pattern is required in the absence of a specific transmitter, this does not mean that the directivity of the antenna should be small. Indeed, let us elaborate on this issue further. A rectenna system is composed of two main components: an antenna and a rectifier. The antenna captures and receives ambient RF energy, which is then converted into a DC signal by the rectifier.

The total efficiency of the system reads

$$\eta = \frac{P_{DC}}{P_{received}} = \frac{P_{RF}}{P_{received}} \frac{P_{DC}}{P_{RF}} = \eta_{received-RF} \cdot \eta_{RF-DC}, \quad (1)$$

where $P_{received}$ is the received power from the antenna, P_{RF} is the power at the rectifier's input, and P_{DC} is the power at the rectifier's output. Focusing on $\eta_{received-RF}$, to increase P_{DC} , we should work on maximizing $P_{received}$, which is related to the antenna gain, G :

$$P_{received} = \frac{\lambda^2}{4\pi} G \cdot P^i, \quad (2)$$

with P^i being the incident power density and λ being the wavelength of the frequency of operation. From Equation (2), it is apparent that G , the antenna directive gain, needs to be maximized.

1.2. Antennas for Wireless Power Harvesting

Rectenna systems usually use high-gain antennas to maximize energy harvesting efficiency in order to reduce the substantial propagation losses and atmospheric absorption related to mmWave frequencies. Recent studies have investigated a range of antenna topologies and fabrication methods, such as printed circuit board (PCB) implementations, waveguide-based structures, and fully integrated on-chip antennas using CMOS and other semiconductor technologies. The operational frequency range, form factor restrictions, and power budget of the application frequently determine the type of antenna to use [17].

To maximize the performance of rectenna systems, a wide range of antenna topologies have been investigated, particularly for applications in wireless power transfer. Planar antenna designs have been presented for multiband and reconfigurable operation. These consist of modified E-shaped microstrip patches, monopole antennas with circular geometries and periodic rectangular strips, and irregular diamond-shaped radiators for multi-resonance behavior. Furthermore, it has been shown that antennas using slit-loaded bow-tie geometries and fan-shaped structures with CPW feeds enable broad operating bandwidths. Back-to-back patch arrangements have been used to successfully expand the beam coverage area for wider angle reception.

In mmWaves, more advanced and compact antennas have been developed for energy harvesting. Examples include dual-patch and Yagi-style antennas, concentric ring slot structures, and reconfigurable Y-shaped patches using p-i-n diode integration. For array-based solutions, folded dipole antennas with coplanar stripline feeds, lens-based antennas minimizing diffraction losses, and electromagnetically coupled patch arrays have been employed to achieve high gain and reduced mutual coupling. Also, the application of metasurfaces has demonstrated beneficial results in increasing angle coverage and harvested power. Innovative designs like triple L-arm slotted patches and flexible textile antennas with inset microstrip are structures that can be part of rectenna systems in mmWaves. Some examples are shown in Table 1.

Table 1. Examples of power harvesters.

Ref. No	Frequency (GHz)	Antenna	Gain (dB)	Main Feature
[18]	28	Series-fed patch antenna array	18	Wide angular coverage
[19]	35	Fabry–Perot resonator antenna	15	High efficiency, 95.5%
[20]	24	Antipodal Vivaldi	8	Textile-based broadband rectenna
[21]	28	Linear antenna arrays	17 (dBi)	Long-range coverage
[22]	24	CP patch array antenna	12.6 (dBc)	
[23]	26	Patch antenna	8.2 (dBi)	High fractional BW (22%)
[24]	24	Microstrip patch array 4×4	13.8	Wireless information and power transfer, integrated system
[25]	5.8	SIW CP antenna	6 (dBc)	Harmonic suppression
[26]	24–40	ME dipole Antenna array	27 (dBi)	High efficiency Wide-angle spatial coverage
[27]	94	Tapered slot antenna	13.5 (dBi)	High PCE

1.3. Phased Arrays and Beamforming for Wireless Power Harvesting

Beamforming allows the efficient direction of electromagnetic energy toward specific targets. The combination of antenna arrays and beamforming enables the high-gain beams with a controlled beamwidth to facilitate both focused power delivery and support for multi-user environments [28]. At higher frequencies, such as those used in mmWave bands, electronically steerable antennas become necessary to overcome higher path losses [29]. Some of the main design challenges in WPT antenna arrays with beam scanning include the interaction, mutual coupling, between antenna elements, the ability to steer the beam up to $\pm 45^\circ$, and maintaining a high overall antenna efficiency. For example, the Rotman lens is commonly used in mmWave energy harvesting applications because it can cover, with its beamforming capabilities, a wide range of angles economically [28]. In the case of WPT, beamforming is useful for scenarios where the receiving devices are mobile, as it allows the base station to dynamically adjust the direction of the transmitted power, ensuring maximum DC energy delivery to the receiver at any given location [29].

A number of efforts have been made to overcome directionality problems. Mesh-like antennas with multiple beaming regions [30,31], multiport, multi-rectifier surface rectennas [32], multi-rectifiers with beamforming matrices [33–35], and multiport antenna arrays [36] have also been presented for high-gain, multi-direction energy harvesting.

2. System Description

Here, we focus on a harvesting host surface. We assume a cartesian tiling of the surface. Each elementary tile (1st level of organization) is a square radiator that can be either near resonance or assembled by numerous pixel sensors. For the sake of an example, we assume a subarray formed (2nd level of organization) of $3 \times 3 = 9$ element radiators also forming a square. We add one more level of organization (3rd level of organization) where 3×3 subarrays of the 2nd level are organized to form the higher level of the antenna structure [37–41]. This organization is shown in Figure 3.

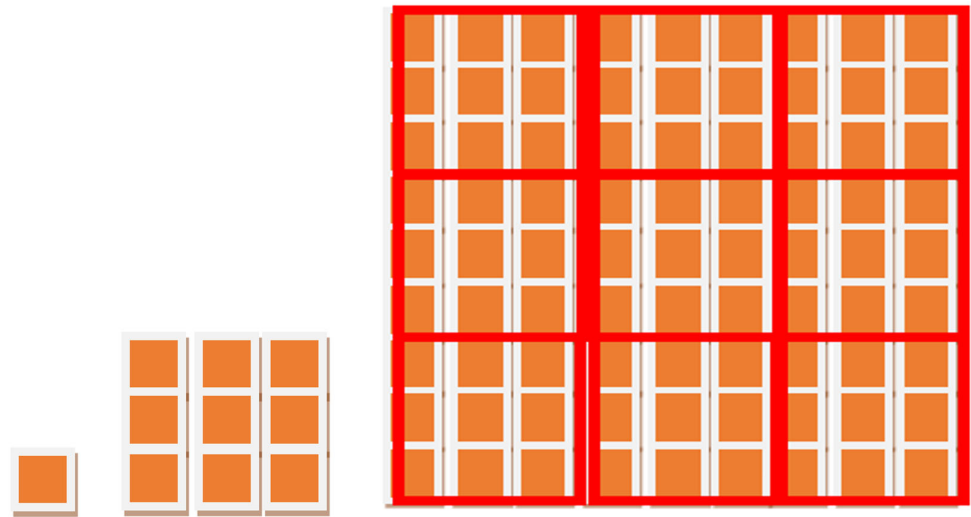


Figure 3. The 3 levels of harvesting-skin-surface organization. From left to right: 1st, 2nd, and 3rd levels of horizontal organization.

Having described the horizontal organization, we proceed now with the description of the vertical one. The elementary vertical structure is shown in Figure 4.

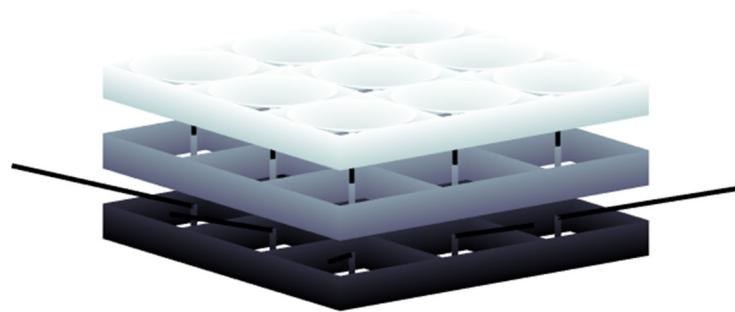


Figure 4. The elementary subarray vertical structure.

Figure 4 depicts (top to bottom) the 3×3 element radiators to be fed by a 9×9 lossless beamformer network (BFN). Below the BFN, there is a 2D power combiner (PC) 9 to 1. The central input of the PC is connected to the central output port of the 9×9 BFN. The ‘side’ inputs of the 9×1 PC are connected to the neighboring 3×3 subarray.

This connection is presented in Figure 5.

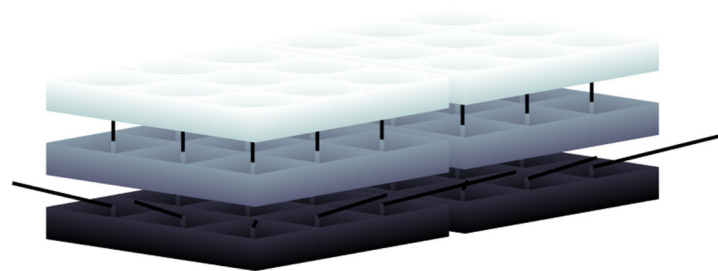


Figure 5. Two interconnected elementary subarrays.

Here, we see the ‘left’ 3×3 subarray feeds the ‘right’ PC, and the ‘right’ 3×3 subarray feeds the ‘left’ PC.

Last, the outputs of the PC are fed to the respective rectifiers to finally convert the incoming microwave power to DC. Off course, those equivalent ‘DC’ sources are to be properly combined to maximize efficiency.

3. Results and Evaluation

To understand the merit of our contributed design, in Figure 6, we present the far-field pattern of the level 2 subarray and that of the level 3 subarray. The second covers much more of the angular domain and at the same time exhibits directivity values that are exceptional.

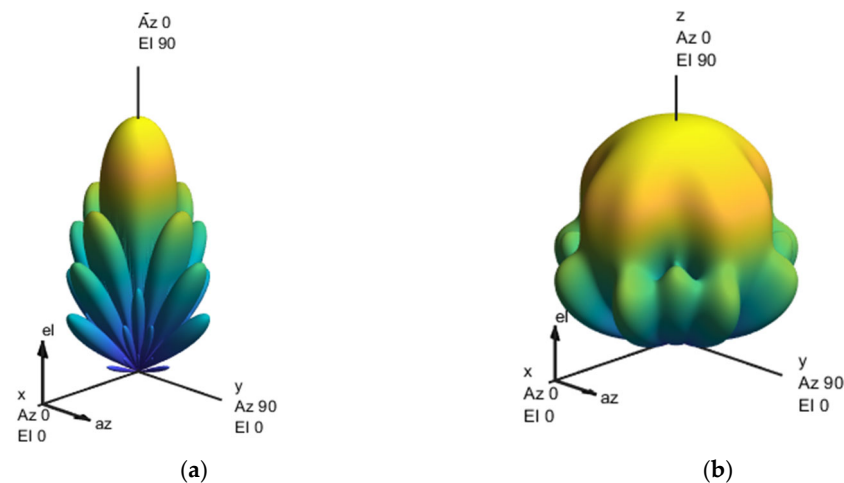


Figure 6. Level 2 (a) and level 3 (b) far-field directivity patterns of the respective interconnected elementary subarrays.

From the previous figure, it is immediately apparent that the directivity pattern of the level 3 subarray covers more angular space than the respective level 2 subarray. Level 2 is the preferred choice when specific Tx is present that should be harvested. On the other hand, level 3 is the proper choice when no specific ambient Tx is present (or recognized).

To demonstrate the physics behind the broadening of the level 3 pattern (while at the same time keeping high values of directivity needed for increased effectiveness), we present Figure 7.

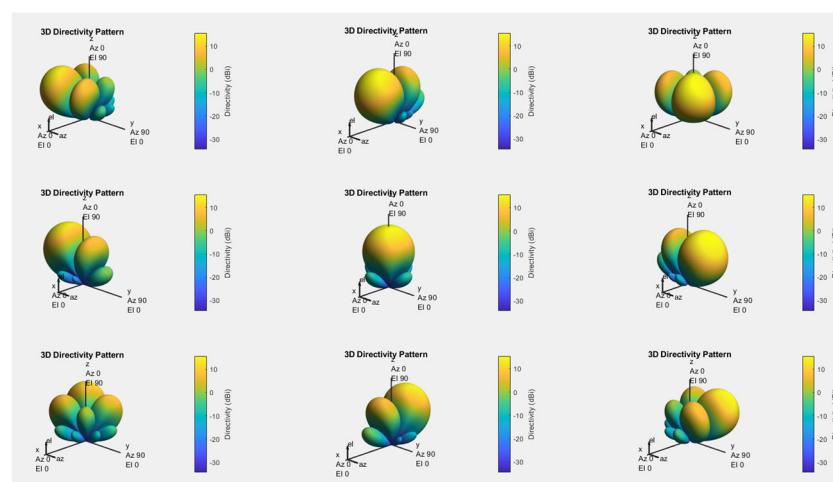


Figure 7. The equivalent directivity patterns of the 9 inputs entering at the 9 ports of the power combiner.

Figure 7 illustrates the patterns of the nine inputs that are entering each one the respective input port of the PC. Those beams point in different but ordered angle directions, thus achieving both high gain and wide angular capability. This is because the final pattern is assembled by those nine different beams that altogether cover the needed angular space. Those nine beams are shown in Figure 8. Figure 8 further advocates our claims, by providing the equi-directivity coverage angular terrain.

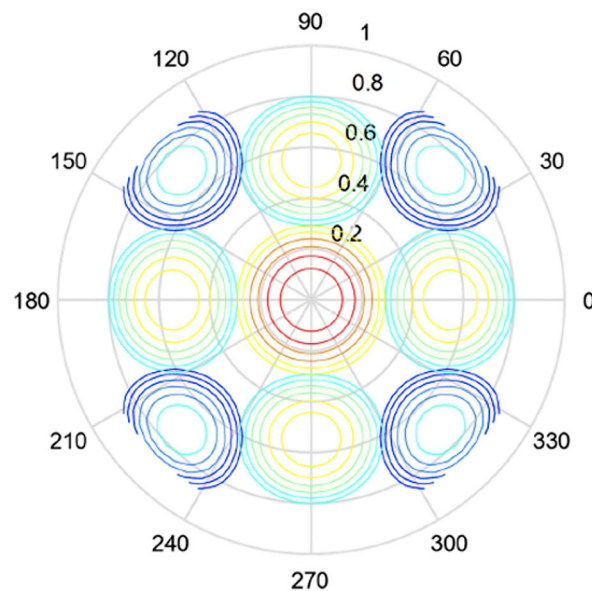


Figure 8. The equi-directivity angular coverage of the signal patterns entering the power combiner.

Previous results indicate that our contribution is a class of array-based solutions where the proper (three-level horizontal and vertical) combination of antenna arrays and beamforming networks enables the high-gain beams with a controlled beamwidth. In this way, our contribution is a scalable and extendable design that merges multiport, multi-rectifier antenna arrays accompanied by beamforming matrices for high-gain, multi-direction energy harvesting.

We envision reconfigurable intelligent harvesting surfaces, or smart skins, assembled by pixel elements. Those surfaces would harvest the near-normally incident electromagnetic power density, with super-directive gain, providing possible new solutions in the quest for renewable energy. Such a harvesting skin can be placed on large surfaces, for example, the outer wall of a large building, as depicted in Figure 9.



Figure 9. The contributed concept: wireless power-harvesting skin deployed on the walls of a building.

4. Conclusions

In the current paper, we contribute a large-scale wireless power-harvesting surface collector (we call it a skin) that employs two levels of organization, both in the horizontal and in the vertical planes. The host receiving surface is tiled, employing square radiators that form hierarchical subarray structures. At the same time, the beamforming network collects the received power in a drainage basin fashion, achieving excess efficiency.

The technological readiness of our proposal is currently at level three, since no prototype is built and characterized via measurements; nevertheless, simulated performance and respective emulated experiments indicate great potential. Indeed, the harvester exhibits both wide angular coverage and elevated antenna gain. Those characteristics secure the harvesting skin's excellent performance.

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