Rectennas for RF Energy Harvesting and Wireless Power Transfer: a Review of Antenna Design

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***Abstract*—Radio frequency energy harvesting (RFEH) and radiative wireless power transfer (WPT) have attracted significant interest as methods of enabling battery-free sustainable wireless networks. Rectifying-antennas (rectennas) are the corner-stone of WPT and RFEH systems and critically affect the amount of DC power delivered to the load. The antenna element of the rectenna directly impacts the radiation to AC harvesting efficiency, which can vary the harvested power by orders of magnitude. In this paper, antenna designs employed in WPT and ambient RFEH applications are reviewed. Reported rectennas are categorized based on two main criteria: the antenna-rectifier impedance bandwidth and the antenna's radiation properties. For each criteria, the Figure of Merit (FoM) is identified, for different applications, and reviewed comparatively.**

***Index Terms*—Antenna, Gain, Internet of Things, Microstrip antennas, Rectenna, RF Energy Harvesting, RF Power Transfer, Wearable Antenna**

I. Introduction

Tesla proposed Wireless Power Transfer (WPT) in the 1900s as a mean of transferring thousands of horse-power [1]. The term "rectenna", describing an antenna connected to a rectifier for harvesting Radio Frequency (RF) power, emerged in the 1950s for space microwave power-beaming applications and for powering autonomous drones [2]. Omni-directional long-range WPT has been hindered by the physical characteristics of the propagation medium, *air*. Thus, commercial WPT has been mostly limited to near-field non-radiative power transfer for wireless consumer electronics charging, or short-range radiative Radio Frequency Identification (RFID) [3].

As the power consumption of semiconductor devices and wireless sensor nodes continuously scales down, it became more feasible to power sensor nodes using ambient Radio Frequency Energy Harvesting (RFEH), or using distributed low-power omni-directional transmitters [4], [5]. An ultra-low power wirelessly-powered system is typically composed of the RF-harvesting front-end, DC power and storage management, and a low-power microprocessor and transceiver.

Fig. 1 shows the architecture of a RFEH wireless node, and the commonly reported implementations of the RF-frontend. The end-to-end efficiency of a wirelessly-powered system, as well as, the architecture of a Simultanious Wireless Information and Power Transfer (SWIPT) network are dependent on the performance on individual components such as: the antenna, rectifier and power management circuit. Multiple literature surveys have been carried out focusing on different components of the system. Table I outlines the power conversion stages, the key component for efficient power conversion, and the relevant literature surveys focusing on each part. Recent surveys focused on the power conversion techniques [4], [6], [7], rectifier topologies [7], [8], or RFEH from a networking perceptive [5], [9]. However, antenna design for RFEH has not been considered as a key parameter in reported reviews. To illustrate, while some surveys considered the antenna's bandwidth and efficiency from a holistic perspective, or specific antenna designs for niche applications such as miniaturized or wearable antennas [8], [10], no detailed analysis has been presented on the impact of certain antenna parameters on the power reception and conversion efficiency.

This survey reviews antenna design techniques in a rectenna, aiming to distinguish the RFEH- and WPT-specific antenna design challenges from standard antenna design for communications. Antennas are compared from two perspectives, end-to-end impedance matching, and radiation properties, in each

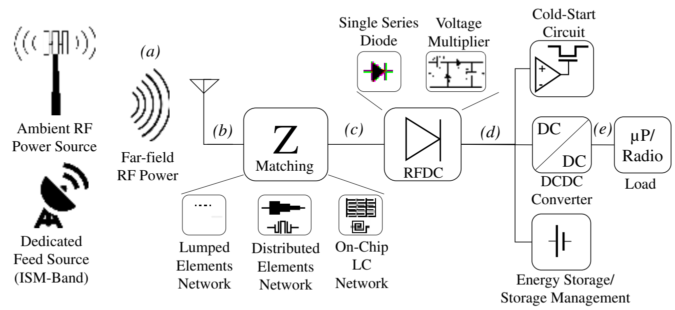

Fig. 1. System architecture of a RFEH wireless node, showing the power sources and conversion stages, as well as commonly reported implementations.

TABLE I
Power Conversion Stages in a RFEH System

Conversion stage	Power source	Focus element	Literature surveys
a-b	Radiated RF plane wave	Antenna radiation characteristics	This survey
b-c	RF guided wave	Antenna and matching network bandwidth	This survey, 2013 [4], 2018 [8], 2019 [10]
c-d	Z-matched RF wave	Rectifier topology and technology	2013 [4], 2014 [6], 2016 [9], 2018 [8]
d	Unregulated DC power	Power management circuitry	2015 [7], 2016 [9]
e	Regulated DC power	Load, network architecture	2013 [4], 2014 [5]

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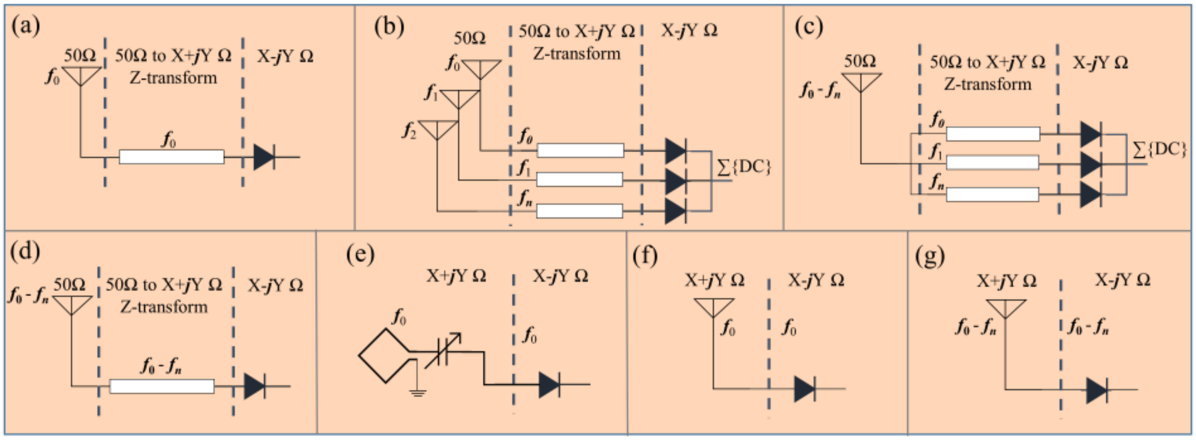


Fig. 2. Rectenna topologies from a bandwidth and impedance matching perspective. (a): Single band rectenna with standard antenna. (b): Multi-band rectenna (formed of multiple mutually coupled antennas) with one rectifier and matching network per band. (c): Broadband rectenna with multiple RF-ports and separate matching networks for each band. (d): Broadband rectenna with a broadband antenna and a broadband matching network. (e): Single band rectenna using an electrically small antenna directly matched to the rectifier. (f): Single band electrically large antenna with complex impedance to conjugate the rectifier. (g): Broadband rectenna with complex impedance to conjugate the rectifier over a range of frequencies. The dashed line represents the measurement plane where a $S_{11} < -10dB$ bandwidth needs to be maintained.

context, the figure-of-merit (FoM) is identified and reviewed in state-of-art antennas. Section II defines the bandwidth and matching challenge in rectennas, and compares the reported approaches to fulfilling the bandwidth requirements of a rectenna. Section III reviews rectennas based on 50Ω antennas, with the matching network design in section IV. Section V reviews antenna-rectifier co-design and matching network elimination techniques. Finally, radiation properties of rectennas are reviewed in section VI.

II. Bandwidth and Matching: A Non-50Ω RF Network

The standardization of the characteristic impedance to the 50Ω constant has been derived as a compromise between attenuation and power-handling in the early-days of microwave engineering [11]. In antennas, the impedance bandwidth, is defined as the range of frequencies where the reflected power is less than 10% ($S_{11} < -10dB$). This has been traditionally referenced to a 50Ω source, due to the fact that Low-Noise Amplifier (LNA), Power Amplifiers (PA) and detectors are conventionally designed with 50Ω input impedance matching.

In rectennas, where the antenna's output is fed directly into a rectifier, the non-linearity of the diode results in a highly-varying input impedance, with a dominant capacitive component [12], [13]. Assuming a 50Ω antenna is used, the main challenge lies in designing an additional RF matching-network to transform the input impedance to the rectifier's at the frequencies of interest, and optimizing it for a certain power level. In this case, an end-to-end impedance bandwidth is required to ensure efficient RF to DC conversion. Thus, although an antenna could achieve a theoretical infinite or ultra-broad bandwidth using periodic elements or self-complimentary geometry, the rectenna's bandwidth will be bottlenecked by the rectifier's matching network.

Multiple rectenna topologies have been presented to maximize the power transfer between the antenna and the rectifier, through minimizing reflection, for single- and multi-band harvesting or WPT. Figure 2 shows a summary of the reported rectenna topologies categorized by their impedance matching architectures. Examples of high performance rectennas, in terms of end-to-end bandwidth (the FoM in this case), from each category are shown in Table II.

While WPT from a dedicated feed and ambient RFEH are distinct rectenna applications, from a bandwidth perspective, achieving an end-to-end match between the antenna, the rectifier and the load is fundamental to achieving high Power Conversion Efficiency (PCE). Nevertheless, WPT rectennas have been more focused on achieving a higher-Q match (lower S_{11}) to improve the single-tone PCE for certain power levels (topologies a, e and f), hence, in single-tone WPT may not be a FoM on its own. However, a broad bandwidth in single-tone WPT improves the systems immunity to detuning, fabrication imperfections and packaging parasitics. On the other hand, RFEH rectennas have prioritized multi-band operation, due to the often low Power Spectral Density (PSD) in single bands, falling into topologies b-d and g.

III. 50Ω Rectennas

A. Single-Band 50Ω Antennas in Rectennas

The antenna design of 50Ω single band rectennas (topology A) has been based mostly on standard antenna designs, such as a Linearly-Polarized (LP) or a Circularly Polarized (CP) radiator patch over a ground plane [14], [23]–[26], dipole antennas [15], [27] and inverted-F monopoles [28]–[31]. Differential single-band rectennas have been based on multiple antenna elements configured as an array with DC combining [23], or hybrid DC and RF combining of multiple patch elements [32]. The effect of size reduction on the rectenna's PCE has been discussed in [33].

As many of the presented 50Ω antennas are single band, which meets the requirements of single-tone WPT, when ambient multi-band RFEH is sought, multiple single-band

TABLE II
COMPARISON OF RECTENNAS BASED ON THEIR IMPEDANCE MATCHING ARCHITECTURE

Lit.	**Topology**	Antenna	Matching	Frequency bands (GHz)	Fractional Bandwidth (rectenna) **FoM**
2018 [14]	A	Narrow-Band Patch	Single-band tapered line	2.45 (single)	4%
2013 [15]	B	Single-band tapes	Single-band LC	0.5, 0.9, 1.8, 2.1	7%, 5%, 3%, 4-5% .
2018 [16]	B and C	Broadband slot, single band slot	T/Pi networks (single diode/band)	0.9, 2, 2.55	15%, 23.7%, 0.07%
2016 [13]	C	Frequency-independent Log-periodic	Transmission-line match	0.55, 0.75, 0.9, 1.8, 2.3	9%*, 3%*, 2.3%, 2.2%, 2.2%
2013 [17]	D	Broadband Yagi-Uda array	8th-order LC (voltage doubler/band)	1.8, 2.1	4%, 3%
2014 [18]	E	High-Q loop	Weighted capacitor bank	0.868	6.9%
2016 [19]	F	High-Z Dipole	N/A	0.55	21.1%
2017 [20]	G	High-Z Multi-band Dipole	N/A	0.95, 1.85-2.4	2%, 30%*

*Bandwidth at $S_{11} < -6dB$

Fig. 3. Multi-band UHF RFEH antennas: Triple band antenna with a lumped inductor and three radiator elements [21] (left), triple band slotted patch [16] (center), and L-probe-fed dual-band patch [22] (right)

antennas have been combined to form multi-band rectennas with suppressed mutual coupling (topology B) [15], [28], with independent DC combining, after the power management circuit stage, making it entirely isolated from the RF harvesting and conversion circuit, requiring multiple power management circuits for each bands, which may decrease the efficiency of the boost converters [14], due to the low DC power from individual bands.

B. Multi- and Broad-band RFEH Antennas

Ambient RFEH is usually associated with multi-band harvesting, thus, multiple methods of improving the bandwidth of standard antenna designs, or methods of forming dual or triple-band antenna arrays have been presented. In this section, bespoke antenna design for RFEH is reviewed, along with classic multi-band antennas with the potential of being employed as rectennas. In this context, the terms “multi-band” and “broadband” antennas are differentiated through the continuity of their bandwidth ($S_{11} < -10dB$) outside the bands of interest.

Coplanar-Waveguide (CPW) monopoles, occupying smaller areas than their microstrip patch antenna counterpart at the same frequency, and producing a LP or a CP wave, are commonly used in broadband ambient rectennas [34]–[36]. A reflector plane can be used for increased isolation, and improved gain resulting in a similar radiation pattern to patch antennas [36]. Slotted-CPW antennas were used to improve the impedance-bandwidth across multiple bands such as the 1.8-2.7 GHz [35] or 1-3 GHz [34], [37].

Slot rectennas, with aperture-proximity feed were designed to have increased bandwidth, as well as multiple proximity feeds for different rectifiers and matching networks targeting different bands. [16], [38], [39]. Patch rectennas have also been presented for dual-band operation using asymmetric corner trimming resulting in dual-resonance [39]. Figure 3 shows some of the reported multi-band antennas utilizing more than one bandwidth improvement technique.

Conventional broadband antenna designs, including frequency-independent antennas, have been used in ambient RFEH as well as proposed for mmWave applications [40]. Spiral antennas: a single element textile rectenna with a single band matching network [41], a spiral array [42], and a log-periodic antenna [13] have been presented. A triangular spiral antenna has also been presented for harvesting energy from 1-3 GHz [43]. A spiral antenna, with unfolded dipole ends was presented for dual-band operation at 900 MHz and the Ultra-Wide Band (UWB) (3-5 GHz) bands [44]. Ref. [45] presents triple band operation using a multi-port rectenna formed of an array of “pixel” elements, with DC combining, with the “pixel” connections optimized through simulation to tune the antenna, the “pixel” rectenna has been compared to $\lambda/4$ monopoles .

IV. ANTENNA-RECTIFIER IMPEDANCE MATCHING

Matching the 50Ω antenna to a non-linear rectifier presents a challenge due to the wide variation in its input impedance with frequency. In topologies A and B (Fig. 2), a common matching network topology is LC matching using lumped components [46], [47], however, the fractional bandwidth is typically lower than most communication bands [15]. Single band stub matching has been commonly used at sub-6 GHz microwave [14], [45], [48] as well as at milli-meter Wave (mmWave) bands [49], [50], usually paired with RF-short quarter-wave stubs at the fundamental frequency and the 2^{nd} harmonic. Therefore, the reported mmWave rectennas have inherently narrow band due to their PCE bandwidth being bottle-necked by the harmonic rejection at the outuput, which makes them specific to single-tone WPT applications in the 24 GHz license-free band. A comparison of lumped and distributed stub matching has been reported in order to numerically defining a maximum PCE of a rectenna [51].

Rectennas in topologies C and D have been presented with more complex matching networks. Full-distributed-line matching networks have been presented for broadband operation [52], [53], with an RF-block-DC-short (DC-pass filter) at the output port [17] or a DC-block capacitor acting as a return path for the diode's harmonics [22]. Rectifier components, such as capacitors in a voltage doubler, have been replaced in [52] by Printed Circuit Board (PCB) interdigitated capacitors, synthesized using commercial Electronics Design Automation (EDA) tools. Other reported broadband rectenna matching networks combine lumped components, for matching the lower frequencies, and distributed elements for creating RF shorts at the input [54]. Varying the load's observed input impedance by the source, known as source-pull technique, has been utilized to design a broadband rectifier of 57% fractional bandwidth (1.25 to 2.25 GHz) with up to 10% higher PCE compared to a lumped or distributed line matching network [55]. While matching networks have commonly been designed to match the antenna across its full 50Ω bandwidth, in [41], [56] broadband antennas have been connected to narrow-band rectifiers.

Hybrid lumped and distributed elements matching networks have been widely used in topologies C and D [13], [16], [22], [54], with series inductors and capacitors being the most commonly utilized lumped components [35]. These avoid complex structures such as interdigitated capacitors which require more accurate modeling and fabrication than standard microstrip lines.

The input power to the rectifier affects the input impedance due to the diodes' non-linearity. Therefore, rectennas have been designed to maximize the PCE for specific input power levels as well as load impedances [14], [45]. In [13], the matching network for the six band rectenna, following topology C, has been designed to match the rectifier at power levels from $-30dBm$ to $-10dBm$ and for load impedances from 1 to 100 kΩ, based on a complimentary conjugate resistance compression network. Moreover, as a result of the predominately capacitive high impedance of the diodes at sub-3 GHz frequencies, broadband rectennas with eliminated matching networks [20], [57], [58], or minimized simplified matching circuits [59], have been focused on $P_{RF} > 0dBm$, and frequencies higher than 1 GHz [58]–[61] due to the lower capacitive impedance of the diode enabling a good match with the antenna, avoiding designing antennas with input reactance $> 1000\Omega$.

Adaptive, or reconfigurable, impedance matching has been presented in Complimentary Metal Oxide Semiconductor (CMOS) rectennas, where the matching network is formed of an on-chip capacitor bank and inductors [62]. Static CMOS matching networks have also been presented for standard 50Ω antennas [62] as well as co-designed loop antennas [18], [63]. In [64], a passive CMOS power-detector has been used to control the switches directing the antenna's output to different rectifiers and matching networks based on the available power. A design-time reconfigurable matching network has been presented using lumped adjustable capacitors, tuned by trimming while measuring the input impedance using a Vector Network Analyser (VNA) [65]. On-board switches, controlled by an external micro-controller, were utilized in [66] to tune the on-PCB matching network capacitors at 900 MHz, demonstrating up to 10% performance improvement. In a reconfigurable microstrip matching network, a Field-Effect Transistor (FET) switch has been used to tune matching stubs for dual-frequency operation [67].

V. Antenna and Rectifier Co-design

Rectennas following topologies E-G in figure 2 are characterized by the antenna's direct match to the rectifier, instead of the 50Ω standard, requiring a minimized or eliminated-matching circuit to deliver power to the rectifier. This section reviews state-of-the-art rectennas employing non-50Ω antennas, in addition to the advantages of matching-network-less rectennas.

A. Electrically Small Antennas

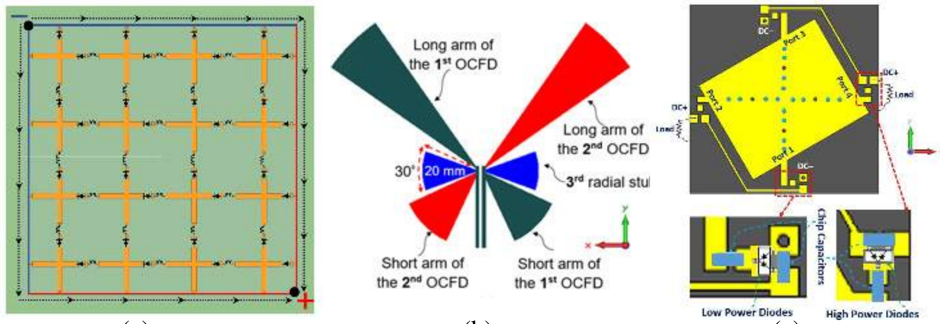
LC resonant loop antennas have been widely used in applications where the system's size is critical. At sub-1 GHz frequencies, where the wave-length could result in a standard distributed-elements antenna occupying more space than the system's overall dimensions, applications such as fully-integrated transceivers for body-implants particularly benefit from using electrically small antennas for WPT [68].

The highly inductive impedance, near resonance, of a small-antenna can be utilized to directly conjugate the rectifier [69], or with an additional on-chip capacitive matching network [18], [70]. Electrically small antennas, down to $ka = 0.645$, compared to $ka = 5.91$ in a normal dipole ($ka = 2\pi r/\lambda_0$), have been reported for sub-1 GHz WPT with LP and CP [69], using Huygens dipole antennas [71].

Multiple on-chip LC coils for radiative WPT have been presented for microwave and sub-1 GHz fully-integrated rectennas. In a fully-integrated 915 MHz CMOS rectenna, a dipole antenna has been directly tuned to match a 3.4Ω source using slot-termination to inductively load the antenna [72]. CMOS rectennas with a Power Management Integrated Circuit (PMIC) and a LNA were also presented with on-chip loop antennas in a standard Silicon-on-Insulator (SoI) chip [73]. A power-harvesting RFID 5.8 GHz transceiver with an integrated coil-antenna has been presented for near-field powering [74]. A dual-band antenna, for 7 GHz WPT and 1 GHz communication have been presented with on-chip tuning capacitors [75].

B. Rectifier Conjugate Antennas

As observed in [12], [13], the typical input impedance of the diode is highly capacitive, and therefore requires



(a) (b) (c)

Fig. 4. Rectennas directly matching the diode's impedance: (a): 4×4 RFEH cross-dipole surface [58], (b): broadband inductive off-center fed dipole (OCFD) [20], (d): all-polarization frequency-selectable off-set patch [57]

an inductive antenna to directly conjugate the impedance. High impedance, inductive antennas have been widely used in RFID tags due to the chips' capacitive impedance [76]. Thus, a similar approach can be utilized to design a RFEH antenna to directly conjugate the rectifier's impedance. Dipole antennas, recently becoming a trend in complex-impedance RFID antennas [76], exhibit high impedance (resistance and reactance) near their resonant frequency. For example, [77] reports one of the earliest dipoles designed to match the resistance of the diode with a low-impedance load. However, only the resistance of the dipole is partially matched to the rectifier. A similar approach was reported when measuring the reception efficiency of polarization-independent arrays using a resistive load simulating the rectifier's real-impedance [78], [79], achieving an impedance bandwidth from 6 to 20 GHz with respect to the purely-resistive dummy load in [79].

Inductive dipoles [19], [20], [80] have been used to match the high capacitance of the rectifier at the band of interest. In a folded dipole antenna, the dual shorted lines (dipole-folds), act as an impedance transformer allowing the design of very high impedance antennas [19]. Alternatively, the offset feed, [20], [57], is responsible for increasing the inductive reactance as well as the real impedance. Combining multiple offset dipole elements with imbalanced bow-tie radial stubs resulted in the dual-broadband high impedance of the antenna [20]. A hybrid filter-matching network structure has been incorporated in the antenna in [81] and a cross dipole array [82] represent the highest frequency direct antenna-rectifier matching rectenna (Ku band). Cross-dipole RFEH surface arrays have been also reported with a real impedance match [79], [83] or a complex impedance match to the rectifier [58]. Figure 4 shows some of the reported rectifier conjugate antennas.

Other antenna structures, such as dual-LP [51], [57] and CP patches [61] have also been used to directly conjugate the rectifier's impedance, providing higher gain compared to omni-directional dipoles. The off-center feed in [57] produces additional narrow-band resonances allowing three bands of operation, as opposed to a standard single-band patch. This approach demonstrates relatively high efficiency independent of the load resistance between 700Ω and 4500Ω at $P_{RF} > 0dBm$, the operation power choice enables easier matching due to the reduced capacitive impedance of the diode. A rectenna array exhibiting only a real-impedance match has been previously presented for a simpler antenna design [23].

TABLE III
KEY RADIATION PROPERTIES IN WPT AND RFEH RECTENNAS

Parameter	Ambient RFEH	Dedicated WPT
Gain	Insignificant [45]	FoM
Beam-width	Wide (Omni-directional)	FoM: Narrow, directional LoS
Polarization	Arbitrary: Dual LP/CP	Single-Pol, CP

VI. RADIATION PROPERTIES IN RFEH AND WPT

The power received, P_{RX} in the Friis model (1), by an antenna, at distance d from the transmitter, is a direct function of the receiver and the transmitter gain (G_{RX}, G_{TX}). While the gain, on its own is often regarded as a FoM, it does not provide a complete picture on the anticipated reception of the rectenna.

$$P_{RX}(d) = P_{TX}G_{TX}G_{RX}(\frac{c}{4\pi df})^2 \tag{1}$$

Antenna properties such as main-lobe directivity and polarization directly impact the amount of power harvested from an incident wave. Antenna radiation properties are the key parameter where ambient RFEH and WPT can be distinguished. While in both applications the propagation medium may be unknown, and its impact on the received wave needs to be considered, knowledge of the transmitting antenna can be exploited. Table III identifies the key parameters reviewed in this section, and their applicability to RFEH and WPT, distinguishing where how the FoM changes with application.

A. Directivity and Gain

In most RFEH and WPT applications, it is assumed that the direction of the incident radiation is unknown by the harvester, with no LoS path. In this effort, multiple antenna designs and placements have been investigated to maximize the received power from an unknown source, independent of main-lobe alignment between the transmitter and the receiver.

Omni-directional rectennas have been widely presented in ambient RFEH rectennas [15], [28]. In [15], [84], the PSD

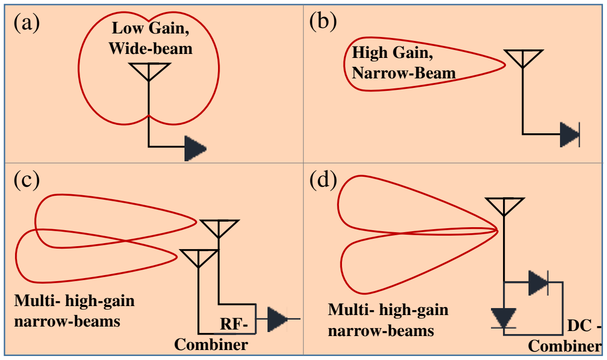


Fig. 5. Rectenna topologies based on the antennas' radiation patterns. (a): Omni-directional antenna. (b): High-gain directional. (c): Multi- high-gain beam antenna with RF combining. (d): Multi- high-gain beam with DC combining.

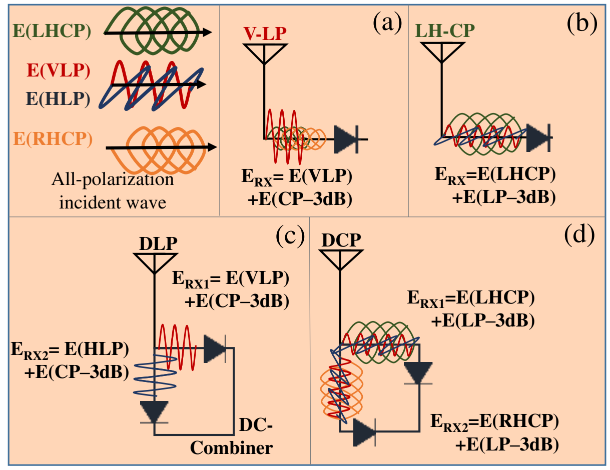


Fig. 6. Rectenna topologies based on antenna polarization, showing the total received power by each antenna from an all-polarized incident wave. (a): single LP antenna. (b): single CP. (c): Dual LP. (d): Dual CP.

has been reported to vary based on the antenna's orientation. Nevertheless, the variation in power has not been explained and hence it is impossible to identify if the change is due to the antenna's radiation pattern, or due to a polarization mismatch.

High gain directional antennas and arrays have been widely-reported for microwave WPT and beaming [85], in addition to RFEH applications; improving the harvesting efficiency from low RF power-densities or overcoming the propagation losses. Yagi-Uda rectenna arrays [17], [86], bow-tie array [87], a spiral array [42], tightly-coupled-Vivaldi array [88], a CPW CP array [89] and a wide-area patch array [23] were among the scalable rectenna implementations for maximizing the incident power density, where the area permits. Other approaches to improve the antenna's gain included Substrate-Integrated Waveguide (SIW) techniques at microwave and mmWave bands, specific to WPT [90]–[92]. However, high-gain rectennas are characterized by narrow-beam width, making receiving arbitrarily-directed waves inefficient. An investigation into the number of antenna elements and ports concluded that higher directivity does not correspond to higher harvested power in ambient RFEH assuming a 3D random incident field, this has been validated through field measurements in urban environment [28]. Based on [28], high gain arrays can be restricted to WPT applications.

In the effort of porting the benefits of higher gain antennas to arbitrary RFEH, packaging or layout solutions have been utilized to overcome directionality problems. A double-patch-antenna wrist-band was presented to harvest power from both directions, for ambient Wi-Fi RFEH [14]. Ambient cellular RFEH antennas have also been designed as 3D boxes [93], and printed or adhered to the walls of an enclosure [48], [94], [95], for reducing the system's area and enabling multi-direction harvesting. In [95], the cubic rectenna structure demonstrates higher energy-reception probability in ambient RFEH, due to the improved antenna diversity.

Improvements to antenna designs to increase the beam-width included auxiliary parasitic patch elements to improve the WPT of a 2.4 GHz 4×1 array [96]. A 6 GHz Mesh-like antenna with multiple beaming-regions was also proposed demonstrating multiple beams for each port [97], [98]. Multi-port multi-rectifier surface rectennas and energy harvesting antennas of omni-directional radiation patterns have been presented for multi-direction and multi-polarization RFEH [58], [60], [78], [79]. Multi-rectifier with beamforming matrices [99]–[101], and multi-port antenna arrays [98] have also been presented for high-gain, multi-direction energy harvesting. A comparison of RF-, Direct Current (DC)-, and hybrid power combining from multiple antennas have been presented in [102].

In conclusion, although high-gain antennas are preferred to improve the harvested power from low RF densities, highly-directional receivers can be undesirable in applications with unknown transmitter direction, such as ambient RFEH, or WPT through an unknown propagation channel. In this effort, multiple methods of multi-beaming were proposed for multi-direction high gain WPT and RFEH.

B. Antenna Polarization for Maximum RFEH and WPT Efficiency

Antenna polarization describes the motion of the field vectors referenced to the direction of propagation from the antenna. Polarization mismatch results in reduced transmission/reception between antennas even with main lobe direction alignment. For instance, no power is received if a vertically LP antenna is used for transmission, and a horizontally LP antenna is used for reception. In this section, reported approaches to maximize the wireless reception efficiency and avoid polarization mismatch losses are reviewed, in this regard, attention is paid to the antenna's ability to receive a wave (maintain higher gain) both through its primary and secondary polarizations, hence the FoM is the polarimetric gain, observed through the antenna's immunity to variation in the polarization angle of incidence, which can be quantitatively compared through the antenna's primary and secondary gains (e.g. left- and right-hand CP) being equally high. A summary of the proposed rectennas' architecture, in terms of polarization, is given in figure 6 with State-of-Art (SoA) examples in table IV.

In cellular communications, where linear-polarization alignment between the base-station and the mobile phone is very

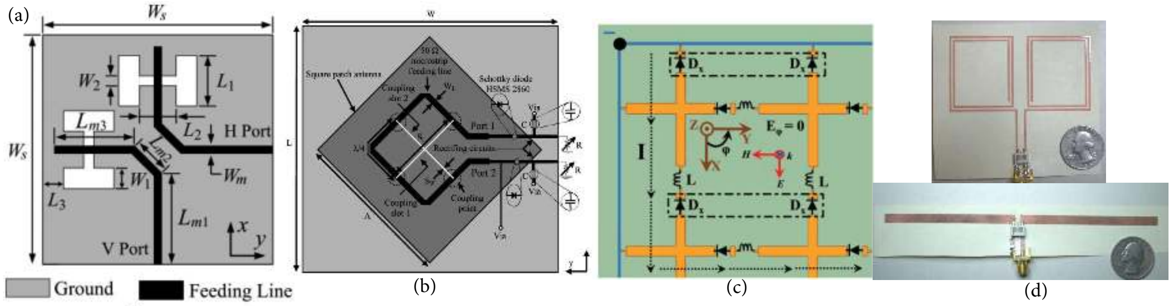


Fig. 7. Polarization independent rectennas: A: dual-LP slot [47], b: dual-CP slot [37], c: dual-LP cross-dipole array [58], d: dual antennas for harvesting near field H- (top) and E- (bottom) fields [105].

TABLE IV
COMPARISON OF RECTENNAS BASED ON THEIR POLARIZATION DIVERSITY

Lit.	Polarization	Antenna and Frequency	Primary Gain (**FoM**)	Secondary Gain (**FoM**)	Bandwidth (MHz)
2018 [14]	a: LP	2.45 GHz Patch	Co-Pol 7.3 dBi	X-Pol -15.2 dBi	50
2018 [103]	b: CP	5.8 GHz Slot	6 dBc	-14 dBc	1000
2018 [104]	c: DLP	2.4 GHz Dual-Slot	H-LP 7.45 dBi	V-LP 7.63 dBi	140
2015 [59]	d: DCP	2.4 GHz Slot	7.9 dBc	7.9 dBc	700

unlikely, base-station antennas have been designed to be dual-polarized [106], [107], or multi-polarized [108]; avoiding polarization-mismatch losses when being received by a phone's LP antenna, regardless of its angle. However, variation in a LP wave's polarization due to multi-path effects remain an unresolved issue. Based on the assumption of multi-polarized mobile base-station, cellular RFEH antennas have been designed as LP antennas; as reported in most ambient RFEH literature [15], [28], [45], [54].

Circularly Polarized (CP) rectennas have been mainly proposed for WPT due to their relative immunity to being mispositioned [42], [50], [109]. CP antennas enable reception of CP radiation with the same direction of rotation (left- or right-hand-side CP) without power losses, in addition to all LP waves with a 3 dB loss (50% power loss) regardless of the polarization angle. Thus, multiple WPT rectennas employed CP antennas to achieve rotation-independence with a CP transmitter. CP rectennas have been reported for the 900 MHz, 2.4 [37], [110], and 5.8 GHz Industrial Scientific Medical (ISM)-bands [103], [109], [111] as well as for mmWave rectennas [50], [112]. CP antennas based on asymmetric geometry have been reported has been reported with wider-beam axial ratio to improve the immunity to mis-positioning in WPT applications [113] along with beam switching for improved angular coverage [101].

In RFEH from arbitrarily polarized waves, polarization-diversity represents a potential solution to polarization mismatch losses [93]. Dual LP rectennas have been demonstrated using imbalanced slotted radiating elements [110], as well as slotted ground planes [114] in proximity fed antennas; rotated feed slots are used to achieve dual LP. Cross dipoles have also been reported for dual-LP rectennas for RFEH [54] along with dual-port patches [57]. It is expected that with dual-LP, the antenna could receive a similar amount of power regardless of the polarization angle. For instance, a stable PCE has been achieved by a dual-LP patch while varying the polarization orientation by 360° [115]. The dual-port/dual-rectifier architecture has been widely reported in ambient RFEH or random-polarization in LP rectennas WPT [35], [39], [57], [116] and CP rectennas [24], [37], [42], [112].

All-polarization, also-known-as multi-polarization, has been presented for entirely overcoming polarization mismatch losses, enabling harvesting CP and LP waves [59], [104], [117], where the two dual polarization-orthogonal LP elements effectively harvest all LP and CP waves. To illustrate, the net vertical and horizontal voltages (V_V and V_H), (2), remain unchanged regardless of the polarization angle. A CP-wave "**E**" follows in (3) and (4) where the power is harvested twice (once by each element) resulting in full reception of the CP component [104], overcoming the 3 dB polarization mismatch loss. Finally, through DC-combining arbitrarily polarized incident waves can be harvested. The dual-port antenna in [118] achieves left- and right-hand CP and LP using a dual-mode SIW cavity. Orthogonal Dual-LP and DCP were both reported to achieve similar net harvested power regardless of the incident polarization after combining the power from both ports [59], [104]. Figure 7 shows the geometry of reported all-polarization rectennas.

$$P_{RX}(\varphi = 90^o) = \frac{V_V^2}{2Z_0} = P_{RX}(\varphi = 0^o) = \frac{V_H^2}{2Z_0} \quad (2)$$

$$E_{LHCP} = \frac{1}{\sqrt{2}}(E_x + jE_y) \quad (3)$$

$$E_{RHCP} = \frac{1}{\sqrt{2}}(E_x - jE_y) \quad (4)$$

Polarization independent surfaces have been presented using a cascaded cross-dipole rectenna array [58], meta-material surface rectenna [78], and receiving meta-material antennas with a dummy resistive-load [79], [83] or a microstrip-transformer connected to a 50Ω RF power meter [119]. A frequency selective surface has also been used to harvest arbitrarily polarized waves [120]. Surface rectennas have been reported at a variety of frequencies and

Dual dipoles have also been utilized to achieve all-polarization operation at Ultra-high Frequency (UHF) (0.75 - 0.95 GHz), receiving up to 13 dB higher RF power by using only 4-dipole elements compared to a single dipole rectenna [117]. Dual orthogonal slotting of the patch's ground plane has been reported for the aperture feed of dual LP rectennas [59], [104], harmonics rejection has also been achieved due to the slotted feed in [59] omitting the need for an independent filter.

Where all-polarization is achieved using dual antenna feeds, the rectifier has been used to combine the incident arbitrarily-polarized wave with the two ports connected as a signal and ground to the voltage doubler or shunt diode [104], [121]. An alternative topology has been presented in [104], [117] where every output is rectified independently with DC combining. A modified charge pump has been presented in [116] to mitigate the effect of imbalance between the vertically and horizontally LP incident power.

To summarize, in WPT applications with a dedicated power source, CP is preferred due to the improved WPT efficiency regardless of antenna's polarization angle. On the other hand, in multi-source harvesting, specifically from ambient sources, all-polarization antennas can achieve better overall reception and maximum portability; a multi-port/multi-rectifier architecture is required to combine the all-polarization power at RF or DC.

VII. Conclusion

In this paper, recent advances in antenna design for RF energy harvesting and WPT are reviewed, presenting a standard categorization of RFEH and WPT antenna design, not presented previously in literature. The three fundamental antenna requirements for achieving high RF to DC efficiency have been identified as:

1) Antenna-rectifier impedance bandwidth at RFEH and WPT bands of interest.
2) Main-lobe alignment between the transmitter and receiver in WPT from a dedicated feed.
3) Polarization match between the rectenna and the incident wave, regardless of the angle and position.

Based on their impedance, rectennas have been classified into 50Ω and rectifier-conjugate, rectennas, with emphasis on the impedance matching across different frequency bands and loads, along with the efficiency of each matching approach.

The radiation properties, from a directivity and polarization perspective, have been reviewed in state-of-art rectennas. Methods of improving the gain through beamforming and packaging to overcome the narrow beamwidth were reviewed. Finally, CP rectennas for WPT were reviewed along with various implementations to achieve polarization-independent reception both for WPT and RFEH.

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