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A Review on Antenna Technologies for Ambient RF Energy Harvesting and Wireless Power Transfer: Designs, Challenges and Applications

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ABSTRACT Radio frequency energy harvesting (RFEH) and wireless power transmission (WPT) are two emerging alternative energy technologies that have the potential to offer wireless energy delivery in the future. One of the key components of RFEH or WPT system is the receiving antenna. The receiving antenna's performance has a considerable impact on the power delivery capability of an RFEH or WPT system. This paper provides a well-rounded review of recent advancements of receiving antennas for RFEH and WPT. Antennas discussed in this paper are categorized as low-profile antennas, multi-band antennas, circularly polarized antennas, and array antennas. A number of contemporary antennas from each category are presented, compared, and discussed with particular emphasis on design approach and performance. Current design and fabrication challenges, future development, open research issues of the antennas and visions for RFEH and WPT are also discussed in this review.

INDEX TERMS Antenna, energy harvesting, IoT, low-power, rectenna, receiving antenna, RFEH, self-powered device, sensors, wireless, WPT, WSN.

I. INTRODUCTION

Autonomous operation of low-power sensors and electronic devices require sustainable power supply rather than just relying on the stored energy in batteries. The emergence of rapidly growing Internet-of-Things (IoT) has introduced numerous interconnected electronic devices and sensors through the Internet [1], [2]. The number of connected devices will expand to be 30.9 billion by 2025 [3]. A sensor node's operational duration is determined by its battery capacity or available energy resources. Historically, batteries have been the most reliable source of energy for sensor nodes and portable electronic gadgets. Periodic battery replacement is required to extend the life of a sensor network [4]. However, there are scenarios where wireless sensor networks (WSNs) are deployed in remote areas or inaccessible locations such as the deep sea, underground, chemical plants, areas of environmental disasters and agricultural farmland monitoring, where it is difficult to replace batteries [5]–[8]. Moreover, sensor nodes may be left unchecked for weeks, months or years. The task of replacing or charging of batteries for a large number of wireless sensor nodes is impractical. Replacement of batteries after a finite time is also troublesome in context of maintenance cost and self-sustainability of devices [9]–[11], not to mention the environmental impacts.

Researchers have been studying various energy harvesting approaches to reduce maintenance costs and enable self-sustainability for remotely deployed low-power sensors [12], [13] and devices. Ambient energy from the environment could be used to energize wireless sensor devices, prolonging operational time [14]–[16] . Solar, heat, wind, electric field, magnetic field, vibration, and RF are the most common sources of ambient energy; an overview of these common sources of ambient energy is depicted in

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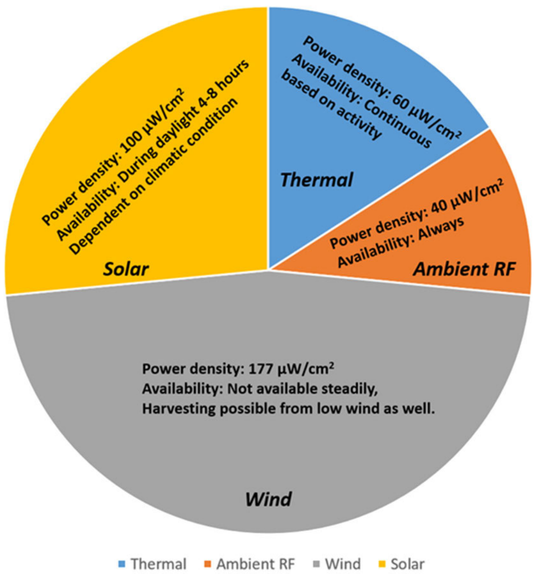


FIGURE 1. Overview of prominent ambient energy sources (based on the data in Table 1).

Figure 1 and Table 1 [4], [8], [17]–[28]. The exponential growth of RF and wireless sources including AM/FM radio, cellular networks, Wi-Fi signals, and digital/analog TV makes RF energy an excellent ambient energy source. An advantage of RF energy harvesting is the ability to convert ambient signals to useful DC power throughout day and night, both indoor and outdoor. Penetration of RF signals into obstacles such as opaque walls or enclosed spaces, makes it a good candidate for indoor applications. In addition, the small physical size and lightweight of RF energy harvesting systems enable portable and wearable applications [9], [29]–[31]. Other ambient energy harvesting technologies, including solar cells, can be paired with various antennas to enable hybrid energy harvesting solutions [32], [33].

Notably, RF power density is low in rural areas. Appliances in remote places can be powered via dedicated RF sources [17], [34], [35]. Automatically transmitting power to the device in need of charge or power can be a viable option to provide a cordless experience using WPT [36], [37]. WPT technologies can be categorized according to the method of coupling, i.e. inductive coupling, electromagnetic (EM) radiation and magnetic resonance coupling [38]. Most of the WPT research have been on inductive coupling and magnetic resonance coupling. Numerous studies have been documented on magnetic coupled or inductive coupled WPT schemes. These schemes operate in the evanescent or near-field region [39]. However, inductive coupling and magnetic resonance coupling are appropriate for short-range applications in which the transmitter and receiver are within a few meters of each other and the distance is strictly related to the loop's dimension and frequency [36], [38]. The research scope of WPT based on microwave power transmission (MPT) has been expanding as it can facilitate long-distance operation. Unidirectional and omnidirectional antennas can be used to sustain the power link for interaction in far-field radiative WPT. Radiated power in propagating electromagnetic waves is received using antennas in the far-field region [38], [40]. However, the efficiency of this method is lower than magnetic resonance and inductive coupling [41] at present and researchers have been investigating different techniques to improve the system efficiency. General frequencies of interest for radiative WPT [41] are 900 MHz, 2.4 GHz and 5.8 GHz. Nevertheless, research on radiative WPT schemes are still in its infancy, and have numerous future applications [42], [43].

Receiving side of RF energy harvesting and radiative WPT systems generally include receiving antenna, matching network, rectification circuit and power management unit. The receiving antenna and the rectifier when combined, are defined as a rectenna. Performance of RFEH or WPT significantly depends on the radiation performance of the receiving antenna. The antenna is the key element of a rectenna that determines the performance of RFEH or WPT, as the antenna is required to capture RF signals. However, impedance matching between the rectifier circuit and the antenna also impacts the optimal efficiency [17], [44]. Design of an appropriate antenna is of paramount importance. Design of the antenna depends on application specific conditions and antenna properties. For example, operating frequency, impedance bandwidth, gain, efficiency, radiation pattern and polarization have significant impact on the received power. Many antenna topologies have been proposed in the literature for ambient RF energy harvesting (RFEH) and wireless power transfer (WPT) applications, focusing on performance enhancement of antennas. Since the advancement of electronic circuits requires low-profile antennas, it becomes a challenge to meet all the strict design requirements. Table 2 illustrates some key challenges of receiving antennas in RFEH and WPT systems.

The purpose of this work is to provide a comprehensive overview of receiving antennas that have been published in the literature for RF energy harvesting (RFEH) and wireless power transfer (WPT). This paper emphasizes on review and comparison of state-of-the-art antennas for WPT and RF energy harvesting devices. This study reflects current challenges on design, fabrication, and integration of antennas for WPT and RFEH. This review also includes introduction and discussion on potential antenna fabrication techniques for practical applications while creating visions for next generation WPT technology and applications. This paper is organized as follows: an introduction to RF energy harvesting and wireless power transfer is provided in Section II. Section III discusses application-specific design requirements of receiving antennas. Section IV provides a comprehensive review on different receiving antenna designs for RFEH and WPT. Section IV is categorized into low-profile antennas, multiband antennas, circularly polarized antennas and array antennas. Section V presents potential fabrication methods for receiving antennas. Section VI presents a discussion

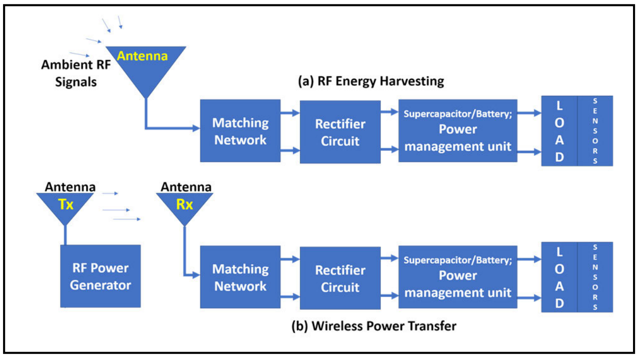


FIGURE 2. Block diagram of (a) RFEH and (b) WPT system.

on diverse applications of wireless charging technologies. Section VII highlights current research challenges, scopes and develops a vision for the next generation of WPT technology and future applications. Finally, Section VIII concludes.

II. RF ENERGY HARVESTING AND WIRELESS POWER TRANSFER

RF energy has the potential to wirelessly power a wide range of applications in situations when other ambient energy sources such as light, vibration, and thermal gradients are absent. RF energy harvesting refers to converting energy from electromagnetic field into electrical energy [45]. RF energy harvesting system or rectenna comprised of receiving antenna that captures RF signals, impedance matching network and rectifier circuit to generate DC power. In radiative WPT a dedicated RF source transmits power toward a specific direction where the receiver is located. Emitted energy from electromagnetic radiation is transmitted via transmitting antenna from a power source to a receiving antenna by electromagnetic waves [38].

The communication channel could be the same for WPT and ambient RFEH scenarios, but the signal source (transmitter) is different. Figure 2 and Table 3 provide basic illustration on ambient RFEH and WPT. RF signals are captured by the receiving antenna from various ambient sources like, TV towers, FM/AM radio station, mobile phones, base stations, wireless network or dedicated RF sources in case of WPT. The receiving antenna can operate on single band, multiband or broadband to receive power from different frequency bands simultaneously. The license-free ISM bands can be used for dedicated RF energy transfer. However, regulations are imposed on the maximum transmitting power of the dedicated RF sources by Federal Communications Commissions (FCC) [46], [47].

The path loss equation can be used to estimate power in RF energy harvesting scenario [48]. In addition, measurement of RF fields can be used to obtain the notion about maximum available power at different location in RFEH scenario. Table 4 depicts example of maximum signal level available in different metropolitan areas in Australia (Table 4A) and different locations (Metro stations and residential areas) in Canada (Table 4B). The table can demonstrate the feasibility of RFEH in civil environments.

In case of WPT, the power received by an antenna at the receiving end of WPT system can be estimated by Friis transmission equation [48], [51],

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi R} \right)^2 \tag{1}$$

where, P_r is the received power, P_t is the transmitted power, G_t denotes the transmitting antenna gain, G_r is receiving antenna gain, λ refers to the wavelength of RF signal, and R is the far-field distance from the transmitting antenna. This equation can provide a useful estimation for the possible upper limit of the range with a given transmitted power. However, it does not consider environmental attenuation that will affect available power at low levels.

An impedance matching network is required to decrease transmission loss and enhance voltage gain and sensitivity from the receiving antenna to the rectifier circuit [52]. Design of matching circuits requires a combination of real (Resistor) and reactive (Inductor or, capacitor) components to avoid power loss that may occur due to using only resistors. Performance of the matching circuit is crucial to achieve an optimum output from the whole system. The main challenge in designing a matching network is the non-linearity of the rectification device with input power and frequency (especially in ambient RFEH scenario). A wide input power range is required as the input power level fluctuates frequently in RF energy harvester. The RF signal received by the antenna is converted to DC voltage by the rectifier circuit [53].

III. ANTENNA DESIGN REQUIREMENTS IN RFEH AND WPT SYSTEMS

RFEH system receives RF power from ambient sources which are usually unknown. Unlike RFEH, in case of WPT system, transmitting antenna comes into play, which is responsible for providing dedicated power to the rectenna. High gain transmitting antenna is preferred to overcome the challenge of long-distance transmission, as the transmitted power becomes radiated to the surrounding. Maximum efficiency in WPT can be achieved with the combination of high gain transmitting antenna and well-designed rectenna. In this paper, we focus on the receiving antenna designs. The selection of receiving antenna is crucial for RFEH and WPT since antenna plays the key role in receiving electromagnetic wave from free space. Usually GSM900, GSM1800, UMTS2100, LTE2600 and Wi-Fi band 2.45 GHz bands are used for ambient RF energy harvesting due to wide availability. So, combining all available sources from different frequency bands is recommended for increasing scavenged power. However, in WPT scenario different factors of the transmitting antenna such as operating frequency, transmitting power, polarization, directivity, and gain are controlled and hence receiving antenna design is straightforward. In order to manage the separation distance, WPT receiving antennas should be designed to adapt

TABLE 1. Ambient energy sources.

	Solar [8, 18, 19]	Heat/ Thermal [8, 19-21]	Wind [4, 22]	Piezoelectric[23, 24]	Ambient RF [8, 17, 19, 25, 26]
Source	Sun	Sun, system losses, body	Wind flow	Difference in pressure, Vibrations,	Radio/TV stations, Mobile phone & base stations, wireless networks, radar, wireless routers
Availability	During daylight (4-8 Hours)	Continuous based on the activity or operation of the system	Depends on weather	Dependent on activity	Always
Harvesting mechanism	Solar/photovoltaic cell	Thermoelectricity, Seebeck effect	Turbine, DC motor, aero-elastic, Anemometer[4]	Piezoelectric devices interfaced with power electronic equipment	Rectenna
Power density[19, 27, 28]	100 μW/cm^2	60 μW/cm^2	177 μW/cm^2[22]	250 μW/cm^3	40 μW/cm^2
Efficiency [17, 18, 20, 21]	11.7% to 26.7% depending on different classification [18]	5-15%[20, 21]	---	~5-30%	0.4% to over 50% at -40 to -5 dBm input power[17, 25] (Can be increased with more input power)
Advantages[45]	Large amount of energy, low-profile harvester, commercially available, well developed technology	Available commercially, compact harvester	Harvesting can be possible even in low wind	Simple and fast power conversion, Output voltage high High durability,	Certainty[26] of available power, commercially available, low-profile harvester circuitry
Disadvantages[19]	Severely dependent on climatic condition, large area requirement, incident light orientation issue	Thermal matching issue, low power, large area requirement	Availability is not steady, harvesting system can be bulky	Material properties linked with coupling coefficient, Expensive material, Dependent on material property	Dependent on distance and availability of wireless signal power, propagation medium (e.g., multipath effects and attenuation through buildings) or weather conditions (e.g., fog, rain, or humid air) can have a significant impact on the propagation of EM waves affecting the received power, low rectification efficiency at low input power.

with the properties of the known transmitting antenna, including bandwidth, polarization, and gain. Evidently, while WPT antennas work primarily in predictable propagation conditions, ambient RFEH antennas perform in unpredictable electromagnetic environments. The low RF power levels in the surroundings make efficient RF energy harvesting a very crucial issue. The scavengeable power levels can be affected by a variety of factors, including received signal parameters

TABLE 2. Key challenges of receiving antennas in ambient RFEH/WPT.

Challenges	Reasons
Received signal amplitude, polarization, frequency, and bandwidth	Unknown in RFEH
Size	Low-profile antenna is required for compact harvester or portable devices.
Sensitivity	Ability to harvest energy and operate at low input power.
Directivity	Omnidirectional radiation pattern is required for ambient source. Unidirectional radiation pattern is required for known dedicated RF source.
Integrability with planar structure	Integration with PCB and matching network or rectification unit for practical applications.
Mechanical robustness	For long operation period or application in inaccessible/harsh environment or underwater
Stable performance with varying environmental condition	Temperature or humidity variation.
Circular polarization/ dual-polarization	Eliminate polarization mismatch for ambient source
Multi/wideband performance	To maximize harvested power, reception from multiple frequency.
Fabrication techniques	Performance trade-offs for low-profile and cost-effective manufacturing process

TABLE 3. Comparison of Ambient RFEH and WPT techniques.

	RFEH	WPT
Power source	Ambient sources such as wireless networks, radio/TV station, mobile tower, wireless router etc.	Dedicated RF power transmitting antenna
Known source (e.g. direction, polarization, frequency, transmitting power)	No	Yes
Receiving antenna properties (For ideal case)	Omnidirectional, multiband/wideband, capture RF energy from random polarization	High gain, multiband/wideband
Availability	Decreases due to lack of source, mostly in rural areas	Can be available on demand
Efficiency	Low efficiency in most cases (can be lower in low power density area)	High due to the availability of dedicated source

(frequency, bandwidth, polarization, power flux density etc.), telecommunication traffic densities and antenna orientation. Hence, RFEH antennas should be able to collect incoming waves with changing polarization and bandwidth considering the unforeseeable conditions. The goal is to providing enough power to switch on the rectifier circuit which is challenging in real-world scenario with only one antenna. Several types of antennas including microstrip patch, spiral, inkjet printed, differentially fed, flexible, array, multiport etc. are found in literature for RFEH and WPT applications. Each type has their pros and cons. Below are the basic selection properties of receiving antennas.

A. FREQUENCY

The operating frequency of the antenna depends on the available frequency at the targeted place of application. Multiband antennas are preferred for harvesting more power than single-band antennas. At higher frequency of operation, amount of received RF power reduces due to high free space path loss (FSPL) over long distances. Multiband antennas designed at reasonably low frequency can be used to avoid FSPL. However, capturing power from several frequency ranges can also be covered with wideband antenna. Wideband antennas have comparatively easier design and can be used in different countries with diverse frequency assignments [54]. Figure 3 illustrates the received power at different frequencies with the same transmitting power. The illustration is based on Friis law [48]. However, in realistic RFEH and WPT scenarios, there will be multi-path loss in real propagation environment hence, the amount of the received power will vary.

B. RADIATION PATTERN

Direction and shape of radiation pattern, beamwidth and polarization of the receiving antenna play significant role in capturing the electromagnetic wave. In ambient conditions, as the orientation of the incoming EM wave is unknown, an omnidirectional antenna is preferred. Unidirectional antenna is required for the dedicated RF transmitter for WPT to cover longer ranges.

C. POLARIZATION

Polarization can be defined in terms of the direction of a transmitted or received wave from an antenna. A mismatch in the polarization of the antennas results in decreased received power. A circularly polarized (CP) antenna is useful because it can receive electromagnetic energy from a variety of polarizations. As a result, a wideband CP antenna can be advantageous for harvesting energy from random polarization especially for RFEH. Moreover, dual linearly polarized antenna provides further advantage in receiving RF power by avoiding polarization mismatch [55], since achieving wide CP bandwidth using a compact structure

TABLE 4. (a) Available RF signal level at different metropolitan area in Australia at different frequency ranges [49]. (b) Available RF signal level at various areas in Canada over different frequency ranges [50].

(a)

Location 1								
Frequency bands (MHz)	50	100	200	500	800	1000	2000	3000
Available signal level (dBuV) (Approx.)	70	110	78	110	97	88	80	41
Location 2								
Frequency bands (MHz)	50	100	200	500	800	1000	2000	3000
Available signal level (dBuV) (Approx.)	41	92	82	88	72	80	78	41
Location 3								
Frequency bands (MHz)	50	100	200	500	800	1000	2000	3000
Available signal level (dBuV) (Approx.)	96	101	78	100	68	70	72	40
Location 4								
Frequency bands (MHz)	50	100	200	500	800	1000	2000	3000
Available signal level (dBuV) (Approx.)	61	72	67	82	62	84	85	42
Location 5								
Frequency bands (MHz)	50	100	200	500	800	1000	2000	3000
Available signal level (dBuV) (Approx.)	87	104	88	108	78	99	95	83

(b)

Location 1 (Metro stations)							
Frequency bands	DTV	LTE700	GSM/LTE850	LTE1700/2100	GSM/LTE 1900	WiFi	LTE2600
Available signal level (dBm)	Max.: -19.97 Min.: -66.27	Max.: -19.08 Min.: -63.91	Max.: -19.73 Min.: -60.86	Max.: -27.11 Min.: -65.79	Max.: -20.16 Min.: -63.13	Max.: -58.25 Min.: -72.98	Max.: -34.34 Min.: -78.89
Location 2 (Residential areas)							
Frequency bands	DTV	LTE700	GSM/LTE850	LTE1700/2100	GSM/LTE 1900	WiFi	LTE2600
Available signal level (dBm)	Max.: -25.97 Min.: -68.12	Max.: -37.38 Min.: -58.72	Max.: -41.62 Min.: -62.22	Max.: -44.17 Min.: -62.94	Max.: -42.95 Min.: -66.09	Max.: -59.80 Min.: -74.53	Max.: -54.26 Min.: -75.86

is challenging. In case of WPT, the polarizations of the transmitted waves is known beforehand. Therefore, choice of receiving antenna can be broad having different kind of polarizations, including linear polarization (LP), right-hand and left-hand circular polarizations (RHCP/LHCP) as long as appropriate level of beam-pointing (from transmitter) and polarization matching can be established and maintained.

D. GAIN

High gain antennas are useful in RFEH and WPT application. In RFEH scenario, increased dimension of an omnidirectional antenna can achieve more power. According to [56], higher directivity in antenna design does not improve harvested power in ambient RFEH. Hence, moderate amount of gain will suffice for ambient RFEH, as long as the antenna is efficient enough. However, high gain antenna will enhance the received power if the power is transmitted from a known source [57]. Gain and directivity are related according to the equation (2) [58]. Low-gain receiving antenna reduces the received power in WPT.

$$G = \mathcal{E}_R D \tag{2}$$

where, G, $\mathcal{E}_R$, and D are gain, radiation efficiency and directivity of the antenna respectively [8], [59].

E. BANDWIDTH

The receiving antennas can be designed to operate at multiple frequency or single frequency. Wide bandwidth is preferred to harvest RF power from multiple RF sources simultaneously. Bandwidth of the antenna is related to antenna Q-factor by the following equation:

$$Q = \frac{f_r}{BW} \tag{3}$$

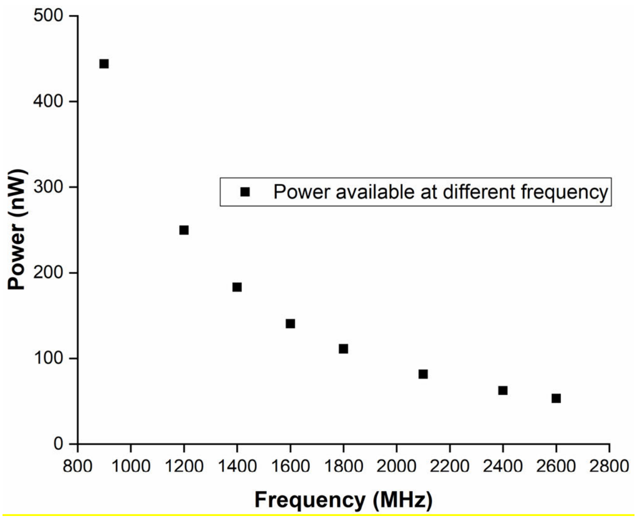


FIGURE 3. Variation of received power at different frequency, considering the receiving antenna (Grx = 2 dBi) is 100 meters from the transmitting antenna (Gtx = 16 dBi), transmitting power is 20 dBm.

where, Q is the quality factor, BW is the bandwidth and f_r is the resonant frequency of the antenna. Bandwidth becomes narrower for high Q antenna. Q decreases with the reduction of antenna size and hence, bandwidth of the antenna becomes wide. Moreover, the Bode-Fano criterion illustrates that, broader bandwidth can be achieved at the expense of higher value of reflection coefficient and good impedance matching is achieved at finite number of frequencies only [60].

Generally, dimension of wideband antennas tends to be larger compared to the narrowband antennas. Design of ultra wideband antenna will be quite inefficient considering the antenna performance bounds. On the contrary, designing multiband antenna with stable radiation pattern, polarization and efficiency with wide frequency band is crucial and challenging. The reflection coefficient requirements are met in most multiband antennas at the cost of degraded radiation efficiency at higher frequency [61], [62].

F. EFFICIENCY AND SIZE

Antenna efficiency is dependent on shape, size, material of antenna structure, frequency, and impedance of the antenna. As the physical size of the antenna decreases, efficiency is also reduced [63]. A trade-off between antenna efficiency and size is expected in RFEH or WPT depending on the intended application.

G. SENSITIVITY

The ability to capture extremely low power in ambient condition is one of the main design limitations of designing rectifying antenna (Rectenna). Losses from dielectric substrate, rectification device, and matching network should be limited as much as possible to increase the rectenna sensitivity and to enable operation in ultra-low power environments [64].

IV. ANTENNA TECHNOLOGIES IN RFEH AND WPT

The antenna is the front-end component of every RF power receiving device, and its performance has a direct impact on the overall RFEH/WPT system efficiency. Hence, the selection and proper antenna design must be approached with particular care. The antennas for RFEH must face critical operational conditions like randomly changing incoming waves covering multiple polarization, ultra-low power density and fluctuating levels of incident power. However, receiving antennas for WPT are designed with the objective of capturing maximum power from a dedicated transmitting antenna in deterministic propagation conditions (known source parameters). In this section, different state of the art designs and types of antennas have been discussed.

A. LOW-PROFILE ANTENNAS

The emergence of modern compact electronic devices enables the antenna engineers and researchers to design small antennas. Patch antennas are one of the most convenient antenna types as low-profile candidate that can be employed for RFEH and WPT. Patch antennas are extremely compatible for wireless devices considering their small foot-print, light weight and inexpensive fabrication cost. Different types of low-profile antenna designs are listed in Table 5 to provide an overview of the current state of the art.

According to the Table 5, one of the most common techniques used in compact antenna for RFEH application is employing fractal geometry in the patch antenna structure. Due to the property of self-similarity, embedding fractal geometry in antenna structure is a potential solution to design compact rectenna [66], [72], [74], [78]–[82]. With the increment of iteration order in fractal structure, the effective length increases. However, fractal geometry can be limited to a few iteration orders. As the number of iterations increases, the complexity of the design geometry increases, which is likely to increase the difficulty of fabrication. [72]. Introducing slots on a patch is also a popular technique to miniaturize antenna [69], [75], [83], [84]. The proposed rectenna in [72] utilized both fractal and slotted geometry technique for the compact design of receiving antenna. The antenna design is depicted in Figure 4. Second iteration of the fractal shape is used in the patch, etched about in the middle of the radiating element on FR4 substrate with 1.6 mm thickness.

The fractal geometry is achieved by the algorithm of iterative function system (IFS), an advantageous method to generate fractal structures based on different transformation techniques like rotation, translation and scaling. The final design of the antenna achieved a dimension of 31 × 18.5 × 1.6 mm^3, which is quite compact for applications where more space is required for other circuitry. The antenna operating frequency ranges from 2.15-2.9 GHz. As the iteration of the fractal increased, the antenna obtained better impedance matching with optimum bandwidth of 850 MHz. RF-DC conversion efficiency of 28% is achieved by the rectenna

TABLE 5. Overview of low-profile antennas for RFEH/WPT.

Refs.	Antenna type	Design technique/geometry/substrate	Dimensions	Operating frequency	Gain (dBi)	RF-DC efficiency of the rectenna (%)
[65]	Aperture-coupled dual linearly polarized patch antenna	Three layers based, 6 mm foam layer between Arlon A 25 N substrate, cross shaped slot on the patch	Patch size 34×34×7 mm^3, Area of foam unspecified, however bigger than the patch.	2.45 GHz	7.7	38.2 @ 1.5 $uWcm^2$ power density
[66]	Patch	Modified Koch fractal patch on high permittivity substrate, Rogers RO6010 with Rogers RO6002 superstate.	20×20 mm^2	2.45 GHz	-.25	---
[67]	CPW fed patch	T-shaped monopole loaded with interdigitated capacitor on FR4 substrate	101.8×46.5 mm^2	866 MHz	2	54 % @ 80 uW/cm^2 power density
[68]	Microstrip-fed dipole	Two poles of the antenna are folded on Rogers 5880 substrate, separated by a ground plane.	62×62 mm^2	900 MHz	1.84	---
[69]	coplanar strip-line fed	Slotted and folded dipole on Teflon substrate	53×17.375 mm^2	2.45 GHz	2.65-3.9	55% @ 1 mW/ cm^2 power density
[70]	Three-layer planar inverted-F	Circular shaped planar inverted-F antenna (PIFA) with two radiating layers, on 0.765 FR4 substrate	3.14×6^2×1.584 mm^3	915 MHz	-20.2	53% (Between 20 cm separation of Tx and Rx)
[71]	Folded dipole	Folded dipole using 0.1 mm thick copper sheet	30×30×10 mm^3	918 MHz	1	23% @ 1 mW input power
[72]	Patch	Slotted fractal radiating patch with partial grounding on 1.6 mm thick FR4 substrate	31×18.5 mm^2	2.15-2.9 GHz	2.2 @ 2.45 GHz	62% @ 0 dBm input power, 28% @ -10 dBm
[73]	CPW fed patch	CPW fed radiating patch with 4 rectangular slots	18 mm × 30 mm^2	2.45 GHz	5.6	42 % @ -10 dBm input power
[74]	Double layer Patch	Fractal patch with bent corners, helical patch between ground and main radiating patch, FR4 substrate	38×38 mm^2	2.45 GHz	3	24% @ -10dBm input power
[75]	Proximity coupled patch	Two annular slot-based patch on thin paper substrate	110×110 mm^2	0.79–0.96 GHz 1.71–2.17 GHz, 2.5–2.69 GHz 2.5–2.69 GHz	2.3 @ 940 MHz,	20% @ 2600 MHz, 22% @ 1800 MHz, 44% @ 900 MHz (Power density 1 uW/cm^2)
[76]	Rectangular patch	Double layer FR4 substrate based, separated by airgap	100x100x5 mm^3	2.45 GHz	8.35	---
[77]	Printed flat dipole antenna	Quasi-circular shaped, modified radiating structure from half-wavelength dipole antenna with rectangular loop on 0.8 mm thickFR4 substrate	110×60 mm^2	ISM 868-/915-MHz	2.6	25% @ 0.25 $\mu W/cm^2$ power density
[78]	Co-axial fed square patch	Fractal geometry based radiating patch on 1.6 mm thick FR4.	60 × 60 × 1.6 mm^3	0.8–1.2 GHz, 1.6–2.1 GHz, 2.2–2.8 GHz, 3.1–4.0 GHz, 5.3–6.4 GHz, 7.0–7.8 GHz	1 @ 900 MHz, 3@ 2 GHz, 5@ 5.5 GHz, 4@ 7 GHz	28% @ 900 MHz, 24% @ 2.5 GHz, 9% @ 1.8 GHz, 17% @ 3.5 GHz, 13% @ 5.5 GHz, 36% 7.5 GHz (input power 0 dBm)

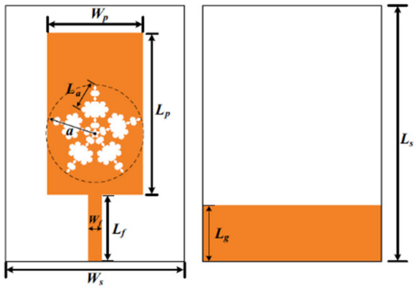


FIGURE 4. Slotted fractal antenna for RF energy harvesting [72].

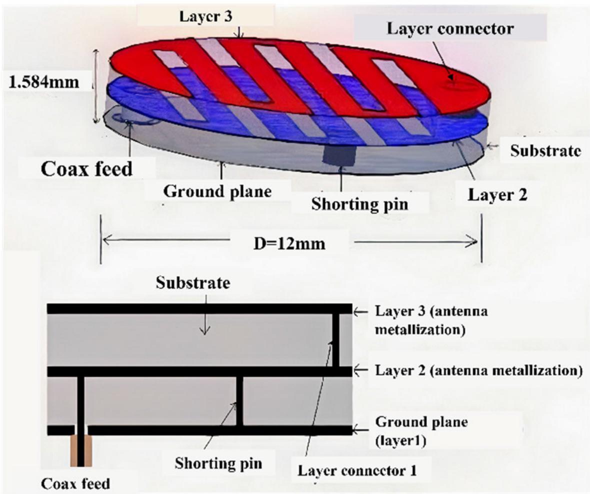


FIGURE 5. Design configuration of the double-layered PIFA antenna [70].

employing the proposed antenna at 2.42 GHz, when the input power is −10 dBm. It can be assumed that, the RF to DC rectification efficiency of the rectenna reduces with the decrement of the antenna dimension. However, selection of antenna dimension should be considered based on the intended application.

Dedicated RF transmitter can be used as a source instead of ambient RF energy in WPT scenario, where it is required for application specific condition [85], [86]. For instance, a tiny circular antenna has been proposed for a deep brain stimulation (DBS) device - a head-mountable device to perform experiment on animals [70]. The tiny planner inverted-F antenna is based on two layers of circular structure, employing meander-line, shorting and stacking technique for the miniaturization of the antenna on 0.765 mm thick FR4, depicted in Figure 5.

Effective current flow length has been increased in the antenna due to meandering and shorting techniques leading to two additional antenna miniaturization methods proposed in [87]. The PIFA structure is ma de circular to facilitate the utilization in the DBS device. The antenna layers are connected via shorting pin, where the location of the shorting pin is crucial in context of antenna performance. However, the antenna suffers from low gain and radiation efficiency due to substantial miniaturization [88], [89], which finally affected the rectenna performance. The proposed PIFA antenna achieved only −20.20 dB of gain, which is substantially smaller than conventional PIFA. Significant amount of transmitting power, 34.77 dBm is required to receive only −3.193 dBm within a 20 cm distance.

The objective of miniaturizing antennas is to use the available space effectively to fit a large radiating element within small volume. An insightful discussion on antenna miniaturization has been documented in [90]. Meander-line, fractal geometry, ground plane engineering, use of capacitive or reactive loading and others are effective antenna size reduction techniques. Meandering technique can be useful in UHF [91] and implantable applications. However, high gain cannot be expected from meander-line antennas as the close radiating arms tend to cancel each other's respective radiation in the far field. Fractal antennas can be potentially used for miniaturization as well as multiband operation. Sierpinski gasket is one of the promising fractal geometries that can lead to multiband antenna design [92], [93]. Other fractal geometries include Sierpinski carpet, Giuseppe Peano, Koch snowflake. All of them have their own drawbacks such as limitation in applying at antenna edge, complex geometry and narrowband operation. However, the enhancement of bandwidth and miniaturization both have been reported by using complementary Minkowski fractal [94].

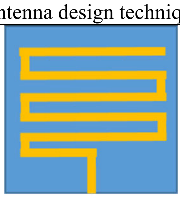
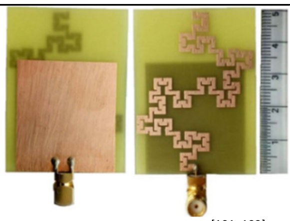
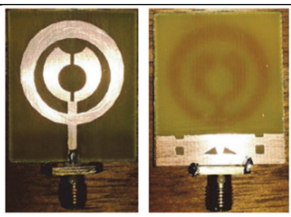
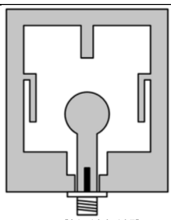
Ground plane engineering methods are usually associated with slots that can arise coupling or interference with nearby electronic devices which can further introduce electromagnetic incompatibility issues. Overall, the trade-off between low-profile antenna and antenna performance is huge, as different design techniques applied to compacting antenna come with the degradation of bandwidth, gain, efficiency and impedance mismatch. [90].

Innovative antenna designs are required to provide a balanced trade-off between antenna dimension and size with a view to achieving maximum efficiency with minimum antenna size. Wheeler was the first one to illustrate the maximum dimension of electrically small antenna is to be '$\lambda/2\pi$' [89]. This can be defined further by '$ka < 0.5$', where 'k'' is the radian/meter and 'a' is the sphere radius of the antenna's maximum dimension [95]. An electrically small antenna restricted by a volume limit, is followed by a minimum Q factor value. The impedance bandwidth decreases with higher Q factor value. Moreover, in comparison with radiation loss of antenna, losses in dielectrics, conductors and other materials in antenna have significant impact on electrically small antenna's efficiency η; illustrated as:

$$\eta = \frac{R_r}{R_r + R_m} \times (1 - \Gamma^2) \tag{4}$$

where, R_r and R_{m} are radiation resistance and resistance of material loss in the antenna and Γ is the reflection coefficient. In addition, due to the existence of capacitive input impedance of electrically small antenna, additional

TABLE 6. Overview of common antenna miniaturization techniques [90], [99]–[103].

Antenna design technique	Pros	Cons
 Meander-line antenna[100, 105]	• Reduction in antenna dimension by introducing meandered microstrip line consisting right angle bends. • Simple design structure. • Potential for lower UHF.	• Unable to provide high gain. • Low radiation efficiency.
 Fractal-based antenna[101, 102]	• Requires smaller area than Euclidean geometry-based antennas. • Can provide input impedance and radiation pattern like large antennas. • Efficient use of volume due to space filling geometry.	• Radiation efficiency degrades due to miniaturization. • May lead to sophisticated design and fabrication complexities. • Numerical design limitations.
 Defected-ground-structure-based antenna[103]	• Increased slow wave factor providing compact design. • Simpler to design and fabrication. • Easier realization of equivalent circuit. • Reduced dimension than photonic band gap (PBG) and electromagnetic band gap (EBG) structures.	• Embedded slots may create unwanted coupling. • Directivity may reduce due to unintended radiation. • Application limited to planer antennas.
 Other techniques[91, 106, 107]: Slot antenna example[108]	• Slotting • Optimizing geometrically, topological optimization • Using shorting pins • Using metamaterial, electromagnetic band gap (EBG) structures etc.	

matching network might be required for the system to work, which can impact on overall antenna efficiency [96]. Nevertheless, this can be reduced by applying different antenna techniques such as capacitive loading or, inductive loading.

Applying topological optimization method of antennas can benefit in achieving low-profile receiving antennas [97], [98]. Pixelated antennas feature designing antennas within application specific boundaries. Three antennas are designed using pixelization technique for the same frequency with three different size that demonstrates the potential of this method in miniaturized antenna design [97]. Although the work focused mostly on impedance optimization, gain optimization is also possible.

The miniaturization of antenna is limited by the application specific RFEH or, WPT condition. It should be noted that common small communications antennas are incompatible with RFEH and WPT. The amount of power received by the device is directly proportional to the effective aperture size and efficiency of the antenna. Regardless of those parameters, wireless communication antennas can be made compact, as the sensitivity of communication devices can be as low as −100 dBm. However, rectifiers can only operate at a particular power level. The practical challenge in designing antennas with small form factor for energy harvesting is to control the performance degradation with reduction of antenna size. Very tiny antennas will be impractical for ambient RF energy harvesting application. Autonomous implantable or wearable applications are also subjected to FCC rules [108].

B. MULTI-BAND ANTENNAS

Simultaneous power reception from different radio frequency bands can be useful where more than one RF source operate at different frequency bands. Moreover, the sources may be located at a random distance from the receiving antenna with varying power budgets [109]. The available RF signals in ambient condition are low in power, typically −5 to −30 dBm, usually multiple frequency bands are used to distribute the signals [110]. Hence, multiband antenna can enhance RFEH in such cases. This section discusses the multi-band antenna designs for RFEH/WPT. Multiband antenna/rectenna for RFEH is challenging due to non-linear variation of the rectifier input impedance with input power

TABLE 7. Multi-band antenna/rectennas for RFEH/ WPT.

Refs.	Antenna design type	Operating bands	Size	Gain	Antenna efficiency	Single frequency rectenna efficiency (RF-DC)	Combined Dual/multiband rectenna efficiency (RF-DC)
[112]	π-shaped multilayered PIFA meandered strip on Rogers 3210	402 MHz, 433 MHz, 2.45 GHz	10×10×2.54 mm^3	-7 dB at 402 MHz, -11 dB at 433 MHz, -15 dB at 2.45 GHz	---	---	---
[113]	Intermittent meander-line on Duriod 5880	600 MHz to 2 GHz	52×50 mm^2	-2 to 6 dB	---	---	---
[114]	Slot loaded folded dipole on Arlon 25N	915 MHz, 2.45 GHz	60×60×29 mm^3	1.87 dB @ 915 MHz 4.18 @ 2.45 GHz	---	33% @ 915 MHz; 23 % @ 2.45 GHz (Input power -10dBm)	34% @ -10 dBm input power
[115]	Printed monopole with meander-lines on 0.83 mm thick Rogers 4003	900 MHz, 1800 MHz	46×30 mm^2	---	---	---	40.8% (Input power @ -20 dBm)
[110]	Planar cross dipole with bow-tie shaped patch on 1.6 mm thick FR4	550 MHz, 750 MHz, 900 MHz, 1.85 GHz, 2.15 GHz, 2.45 GHz	160×160 mm^2	2.5 dB @ 550 MHz, 3.4 dB @ 750 MHz, 3.6 dB @ 900 MH, 4.9 dB @ 1.85 GHz, 5 dB @ 2.15 GHz, 4.4 dB @ 2.45 GHz	---	---	80% (Input power unspecified)
[116]	L-probe stacked patch using Rogers 3003	925MHz, 1850 MHz, 2150 MHz	200×175×46.6 mm^3	8.15 dB @ 915 MHz, 7.15 dB @ 1850 MHz, 8.15 dB @ 2150 MHz	---	25% @ 2170 MHz, 32 % @ 1820 MHz, 42% @ 925 MHz (-10 dBm input power)	50%
[117]	CPW fed patch with stepped ground plane on FR4	900 MHz, 1800 MHz, 2100 MHz, 2.4 GHz	48×42 mm^2	1.1 dB @ 900 MHz, 2.2 dB @ 1800 MHz, 2.1 @ 2100 MHz, 2.2 @ 2.4 GHz	---	38% @ 900 MHz, 27% @ 1800 MHz, (Input power 0 dBm)	---
[118]	Circular shaped printed monopole on FR4	900 MHz, 1800 MHz, 2100 MHz,	130×80 mm^2	2.6 dB @ 900 MHz, 3.6 @ 1800 MHz,	94-96%	25%@1820 MHz, 27% @ 2150 MHz (Input power – 7dBm)	---

TABLE 7. *(Continued.)* Multi-band antenna/rectennas for RFEH/ WPT.

		2.45 GHz		3.8 @ 2100 MHz, 4.7 @ 2.45 GHz			
[119]	Corrugated slot line based microstrip patch on Rogers RO4350	900 MHz, 2100 MHz, 2.36 GHz	70×66 mm^2	1 dB @ 900 MHz, 2.64 dB @ 2.025 GHz, -0.19 dB @ 2.36 GHz	42.2% at 0.9 GHz, 61.3% at 1.575 GHz, 72.6% at 2.025 GHz, 32.8% at 2.36 GHz	47 % @ 2.025 GHz, (Input power @ -11.1 dBm)	---
[120]	Printed monopole with fractal element on 0.8 mm thick Arlon substrate	900 MHz, 1800 MHz	100 × 60 mm^2	0.95 dB @ 870 MHz, 3.15 @ 1830 MHz	90% at 0.87 GHz, 83% at 1.83 GHz	62 % @ 880 MHz (15.9 $\mu W/cm^2$) 50% @ 1910 MHz (19.1 $\mu W/cm^2$)	---
[121]	Truncated square patch with slots on FR4 substrate	4.75 GHz, 5.42 GHz, 5.76 GHz, 6.4 GHz, 6.9 GHz, 7.61 GHz	40×45 mm^2	5.5 dB @ 4.75 GHz, 6.3dB @ 5.42 GHz, 6.75 dB @ 5.76 GHz, 7.1 dB @ 6.4 GHz, 7.1 dB @ 6.9 GHz	---	2% @ 4.75 GHz, 1% @ 5.76 GHz, 0-2 % @ 6.4,6.9,7.1 GHz (Input power -10 dBm)	---
[122]	Cube antenna using 3D printing and screen printing	900 MHz, 1800 MHz, 2100 MHz	50×50×50 mm^3	-0.8 dB @ 900 MHz, 4.7 dB @ 1800 MHz, 2.3 dB @ 2100 MHz	---	---	---
[123]	Differentially fed slot antenna using FR4 substrate and copper sheets	2.1 GHz, 2.4-2.48 GHz, 3.3-3.8 GHz	120×120×30 mm^3	7 dB @ 2 GHz, 5.5 dB @ 2.5 GHz, 9.2 dB @ 3.5 GHz	85% at 2GHz, 75% at 2.49 GHz, 72% at 3.4 GHz	37% @ 2 GHz, 19% @ 2.5 GHz, 12% @ 3.5 GHz (Input power -15 dBm)	---
[75]	Nested annular slot based dual antenna approach on paper substrate	900 MHz, 1750 MHz, 2.45 GHz	110×110 mm^2	1.3 dB @ 900 MHz, 5 dB @ 1750 MHz, 5.5 dB @ 2.45 GHz	---	47% @ 900 MHz, 22% @ 1.8 GHz, 20% @ 2.6 GHz (At 1 $\mu W/cm^2$)	---
[124]	Stacked circular slotted patch	0.908-0.922 GHz, 2.35-2.50 GHz	120×120 mm^2	5.41 dB @ 918 MHz, 7.94 dB @ 2.48 GHz	---	19% @ 900 MHz, 17% @ 2.45 GHz (Input power -10 dBm)	---

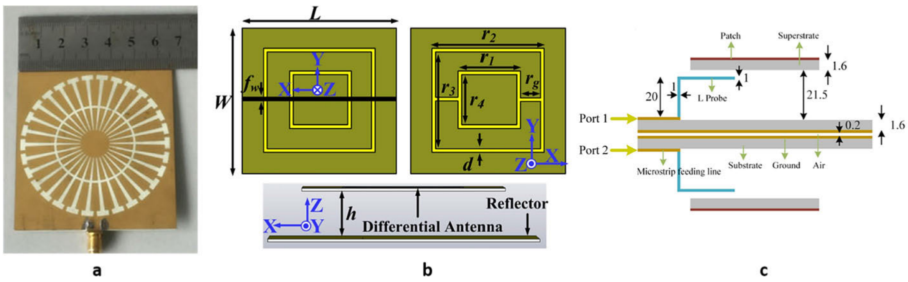


FIGURE 6. Multiband antennas for RFEH; (a) LSP resonator based annular ring slot [119], (b) slotted differentially fed with reflector [123], (c) stacked dual port with L probe feeding [116].

level, frequency and load impedance. Input power of a multiband antenna is the summation of available input power at individual frequency bands, it can be illustrated as [111],

$$P_T = \sum_{i=1}^{n} P_{fi} \tag{5}$$

where, n is the number of frequencies, P_{fi} is the power received at i'th frequency and P_T is the total available power due to multiband operation. Table 7 summarizes some recent multi-band antennas for RFEH/WPT.

Most multiband antennas are proposed to cover GSM-900, GSM-1800, 2100 MHz and 2.4 GHz bands due to the availability in environment. However, other bands are also considered like medical implant communication system (MICS), industrial, scientific and medical (ISM) and C band [112], [121]. It has been shown that PIFA structures with meander stripes and π-shaped radiating element can obtain resonance in dual band [125], [126]. This method has been applied in implantable triple band rectenna design for biotelemetry application [112]. The two fundamental frequencies are achieved by meander-line and stacking of the radiating strips. Excitation of a harmonic mode in the meander shaped strips enabled a third operating band at 2.45 GHz. Folding half-wave dipole antenna and introducing slots can provide dual resonances [114]. High gain dual band antenna using printed broadband Yagi antenna has been proposed for ambient RF power scavenging. Broad half power beamwidths (HPBWs) has been achieved, 110° and 170° at 2.15 and 1.85 GHz, respectively, which can facilitate less precise placement of the rectenna to achieve good power conversion efficiency (PCE) [127]. Dual band rectenna operation is introduced based on printed monopole antenna, inspired by second order Koch fractal based arm for low frequency and folded strip-line for higher frequency bands [120]. Multiband antennas based on spoof localized surface plasmons (LSP) resonator, dual-port L-probe feeding, multiple radiating line with stepped ground plane, slot loaded square patch, 3D printed cantor fractal, differentially fed slot have been also reported in literature for different rectenna applications [116], [117], [119], [121]–[123]. Impedance bandwidth of a quad band 'circular arc connected strip-line' patch based antenna has been improved by using stepped ground plane [117]. Proximity coupled feeding can help improving the impedance bandwidth of the receiving antenna

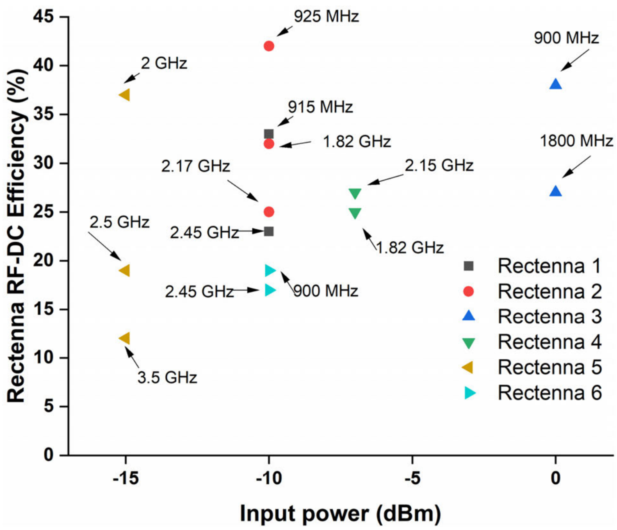


FIGURE 7. RF-DC efficiency of rectennas utilizing different dual/multiband antennas; Rectenna 1 [114], Rectenna 2 [116], Rectenna 3 [117], Rectenna 4 [118], Rectenna 5 [123], Rectenna 6 [124].

as well [121]. Figure 6 illustrates some multiband antenna designs opted for RFEH/WPT.

Several antenna techniques that have been reported for multiband RFEH/WPT are highlighted below.

- Slotted ring antenna
- Stack antenna
- Differential antenna
- 3D printed antenna

Resonance at multiple bands have been obtained by slotted ring antenna depicted in Fig. 8(a). Multiple resonant modes have been achieved using annular ring slot patch surrounded with T-shaped periodic array of slots. The degree of electromagnetic energy coupling has been enhanced using a metal disk by the end of the microstrip conductor and Rogers RO4350 has been used as the antenna substrate. [119].

Back to back placement of patch antennas using stacking technique and dual port feeding is an effective way of achieving high gain with the ability to capture RF power from nearly all directions at GSM-900, GSM-1800 and UMTS-2100 bands [116]. L probe feeding method [128] is found to be improving the bandwidths of the operating bands as well. High isolation is provided by back to back placement of the

TABLE 8. LP vs. CP antenna given in light of RFEH and WPT.

Features [129-134]	Linearly polarized antenna	Circularly polarized antenna
Collection of RF energy from random polarization	No	Yes
Long range power transmission/reception	Yes	No
Variation of output voltage in rectenna due to change in Tx/Rx rotation	Yes	No
Fade resistant	Less	More
Alignment to the Tx antenna	Necessary	Not necessary
Feasibility of energy transmission to mobile devices	Less	More
Optimised global efficiency	Less	More
Multipath effects	Sensitive	Insensitive

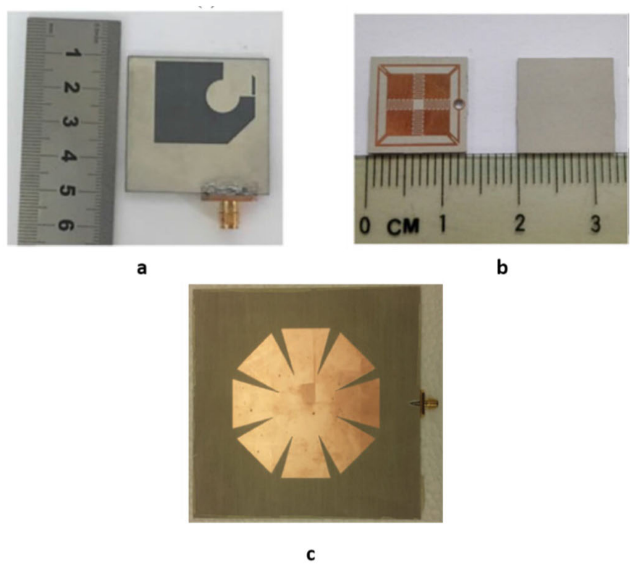


FIGURE 8. Circularly polarized antennas for WPT/RFEH; (a) wide slot [165], (b) implantable miniaturized [46] and (c) tapered slit [134].

ground plane, enabling similar performance for both antennas with unidirectional radiation. Rogers 3003 has been utilized as substrate and superstrate for this antenna.

Multiband antenna with differential feeding can be useful in suppressing harmonics with reduced cross-polarization levels while yielding larger output power than that of single ended patch antennas [123]. Multiband characteristics have been achieved by two square slots on the ground plane. The antenna is printed on 1.6 mm thick FR4 substrate and a metal reflector plane has been placed to enhance the gain.

3D printing technology can facilitate low-cost fabrication of antenna and rectenna by proficient use of volume. A 3D printed multiband antenna based on system-on-package concept facilitated the rectenna circuit inside a cube structure [122]. Cantor fractal structures have been utilized in this antenna as multiband radiating element on different faces of the cube package.

Figure 7 illustrates the RF-DC power conversion efficiency of different rectenna based on multiband receiving antenna at different frequency bands. Antennas that operate at the lower end of the frequency spectrum captured more power. As seen from the figure, the rectennas achieved considerably low RF-DC efficiency at higher frequencies.

C. ANTENNA POLARIZATION

Performance of an RFEH or WPT system could make significant difference based on the choice of circularly polarized (CP) or linearly polarized (LP) receiving antenna. Since electromagnetic waves are broadcast on single plane in linear polarization, a linearly polarized receiving antenna is required to be fixed upon the same plane as the transmitting antenna, to receive optimum RF power. Hence, a linearly polarized receiving antenna does not have much of freedom of orientation. However, greater range can be achieved by LP antennas due to concentrated emission, which is more than a CP antenna of same gain. Conversely, the vagueness of incoming ambient RF signals negatively affects the received power of the ambient RFEH system, if linearly polarized antennas are used. For instance, performance of wearable RF energy harvester can be degraded with the motion of the object or human. On the contrary, electromagnetic waves are emitted in a corkscrew style in CP antennas. Now, applications can decide the type of antenna to be used. If the orientation of the transmitting signal is known and receiving appliance can be located on the same plane of the transmitting antenna, a linearly polarized antenna can be considered. However, if the incoming RF signals' polarization is inconsistent, appliances could be benefited more by circularly polarized receiving antenna with stable performance. A comparison between LP and CP antennas is given in light of RFEH and WPT application in Table 8.

A wave's polarization can be defined with regards to the radiated wave or received wave in a specific direction by an antenna [58]. CP antennas can provide better flexibility than linearly polarized antennas in wireless systems. CP antennas are well-found with certain advantages such as reduction of fading effect or multipath interference due to reflected RF signals from different objects and ground, independence of orientation between transmitter and receivers and immunity to the effect of 'Faraday rotation' in ionosphere [135]–[139]. RFEH and WPT system performance can be significantly enhanced by using CP antennas due to their improved invulnerability of polarization mismatch loss and multipath distortion which can facilitate RFEH or WPT system with greater flexibility of placement and signal reception [140]. Two orthogonal components of electric field are the requirements to achieve circular polarization in the far field region. A circularly polarized antenna design can be obtained, if the total electric field of the antenna has two orthogonal components with 90° phase difference and equal magnitudes [58], [135], [141], [142]. Generally, CP antenna performance is evaluated by considering axial ratio (AR) $<$3dB as a figure of merit. However, most conventional circularly polarized microstrip antennas suffer from low

TABLE 9. Examples of CP antenna designs.

Basic CP antenna types[136]	▪ CP Microstrip Patch Antennas ▪ CP Slot Antennas ▪ CP Wire Antennas ▪ Spiral Antennas ▪ Helix Antennas ▪ Quadrifilar Helix Antennas and Printed Quadrifilar Helix Antennas ▪ CP Dielectric Resonator Antennas ▪ CP Horn Antennas ▪ CP Arrays				
Refs.	CP Antenna Design type/technique	Operating frequency	3 dB AR bandwidth	Gain (dB)	Remarks
[148]	Bowtie dipole with co-axial feeding 90° hybrid feed network	0.94-1.7 GHz	51.8%	9	Gain increased by connecting bowtie patches. However, large reflector ground plane increased overall size. Supporting frame is required for mechanical stability.
[143]	CPW feed nesting L slot on the ground	1.77-6.06 GHz	60.9%	3.9 (Avg.)	Simple feeding structure is used with 80 mm reflector.
[154]	Ground slotted triangular monopole with branched microstrip feed	1.99-4.28 GHz	46.8%	2-2.6	Broadband circular polarization performance achieved with simple compact design structure.
[155]	Dual band dielectric resonator with modified patch	1.9 GHz, 2.4 GHz	3.16%, 5.06%	1.4, 1 (Avg)	Compact design with low AR bandwidth and gain.
[156]	Dual band printed monopole with semi-circular patch and Rectangular L-shaped adjusting stubs, ground connected complementary metal structure	2.5 GHz, 5.8 GHz	1.65%, 11.9%	<2 dB, 1.3-4.5 dB	Single fed, simple and compact antenna, advantageous for easy circuit integration.
[157]	Dual band folded annular slot with meta surface	2.5 GHz, 3.5 GHz	0.0032%, 4.28%	6.52, 7.04	Simple design but low AR bandwidth with moderate antenna size.
[158]	Square radiating element with cross slot and no-resistor feed network	0.961-1.204 GHz	6.8%	5.4	PTFE substrate-based design with a large height of 20 mm.
[159]	Radiating patch with inverted U-shape and I and L structured strips, simple square shaped frequency selective surfaced placed below the patch	2.4, 3.5, 5.3, 5.8 GHz	5.4%, 8.3%, 3.7%, 2.9%	5.95, 6.92, 6.37, 6.07	Simple design. However, overall antenna height is large, about 30 mm.
[160]	Slot loaded open ended ground plane with stair formed dielectric resonator and a stub with open circuit	3.844-8.146 GHz	46.0%	3.9	Wideband performance, 92% radiation efficiency with simple hybrid structure.
[149]	Crossed dipole with reflector, rotating circular and straight dipole printed on FR4 substrate	1.01-2.01 GHz	41.3%	6	Large in overall dimension with 50 mm antenna height.
[161]	Extended stub from square slotted ground plane, perpendicular to modified microstrip feedline	3.5-9.25 GHz	40%	0.8–4.5	Single fed, simple and compact antenna with 25×25 mm^2 size
[150]	Crossed stripped dipole with dual cavity backplane	1.9–4.4 GHz	66.7%	9.7	Overall antenna dimension increased due to dual cavity, 36 mm height.
[151]	Cross-looped parasitic radiator based cavity-backed crossed dipole	3.14-6.34 GHz	53.4%	10.2	Antenna mounted by semi-rigid coaxial cable with cavity backed structure. Could be vulnerable in context of mechanical stability during integration.
[162]	Multilayered patch fed by aperture coupling with dual Y shaped slot	3.28-6.76 GHz	50.4%	8.5	Compact design with large ARBW
[152]	Differentially fed cross dipole with parasitic patch and delay line phase shifter	1.5-2.8 GHz	31%	8	Large in dimension, 140×140 mm^2.
[153]	Parasitic element based crossed dipole with shorting pin	0.65-1.25 GHz	51.6%	4.03	Large in dimension, 138×138 mm^2, height 16.6 mm.
[163]	3D printed square patch with L-slot, loaded with shunt varactors at edges.	1.65-2.17 GHz (Tunable)	3%	2.6-4.5 (at different bias)	Complex antenna fabrication process.
[164]	Microstrip fed inverted L-shaped parasitic radiating element and modified slot loaded ground plane	3.2-8.4 GHz	82%	3.3	Compact and simple design with wide ARBW.

AR bandwidth [143]. Table 9 illustrates some of the basic CP antenna types and some common techniques to design circularly polarized antennas. Though most antennas reported for the application of RFEH or WPT system are linearly polarized [73], [116], [144]–[147], applications such as RFEH and the WPT system will necessitate the development of novel circularly polarized antennas with great performance.

As seen from Table 9, dual or multiband CP antennas tend to have low axial ratio bandwidth. Most sophisticated and geometrically large CP antenna designs resulted in good performance in lower operating frequency bands [148]–[150]. These kind of antenna designs can be useful in RFEH or WPT at the cost of design complexity or large size.

However, cavity backed, and crossed-dipole antenna designs may not be potential for RFEH or WPT based portable applications due to their comparatively large structure [150]–[153]. In addition, CP antennas with omnidirectional radiation pattern provide additional advantage in RFEH system since these antennas can independently receive radio frequency irrespective of wave's polarization diversity and insensitive to multipath effects.

CP microstrip antenna or CP slot antennas are good candidates for RFEH and WPT systems due to their low-profile, low manufacturing cost as well as ease of integration with power conversion circuitry [124], [166]. Figure 8 depicts different designs of circularly polarized antenna for RFEH/WPT application. Recently, circularly polarized receiving antennas are being reported for RFEH and WPT [46], [167], [168]. Design of a patch antenna with dual circular polarization has been also illustrated for wireless power transmission [169]. The antenna is facilitated with harmonic rejection property by T-shaped slot and U-shaped resonator. A circularly polarized antenna design based on two cascaded skew planar wheel antenna has been reported for RF energy harvesting to power up IoT connected temperature sensor [170]. Other straightforward design methods of CP antenna include circular radiating patch along with L-shaped perturbation [134], adding diagonal slits at the edge of radiating patch and symmetrical meandered slits [165]. Gradually decreasing the length of tapered slots in diagonal direction on radiating element is also able to generate CP radiation effectively with simple antenna design for wireless power transfer and energy harvesting. Table 10 illustrates CP antenna design techniques reported in literature for RFEH and WPT. Nonetheless, a dual linearly polarized (LP) antenna may be found useful in some applications as it is difficult to achieve large CP bandwidth and CP beamwidth values with complex design. Dual-LP rectennas can extract orthogonal waves and combine them to form a DC signal using two rectifiers [171], [172].

D. ANTENNA ARRAYS

Some applications require more power than a single rectenna can provide. Mobile phone manufacturers and researchers have been already racing to develop self-charging devices using RFEH or WPT techniques [174]–[176]. Powering unmanned aerial vehicles (UAVs) wirelessly while in mid-flight is a great area of interest for research as well [177], [178]. In such cases, single antenna is unable to suffice the power-hungry application. For instance, array antenna inspired microwave powered mini electric vehicles were introduced in 2007 [179]. The received power could be more useful for power hungry applications if a rectenna array or antenna array is used to capture RF power rather than using a single rectenna in RFEH or WPT application.

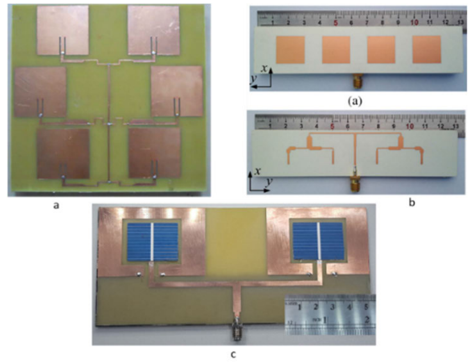


FIGURE 9. Array antenna for RFEH/WPT; (a) microstrip antenna array [183], (b) 1 × 4 patch array [187], (c) solar cell antenna array [186].

Electromagnetic waves can be captured using two or multiple antennas. An antenna is referred to as array antenna, if the total received signal power is enhanced using two or more antenna elements by combining the output of each antenna [180]. Improved performance over a single antenna is obtained through combination and processing of signals from multiple antennas. The signal combination through feed network is equally vital as the antenna elements of the array. Advantage of array antennas include overall increment in gain, rejection of interference, beam steering for sensitivity towards a fixed direction, diversity reception etc. There are some factors that control the radiation characteristics of an array of identical elements, such as, design configuration of overall array, relative structure of different element, amplitude of element excitation, distance among elements of array and array element's phase of excitation [58], [180], [181].

It has been investigated and illustrated that an increase in the number of antenna elements in an array can lead to better performance of the DC-combiner. The research was conducted using a planar 2 × 2 array antenna, as higher available RF power leads the rectifier to work in a higher efficiency region, [182]. Recently, more attention is being given to antenna array design for WPT and RFEH. Different designs including Printed Yagi antenna array [127], square patch array [183], dielectric resonator antenna array [184], differentially fed array [185] and solar-cell integrated antenna array [186] have been reported in literature recently. Figure 9 depicts some designs of antenna array reported for RFEH or WPT.

TABLE 10. CP antennas for RFEH/WPT.

Refs.	Antenna design technique	Operating frequency (GHz)	3dB AR ratio bandwidth	Gain (dBi)	RF-DC Efficiency
[131]	Coaxial fed circular patch with unbalanced circular slots on FR4	2.45	1.22%	3.6	55% @ 10mW/cm^2 Power density
[169]	Square patch with 45° rotated U-shaped resonator inserted in T-shaped slot on FR4	2.45	4.08%	8	70% @ 10 dBm input power
[133]	Circular shorted annular ring-slot on appropriate position of the Arlon 25 N substrate	2.45	8.34%	5.25	50% @ 10 µW/cm^2
[168]	Coaxial fed circular patch with e-shaped slot on Rogers 4003	2.4	1.24%	5	---
[165]	Circular radiating patch along with L-shaped perturbation and wide slot on Teflon substrate	5.8	37.7%	6.4	63% @ 10 mW/cm^2 power density
[46]	Diagonal slits at patch edge and symmetrical meandered slits on Rogers 3010	.915	1.21%	-29	N/A (Intended for implantable application)
[134]	Gradually decreasing in length tapered slots in diagonal direction on radiating element printed on Rogers 4003 and feedline and ground printed on another Rogers 4003	.900	3.3%	5.6	40% @ 10dBm input power
[173]	Square loop slotted patch fed by a feed network containing microstrip feedline, phase shipter, Wilkinson power divider, Y-structured feeding stubs using Rogers 4003 substrate	1.68-2.8 GHz	48.4%	2.9-4.5	42% @ 15 µW/cm^2 (2.4 GHz)

Collected RF energy can be enhanced by antenna arrays with large aperture dimension. Antenna arrays with uniform excitations distribution are typically used as the receiving components of rectennas in order to maximize the amount of captured power. The amount of harvested RF power sharply decreases with the variance of incident angle of incoming wave, if the beamwidth of the receiving array is relatively narrow. Rectenna arrays with enhanced beamwidth could address the issue [187]. On the flip side, rectenna arrays may suffer degraded efficiency due to close position of antenna elements and inter-coupling effect. Investigation of isolation structure in rectennas are performed to decrease level of coupling effect, raising efficiency and gain of the array [188], [189]. Recently, rectenna designs based on solar cell integrated antenna array are also proposed in literatures [186], [190]. Transparency of the antenna materials can be an issue since the incident light may be absorbed by the material. This will likely affect the efficiency of solar cell. Moreover, fabrication process of these kind of transparent antennas is expensive.

Nevertheless, array-based RF power harvesting system can be comprised of two different array configurations. These two topologies have been used in conjunction with 2×2 antenna and rectenna elements to compare the performance [182]. One of them is to arrange the antenna array to channel the RF power to a single rectifier. Due to the higher power delivered to a single rectifier, this architecture harvests more power near the main beam. Another strategy is to use a different rectifier for each antenna in order to harvest DC power independently. The DC power harvested from all rectifiers can then be combined in a variety of ways, including parallel, series, and hybrid configurations. Using this design, more received power is obtained with a broader pattern, which made the arrangement less sensitive to incident angle variations.

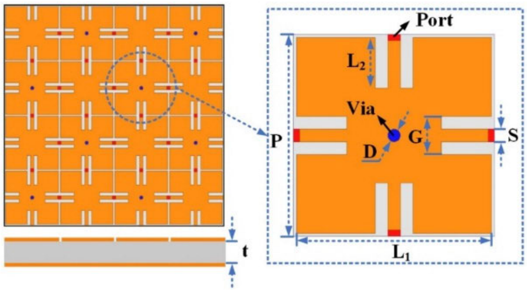


FIGURE 10. A Dual-band rectifying metasurface array for ambient RFEH and WPT [208].

Though array antenna designs are reaching a level of maturity with the advent of modern design methods and technology [191]–[194], new rectenna research based on innovative array antenna with additional features is still in infancy. Antenna array design and investigation in WPT/RFEH system design is one of the most important research issues for rectenna. Compact array structures overcoming the constraints of RFEH or WPT receiving network scheme and array configuration have potential research scope. The price of using attractive features of array antenna is paid by increased cost and complexity. The issues related to array antenna feed network are balanced and traded-off with the mechanical constraints of single elements. However, inexpensive and effective feeding network can be designed and fabricated with the advanced application of solid-state technology [58]. The discussion below briefly highlights some of the array antenna design aspects and techniques.

1) FEED NETWORK

Distribution of excitation in feed network is one of the major steps in designing antenna array. It is a significant challenge to reduce the complexity of the feeding network while maintaining efficiencies that are comparable to the theoretical maximum. Since each antenna element is responsible for gathering the impinging RF wave and converting it to DC power, it is preferable for the feed network in receiving arrays to be simple, light, and straightforward [195]. A microstrip array antenna design method has been documented based on efficiency of power transmission optimization [183], [196]. Feasibility of feed network fabrication is investigated based on the optimization procedure. Amplitude and phase distribution of incident wave on antenna elements are generated by the optimization. The optimized values of phase and amplitude have been used to design the feeding network of the antenna, depicted in Fig. 12 (a). The feeding network of the 4-element antenna depicted in Fig. 12(b) is designed using a distribution of optimal excitation. In [186], solar cell based two element antenna array feed network is designed using parallel microstrip feedline. Simple 2-element series-fed network based array antenna and 4-element cascaded array based T-junction power divider and two 2-element series-fed array are also reported for WPT application [197].

2) UNIFORM AND NON-UNIFORM ARRAYS

Uniform array antennas are those consisting of uniformly excited radiating elements with similar layouts. In non-uniform arrays, amplitude distribution is non-uniform while the inter element spacing remains uniform. High directivity with smaller beamwidth is achieved in uniform array [198]. In WPT scenarios, uniform transmitting arrays can facilitate simplicity and ease of maintenance [195].

3) METAMATERIAL ARRAY

Attractive features of metamaterials have introduced many potential applications in variety of areas in engineering including electromagnetic energy harvesting [43], [199]–[203]. Absorption of electromagnetic energy in metamaterials can be achieved within particular frequency spectrums. Metamaterial energy harvesters enable electrical loads to capture energy [204], [205]. Metamaterial arrays are advantageous over traditional antenna arrays in context of disruptive coupling of array elements and compactness of structure. As a result of constructive coupling among array elements, enlarged bandwidth can be achieved with metamaterial arrays. Among different kind of metamaterial array structures for energy harvesting, split ring resonator (SRR) based arrays are most prominent. It has also been reported as potential for increased conversion efficiency. Utilization of metamaterial arrays is a convenient technique to enhance receiving antenna performance as well [206]. A metamaterial array-based superstrate technique is introduced for rectenna applications [207]. The receiving antenna's gain has been enhanced by stacking a metamaterial superstrate on top of a standard patch antenna. In the integrated rectenna, there are three layers: a superstrate with 4×4 metamaterial unit cell (4-leaf clover shaped) arrays, a simple rectangular patch antenna with co-axial feeding, and a rectifier circuit. The metamaterial integrated antenna exhibits 6.12 dB increment in gain than the standard patch antenna without the metamaterial superstrate. Higher gain from the receiving antenna raised the captured RF power at the rectifier input, which led to higher output DC power and overall efficiency. Figure 10 depicts configuration of a dual-band metasurface array proposed for ambient RF energy harvesting and WPT [208]. The concept of embedding rectifying diodes within the texture was used to design the proposed rectifying metasurface. Via and via-free units are alternatively positioned in the rectifying metasurface array. The metasurface is efficient over a broad input power range when various diodes are used. According to recent research achievements, Metamaterial will play an essential role in ambient RF energy harvesting and wireless power transmission in near future with greater progress in miniaturization, higher efficiencies, lower sensitivity thresholds and other exciting features [209].

TABLE 11. Overview of array antennas for RFEH/WPT.

Refs.	Design configuration	Antenna array elements	Operating frequency	Size	Gain (dBi)	Radiation efficiency (%)	RF-DC efficiency (%)
[182]	Modified Koch-fractal structure based radiating element on high dielectric	2×2	2.45 GHz	360×340 mm^2	4.5	---	70% (Input power unspecified)
[127]	Printed quasi-yagi with double sided parallel feeding on RT/Duroid 5870 substrate	1×4	1.8-2.2 GHz	190×100 mm^2	10.9 dB @ 1.85 GHz	---	34% @ 1.8 GHz (Input power -20 dBm); 50% expected @ -10dBm input power
[183]	Square patch array with inset feeding on FR4 substrate	3×3	915 MHz	300×300 mm^2	10.5	84.14	41% @ 10 dBm input power
[189]	Dual monopole array with folded 3D meandering on 0.1 mm thick flexible substrate	2-element folded structure	900 MHz	35×56×12 mm^3	0.3 dB	48	---
[184]	Rogers TMM10i material based dielectric resonators on 0.1 mm copper ground plane	5×5	5.5 GHz	148×122.6 mm^2	---	65% (Power absorbing efficiency)	---
[187]	Dual Rogers-4350B substrate based patch array, feedline and patch printed on opposite substrate	1×4	5.8 GHz	129×30 mm^2	---	---	50% @ 1276 $\mu W/cm^2$ Power density
[185]	Differentially fed Dolph-Tschebyscheff on RT Duroid substrate	1×6	5.8 GHz	---	14.29 dB	---	22% @ -10 dBm input power (Approx.); 82.4% at 232 $\mu W/cm^2$
[186]	Multicrystalline solar cell based planar array on FR4 substrate	1×2	2.4 GHz	---	6.24 dB	54.5	35% @ 6 mW/m^2 power density

4) BEAMFORMING, BEAM SCANNING AND BEAM STEERING

Beamforming technique using antenna arrays can result in high-gain multiple beams simultaneously with controlled beamwidth. Steering and changing the direction of a single main beam of an array is referred to as beam scanning. The beam scanning method is potentially a promising technique to direct microwave power after finding the location of receiving appliance in WPT scheme [210]–[212]. The pivotal component for beamforming and beam steering is phased array antenna [213]. Electronic beam steering has certain advantages over mechanical beam steering in terms of compatibility with different application, size and speed [214]. Printed microstrip-fed reflect array antennas are advantageous in the application of WPT system as transmitting antenna. High gain directive performance can be achieved from reflector antennas along with beam steering facility [215]. Nevertheless, adaptive beamforming technique can provide solution to transfer radiated power towards desired direction, if the location of receiving device remains unknown or power required by multiple remote devices [216]. Above all, a robust and efficient antenna array with impeccable scanning performance and high gain is a vital requirement of wireless power transmitting system. Major design challenges in WPT beam scanning antenna array includes, mutual coupling of array elements, beam steering capability of ±45° and antenna efficiency [217].

V. FABRICATION METHODS

One of the most popular antenna types in wireless communication is patch antenna due to the attractive features of robustness. However, with the advancement of new fabrication technology, new antennas are also being

TABLE 12. Potential fabrication techniques of antenna for RFEH/WPT.

Fabrication Techniques	Advantage	Materials and Methods	Challenges
3D Printed[122,219-222]	• Cost effective • Fabrication of highly complex structure • Utilization of full volume • Housing for circuitry • Quick prototyping • Mechanical stability	ABS (Acrylonitrile Butadiene Styrene), Silver nanoparticle ink, glass hemisphere, materials based on polylactic acid (PLA) materials, Printrbot Play printer, Robo R1 + 3 3D printer, carbon pigment paint, copper paint, gallium, Conductive epoxy, conductive, thermoplastic filaments, carbon-black, graphene.	• Metal connector attachment issue • Antenna and subsystem connection
Inkjet-printed[223-225]	• Environmentally friendly • Low cost • Easy mass fabrication	Silver nanoparticle ink, Dimatix DMP 2831 printer, Cardboard, paper, Melinex 339 polymer.	• Challenging substrate material • Absorption of ink • Low conductivity and efficiency
Textile[226-31]	• Light and easy fabrication • Easy flexible integration • Robust • Relatively inexpensive • Easy integration with garment	Copper coated woven fabric, polyester felt, woven polyester, conductive fabric, felt, conductive non-woven fabric, pile and jeans.	• Narrow value of textile materials' permittivity impacting thickness and performance • Robust performance in different operating condition. • Reliability of textile and rigid subsystems connection
On-chip[232-235]	• Small scale antenna • Chip integration facility • Potential for microsystems	Chip-scale wafer-level technique, bonded wafer glass, CMOS process.	• Designing OCAs with high gain and efficiency is challenging due to low resistivity and high permittivity of Si/SiGe substrate[245]. • Expensive fabrication. However, integration of all parts of a system (RFEH/WPT) may provide cost-effective solution.

investigated, including 3D printed antenna, ink-jet printed antenna, flexible substrate-based antenna and on-chip antenna (OCA). This section describes some of the new antenna fabrication techniques in light of RFEH/WPT applications.

A. 3D PRINTED ANTENNAS

3D printing is one of the most exciting technologies that is revolutionizing the design and manufacturing industries. Manufacturing prototypes from three-dimensional computer-aided designs becomes easy, cost-effective and faster with this technology [218]. 3D printing has been able to attract antenna design engineers' attention over the past few years, including the recent increment in fabricating electromagnetic structures as well [219]. 3D printed antennas support wider application area with greater design flexibility and precision. One of the most significant advantage of 3D printed antenna is the utilization of the whole volume of antenna with highly complex design, which can be effective to achieve good performance in lower frequency bands. 3D printed antennas have great potential application in RFEH/WPT systems due to the flexibility of design to accommodate the rectenna circuitry. A 3D printed cube antenna with the capability to house the matching network and rectifier circuit has been proposed for ambient RF energy harvesting to provide power to IoT devices [122].

The inner bottom side of the cube has been used to house the triband rectifier circuit and matching network. The other five outer faces of the cube are utilized to accommodate the antenna radiating elements. 3D printing technology based Origami folding inspired by a cube is depicted in Figure 11 [146]. In this structure, the space inside of the cube has been used to place the electronic circuitry, while the outer faces are used to house the receiving antenna for RF harvesting sensors. These type of on package antenna can provide the power harvesting or receiving structures

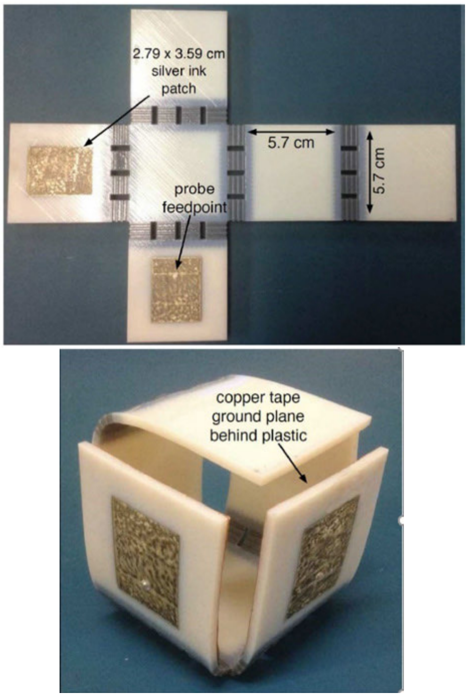


FIGURE 11. (a) Patch antenna on unfolded 3D-printed cube. (b) "Origami"-folded cube antenna [146].

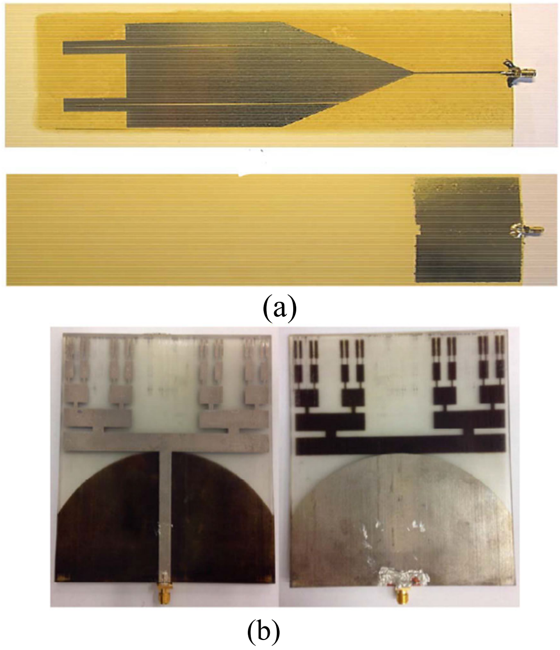


FIGURE 12. (a) Inkjet-printed monopole antenna [224]; (b) Inkjet-printed cantor fractal antenna [223] for RFEH application.

with a safe enclosure for remote deployment. However, some challenges remain, including requirement to fit printed circuit board, cost of supporting material, fabrication time, and feasibility to open/close or folding of the cube sides when necessary. Some approaches used 3D printed substrate material for the antenna [237], [238]. Printing of antenna from conductive material is also possible. Nevertheless, the method of attaching connectors to 3D printed antenna can be crucial for the antenna performance leading to overall system efficiency [219].

B. INKJET-PRINTED ANTENNAS

Environmental effects due to the choice of materials for wireless devices are vital. Recently, manufacturing techniques based on environmentally friendly materials are growing trend with the help of additive manufacturing like ink-jet printing. Wood and paper-based antenna holds great potential as green platform for RFEH, WPT, radio frequency identification (RFID) and WSNs [239]–[243]. Fabrication of biocompatible antenna with inkjet printing will open new windows of RFEH and WPT applications for implantable medical or wearable technology. However, radiation efficiency of the antenna can be affected by the dielectric loss from the type of eco-friendly conductor and substrate being used [224]. Conductive traces with order of conductivity up to 106∼107 S/m can be achieved by inkjet printing technology [244].

WPT and RFEH devices supported by inkjet printing technology has been also proposed [245]–[247]. Figure 12 represents fabricated prototypes of two inkjet-printed antennas. Figure 14(a) depicts a planar monopole antenna with partial ground plane [224]. The design has been printed on a thin commercial packaging cardboard using 'Harima NPS-JL' silver nanoparticle ink with Dimatix DMP-2831 printer. A dielectric coating was printed on the cardboard before printing the antenna to address the ink absorption and rough surface problem. The cantor fractal antenna presented in figure 14(b) has been fabricated using the combination of 3D printing and 2D inkjet printing [223]. The substrate material VeroClear is printed by Stratasys Objet 260 Connex 3D printer. The antenna elements are printed using multilayer silver nanoparticle ink by Diamatix DMP-2831 inkjet printer. A major advantage of these inkjet-printed antennas can be considered when harvester or receiver require very thin platform and more space for power management circuitry.

C. TEXTILE ANTENNAS

The fast advancement of wearable technology has the potential to change and revolutionize many aspects of life. Wearable devices can support a great range of applications such as biomedical sensors, WBANs and IoT. Textile antennas can be referred to as the antennas which contain textile materials as conductive element and substrate [248]. A great research scope lies for textile antennas as power receiver for wearable and other portable systems replacing uncomfortable and bulky solutions provided by flexible batteries [249] and rigid traditional batteries [250]. Textile antennas are fabricated using conductive textile or conductive fabric as radiating element and other fabrics are used for substrate. For instance, nickel and copper plated polyester based fabric

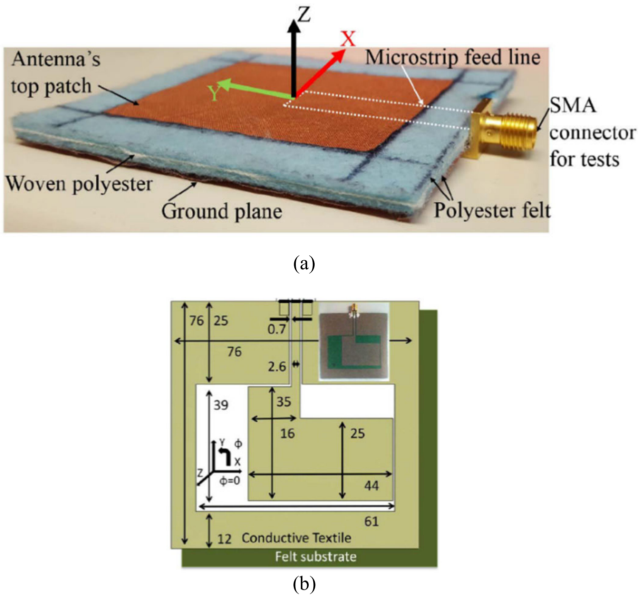


FIGURE 13. Textile fabric antennas reported for power harvesting wristband (a) [229] and WPT (b) [230].

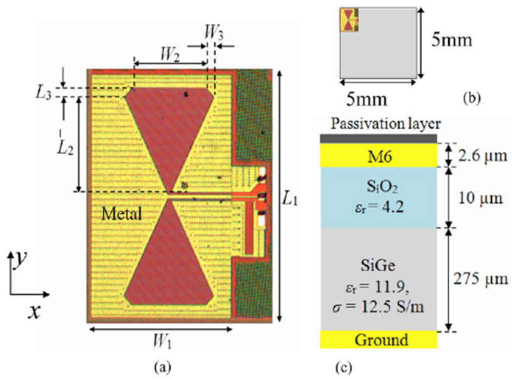


FIGURE 14. W-band on-chip antenna [236].

and denim have been used to fabricate the radiating patch and substrate of the antenna respectively [227]. A flexible wristband has been reported for power harvesting application based on a fabric antenna operating at 2.45 GHz (Figure 13), where the sensitivity of input power is −24.3 dBm. Polyester-felt and woven polyester has been used as substrate where copper-coated woven polyester fiber has been utilized as conductive fabric [229]. Potential application of textile antenna technology lies in wireless power harvesting or transfer for wearable electronics, on-body sensors, and protective equipment for rescue operations.

The addition of screen-printed antennas to the wearable receiving antennas for RFEH is a recent development. Screen-printing method can be utilized to map various layers of antenna on a flexible polycotton substrate. An array of broadband rectennas with 16 and 81 bow-tie antenna elements has been printed on a cotton t-shirt via screen printing using conductive paint [251]. Connections between surface mount diodes and conductive fabric substrates were shown to be reliable when using silver paint.

D. ON-CHIP ANTENNAS

The demand for implantable sensors has been increasing in recent years. The main design constrains in implantable devices are mobility and risk of infection which puts severe challenge for data transmission and power supply of the implantable sensor devices [252]. Wireless powering of such tiny devices can be a feasible solution by on-chip antennas with energy harvesting circuits in small space [253]. Modern semiconductor technology is enabling researchers to take advantage of miniaturizing the antenna to a few millimeters of scale. On-chip antenna based wireless power receivers are being used in implantable devices [235], [254]. An on-chip receiving antenna have been also used to power a pacemaker wirelessly [234]. An electromagnetic energy harvesting circuit using an on-chip antenna has been illustrated to energize ultra-low power implantable devices [252]. However, the loss due to absorption of signals in human body is still a great challenge for tiny antennas. Efficient and compact antennas with advanced silicon technology have the prospect for fabrication of fully integrated systems with high performance. A W-band on-chip antenna using BiCMOS technology for wideband application is depicted in Figure 14 [236].

In addition to the potential receiving antenna fabrication methods discussed above there are transparent antennas available for the application of RF energy harvesting [190], [255]. Thomas *et al.* presented a transparent antenna based on transparent conductive oxide (AgHT) for solar panel integration and RFEH [256]. The antenna is a CPW-fed cone-top-tapered slot antenna on a thin AgHT-4 polymer film. The antenna is initially laminated on a 2-mm-thick glass before being sandwiched between the 2-mm-thick glass and an a-Si solar panel. Aside from AgHT based transparent antennas, there are more transparent antennas employing other materials such as, thin silver and gold films, metal-doped oxides metal meshes, and organic conductors like graphene [257].

VI. APPLICATIONS OF WIRELESS CHARGING

Ambient RF energy harvesting and WPT are sustainable, cost-effective and green energy solutions. They can provide an alternative energy source for portable low-power devices that have a broad range of applications in different sectors such as agriculture, healthcare, manufacturing, mining, smart cities, etc. When it comes to applications of WPT, the most widespread use is passive UHF radio frequency identification (RFID) technology at around 900 MHz. Passive RFID tags are activated by the power received during communication from an RFID reader. RFID tags and RFID sensors embedded in tiles and other building materials could enable new energy-efficient IoT and WPT applications [258]. RFEH and WPT are expected to revolutionize the wireless

TABLE 13. Overview of RF powered WSNs.

Refs.	Application	RF power source	Receiving antenna	Distance covered	Wireless power charging technique	Output	Remarks
[268]	Powering up autonomous WSN device in vehicles	Agilent N5158A	50 Ω COTS 3dBi antenna	1-4 meters	WPT (Dedicated)	Max. DC output 500µW-10 µW	At 4 meters distance the WSN device can transmit a packet at each 20 seconds of interval
[269]	Measurement of light level and temperature and transmission of measurement data wirelessly	1 MW UHF television broadcast transmitter, cellular base transceiver station	6dBi gain	10.4 km (From 1MW TV transmitter) , 200 meters (From cellular base transceiver station)	Ambient RFEH	---	Fully ambient RF powered prototype, sensitivity -18dBm
[270]	Wireless humidity and temperature sensor	---	8.655 cm long quarter wave monopole antenna	2.5 m	Ambient RFEH	48 µJ; 1.8 V for 4 ms (1 operation cycle)	Picking up the sensing values and transmission is performed within 1 operation cycle (4ms); sensitivity -6 dBm
[271]	Autonomous Wireless Sensor Networks	Ambient RF energy at GSM-1800, UMTS-2100 and LTE-2600	Horn antenna; 0.8-18 GHz, 7-13 dBi gain	---	Ambient RFEH	Harvested power approx. 25 µW	Harvested power will suffice to power up temperature, humidity, Bluetooth transmitter, wake-up receiver and RFID based sensors. However, horn antenna has been user as the receiver in this experiment.
[272]	Powering wireless gas sensor node	Ambient RF energy at 900 MHz	---	---	Ambient RFEH	Charging of supercapacitor up to 5V by 400 seconds at 0 dBm input power	Perpetual operation of sensor node has been claimed. However, -20 to 10 dBm input power range has been considered in the application. The supercapacitor will take more time at less than 0 dBm input power changing the data transmission cycle.

charging technology of smart devices (smartphone, smart watch) and other consumer electronics (global positioning system (GPS) devices, e-readers, wireless headphone, smart wearable sensors in medical healthcare) with true cordless experience. Smart farming or precision agriculture can be facilitated by remotely powered IoT sensors, wireless devices for tracking and monitoring of livestock and equipment, and sensing devices such as soil moisture, water tank level and temperature sensors. Other long-range application may include, home automation and industrial control. On demand or schedule-based power can be also provided if the application requires. The benefit of wireless power transfer solutions, is that the cost of manual labor can be reduced significantly in the case of large scale deployment of sensors [259]. Some of the application schemes are highlighted and explained in the subsequent sub-sections.

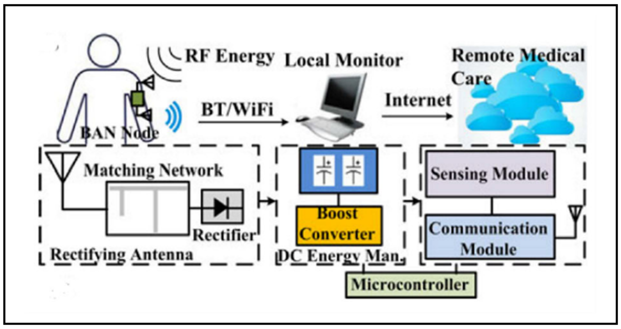


FIGURE 15. Future battery-less body area network sensor [119].

A. WIRELESS SENSOR NETWORKS

One of the major design constraints of wireless sensor networks (WSN) is the power scarcity associated with the sensors. Researchers are exploring new energy sources with enhanced reliability for WSNs. WSNs are comprised of many sensor nodes which are typically supplied by batteries. They are usually equipped with low processing power, short data storage capacity and limited power capacity [260], [261]. In addition to the finite life span of some batteries used as an energy source for WSNs, the problem of leakage current consumes the power even in unused low power states. Moreover, unavoidable weather conditions (e.g. extreme temperature) may damage batteries which will also lead to environmental pollution. Two models of RFEH can be used in WSN. One with two radios, in which one radio is used for RF energy harvesting while the other one communicates with the rest of the sensor nodes. The other model employs the same radio for RFEH and communication purpose simultaneously. However, using a single radio model can minimize the design complexity of hardware as the dual-radio model may require separate antennas operating at different frequency [262], [263]. Moreover, dedicated RF sources using WPT can be used to keep sensors alive. In addition, simultaneous wireless information and power transfer (SWIPT) technology has the potential to combine power and information transfer aspects in modern wireless sensor networks [264]. The SWIPT concept merges the WPT schemes with WIT (Wireless Information Transfer) and introduces a new research direction, whereas WIT used to be a separate research area [265]. Nevertheless, the application area of RFEH and WPT in wireless sensor network is evolving. However, most of the literature that investigated the feasibility of RFEH and WPT in WSNs, did not consider long distance performance of the sensor network. Sensing devices that have a low power requirement are capable of utilizing harvested RF power [266]. Distance from the RF power source is vital to estimate the maximum input power available at the receiving end. In addition, the sleep time of sensors in the network is one of the major concerns during the charging process of the device [267]. Investigation of maximum time delay allowed between data transfer cycles is required in time-dependent applications. Table 13 provides an overview of RF powered WSNs using WPT and ambient energy harvesting techniques.

B. WIRELESS BODY AREA NETWORKS AND WEARABLE DEVICES

Long-term monitoring of health can be performed by wireless body area networks (WBANs) without affecting people's daily lives. WBANs provide a smart and inexpensive solution to health monitoring as a part of medical diagnostics [273], [274]. WBANs have received increasing recognition along with the emergence of wearable technology for Internet of Things (IoT) based healthcare applications [275].

Many low-power wearable communication and sensing technologies are being inspired for WBANs. Researchers emphasize wearable/on-body and implantable sensors to capture and transmit vital health parameters. On-body wearable devices or in-body implantable devices such as, pacemakers are expected to operate for long periods without replacing batteries. Moreover, batteries are usually the heaviest component in almost every WBAN devices [276]. Furthermore, most battery technologies come with corrosive electrolytes or flammable organics which is a health hazard and incompatible for in-body or wearable application from biomedical point of view [277]. RFEH and WPT provides an alternative green energy solution to wirelessly charge wearable or implantable devices.

Radiative near-field WPT based solutions can also be suitable for on-body or, implantable application. Moreover, this method is less prone to the misalignment issue between transmitter and receiver that happens in near-field coupling based WPT [278]. There are still challenges for RF powered wearable devices in context of flexibility; fabrics are broadly suitable for lightweight, low-cost and flexible performance [229]. Stable radiation pattern and reliable efficiency of the antenna in the receiving system is one of the most crucial factors if the person is mobile. In addition, reliability for interfacing rigid and flexible subsystems and efficient power management circuit for extremely low RF input power are required [229], [279], [280].

C. INTERNET OF THINGS (IOT)

The quality of life is expected to be improved in large scale by the intelligent infrastructure of IoT, enabling the utilization of numerous devices connected through Internet. Most modern industries will see a new paradigm of advancement through IoT. IoT devices typically have wireless transceivers, sensors, processors, and a power source for data acquisition and communication [281]. However, power source issue is one of the main constraints that have limited the full-scale adoption of IoT technology. RF energy scavenging and WPT can provide a sustainable energy solution for long term operation of IoT devices, where replacing or recharging batteries is not feasible. The efficiency of embedded systems in IoT framework has been advanced in recent years towards achieving the target of fully autonomous sensors with the

TABLE 14. Wireless sensor nodes for agriculture [286], [288], [289].

Name	Sensors included	Power consumption in active mode	Power consumption in sleep mode	Power supply
MICA2DOT	Accelerometer, temperature, light	15 mW (@3V)	75 µW	3V Coin cell battery
MICAz	Light, temperature, humidity, barometric pressure, accelerometer, GPS, RH, acoustic, video sensor, microphone, sounder, magnetometer	24 mW (@3V)	75 µW	2×AA Battery
MICA2	Light, temperature, humidity, barometric pressure, accelerometer, GPS, RH, acoustic, video sensor, microphone, sounder, magnetometer	24 mW (@3V)	75 µW	2×AA Battery
Cricket	Light, temperature, humidity, barometric pressure, accelerometer, GPS, RH, acoustic, ultrasonic, video sensor, microphone, sounder, magnetometer	24 mW (@3V)	75 µW	2×AA Battery
TelosB	Light,temperature, humidity	10 mW (@3V)	8 µW	2×AA Battery
IRIS	Light, temperature, RH, barometric pressure, acceleration, seismic, acoustic, magnetic and video	24 mW (@3V)	24 µW	2×AA Battery
Davis 6345CSAU[300]	Wireless Leaf & Soil Moisture/ Temperature Station	0.42 mW (@3V)	---	CR123A 3V Lithium battery (Extended lifetime by solar panel)

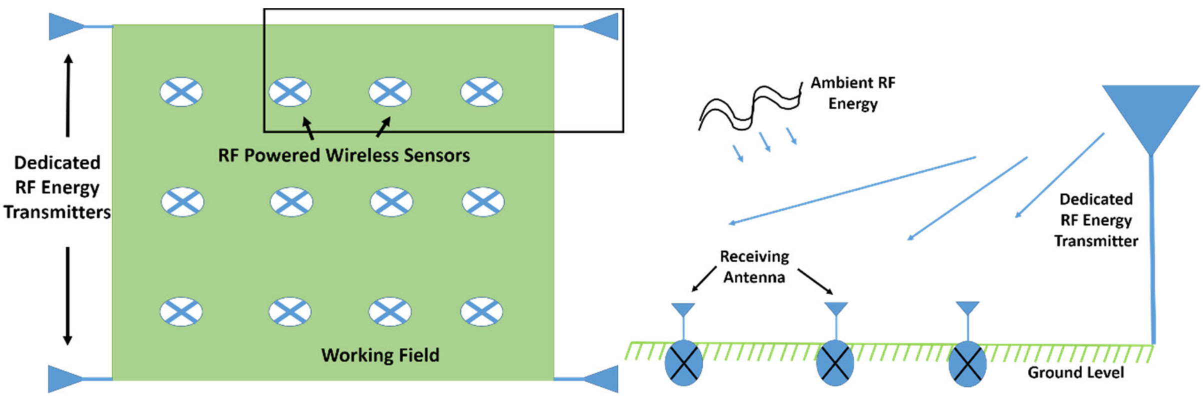


FIGURE 16. Potential architecture of RF energy harvesting/WPT for remotely deployed wireless sensor.

help of low power radio and microcontrollers [282], [283]. Stability and viability of RFEH and WPT in IoT devices need to be considered by removing the local on-board energy sources, reducing environmental pollution and maintenance cost as well as making the device compact.

D. SMART FARMING/AGRICULTURE

The demand for food is rising prominently with the rapid growth of world population. Food security will be a significant concern as the population of the world is expected to be approximately 9.7 billion by the year of 2050 [284]. Deployment of wireless sensor networks (WSNs) has been an acceptable solution over the years for precision agriculture; smart agriculture with process automation [285], [286]. In addition, a paradigm shift in agricultural technology is emerging due to the application of IoT sensors along with the WSNs [284], [287]. However, power supply for autonomous sensors in the agricultural domain is still a dominant issue. Table 14 illustrates power consumption information of some sensor nodes available for agriculture. Solar power has been utilized to extend the battery lifetime of agriculture sensor kits such as the 'Davis 6345CSAU' [288]. Nevertheless, the dependence of solar power on climatic condition is inevitable.

These sensors could be repowered by replacing the battery [286]. However, this becomes a significant challenge for mass deployment of sensors over large area, leading to great human effort as frequent change of batteries is not a viable solution for farmers. In such cases, RFEH or WPT technology-based sensors can provide an alternative solution for self-powered operation or, extending the lifetime of sensors without having to replace batteries often. Architectures of WPT enabled IoT devices are of increasing interest to researchers. Figure 16 depicts a potential application architecture of RF Energy Harvesting/WPT based solution for remotely deployed wireless sensors in agricultural farmland. Extending the operating time of soil sensors in agriculture by RFEH/WPT can provide a long-term solution to remotely charge wireless sensor with minimum maintenance, irrespective of climatic condition. More controlled and reliable monitoring over agricultural services like irrigation, fertilization, pesticide spraying, animal and pastures can also be achieved.

VII. RESEARCH CHALLENGES, SCOPES AND FUTURE WORK

Open research scope and challenges are highlighted in this section under the prism of the antenna design techniques discussed in this paper for RFEH and WPT. A large number of antennas are documented for RF energy harvesting application, whereas the number of reported antenna designs for radiative wireless power transfer is not significant. In addition, practical design issues should be considered during modelling of antennas for applied research. This section is categorized as below:

A. DESIGN VISION

Power supply is often one of the most critical limiting factors for the widespread development of smart technology, WSNs, wearable electronics, wireless systems, portable electronic devices and IoT sensors. Looking into the future, making the receiving antennas efficient, compact, cheaper and practically feasible are some of the viable solutions to achieve the optimum goal of RFEH and WPT technology. Increasing the number of potential and remotely powered applications imposes new design constraints for antennas.

The key differences between the propagation conditions (received signal parameters) in RFEH (unpredictable) and WPT (deterministic) which are mentioned in section III, are required to be considered in designing the receiving antenna. Degradation of radiation efficiency and gain with the reduction of antenna size should be taken into consideration for application specific design. Compact antennas with overall satisfactory performance of gain, efficiency, radiation pattern, single/multiband operation, polarization and sensitivity are still in strong demand. Trade-off between antenna performance and new design techniques are dominant issues for specific cordless appliance. Prior to designing an antenna, it is critical to keep the application scenario and surrounding environment in consideration. For instance, if the intended application is powering sensors located in frequently inaccessible areas, then the design has to be robust and mitigate wear and tear of harsh environments or changing climatic condition (such as in agricultural). Integrability with existing sensors can be considered as well to avoid expense of deploying a completely new set of sensor nodes connected with RFEH/WPT device. In case of mounting the rectenna on external casing of sensors in smart agriculture, the antenna should be able to sustain weather conditions, a wide range of temperature and humidity in outdoor environments. On the other hand, in case of wearable application the antenna should be extremely small, maintaining satisfactory performance even with the presence of human tissue instead of deteriorating the power reception rate due to coupling between antenna radiating element and lossy human tissue. Moreover, antenna performance tends to degrade when it is mounted with sensors or electronic circuits and create issues like decrement in gain and shifting operating frequency, which can substantially reduce the received power. Utilization of circularly polarized antenna and array antenna as receivers can support new potential applications while imposing new challenges for efficient power reception. Hybrid antenna design technique like solar panel integrated antenna may provide added advantage. Highly flexible antennas with mechanical stability can be fabricated without degrading electrical properties by injecting liquid metal to microfluid channels [290], [291]. Feasibility study of other antenna design methods including liquid metal antenna based on conductive liquid and micro-fluidic based patch antenna can be advantageous for future biomedical, wearable, flexible or stretchable technology. Another one of the latest trends is multidirectional receiving antenna that can facilitate rectenna system with multidirectional power receiving capability [292]. In case of multiple RF power transmitters in a WPT system, multidirectional antenna/rectenna could provide consistent radiation efficiency, enhanced peak gain, and sufficient conversion efficiency.

B. RECEIVING ANTENNA DESIGN USING COMPUTATIONAL INTELLIGENCE

The application of computational intelligence (CI) has had an increasing impact on the solution of complicated problems in antenna designs. The area of Evolutionary Computation (EC) has grown in recent years as a means of solving difficult optimization problems. Several Evolutionary Algorithms (EAs) have been developed and applied to a range of issues in the fields of microwave components, antenna design, radar design, and wireless communications over the past few decades. Nature-Inspired Algorithms, for example Particle Swarm Algorithm (PSO), Differential Evolution (DE), Ant Colony Optimization (ACO) etc. are gaining prominence in the antenna designers community as examples of CI approaches [293], [294]. Furthermore, artificial intelligence techniques and approaches like machine learning can be combined with intelligent optimization algorithms to achieve optimal design of an antenna. For instance, a hybrid method to design wire antennas has been presented using artificial intelligence approach incorporated with Simulated Annealing (SA) algorithm [295]. The use of mainstream and emerging evolutionary algorithms in antenna design for WLAN, satellite, thinned arrays, RFID, and other applications is becoming increasingly popular; receiving antenna design for RFEH and WPT using computational intelligence, on the other hand, is still a relatively unexplored field. Intelligent optimization methods have promising potential for use in the development of efficient receiving antennas in the field of RFEH and WPT. They can be used to achieve innovative antenna structures that are not possible to design using the built-in optimizers of conventional electromagnetic simulators.

C. FABRICATION METHODS

New fabrication methods hold great potential for efficient and effective manufacturing of receiving antenna designs for RFEH and WPT. Nowadays, some of the emerging antenna fabrication techniques including 3D printing [146], inkjet printing [224], flexible or conductive textile technologies can create new dimensions of application [227]. 3D printing can be used to fabricate antenna structure with the sensor body which can aid the scarcity of space for antennas. Moreover, efficient use of volume can be achieved with 3D printing technology that can facilitate low frequency of operation with a small antenna volume. Investigation of antenna performance using new substrates based on novel efficient materials has a great research scope. However, exploration of new fabrication techniques should be cost-effective.

D. INTEGRATION WITH EXTERNAL CIRCUITS AND HARDWARE

Integration of antennas with matching circuits, rectifiers, storage (supercapacitor battery), IoT devices, sensors and other subsystems is an important issue that needs to be observed carefully. Designed antennas should be easier to mount with appliances and planar circuits. Most reported antennas are only used to show the proof of concept in measurement, while practical application in powering up portable devices will impose new challenges. Performance of the antenna could be affected by the close existence of other subsystems. For instance, integration of the antenna with printed circuit board (PCB) may impact the antenna performance if the PCB is placed in near-field region of the antenna since the PCB also has a dielectric value. Performance of the antenna may get disrupted due to the interaction between antenna and any metallic structure or, other electronic components in the appliance. As a result, the power receiving capability may decline. This can be avoided or reduced before the fabrication process by tuning and optimizing the antenna in simulation and considering the possible presence of other objects in close proximity. Effects produced by the PCB components can be studied and reduced by relocating the conductive components that impacts the antenna [296]. Antenna can be considered as a part of the PCB and same ground plane can be utilized for other circuit parts. Design decisions on antenna can save significant effort and cost in the beginning of the wireless product or appliance development cycle [297]. Optimized radiation efficiency can be achieved by placing the radiating element at a corner of circuit board allowing for the remaining board area to be dedicated to other components. Antenna radiation may be shielded due to the existence of metallic housing of device components. In such cases, simulation or measurement of the antenna in the early phase can prevent serious issues. The metallic casing can also be used as antenna ground plane in modern designs [298]. In case of placing antenna over conductive body or metal housing, cutting away the part of the metal casing immediate behind of the antenna or, increasing the separation in-between may provide a feasible solution. Consideration of the respective application scenario can provide balanced trade-offs between available space and placement position of antenna and performance.

E. RECEIVING ANTENNA PERFORMANCE EVALUATION

Performance investigation of receiving antennas are expected to provide a clear idea of power receiving efficiency of the antenna being used. Most articles report rectenna's RF to DC rectification efficiency. However, power receiving ability of the antenna used in the rectenna is an important factor that needs to be emphasized. In addition, most rectenna performance is measured in anechoic chamber using a horn antenna as a transmitter, which barely reflects the practical scenario as the distance between transmitter and receiver ranges up to only a few meters. As a result, high efficiency is found. However, real world applications may report lower efficiency due to path loss originating from distance and environmental loss. Also, investigation of antenna performance according to the rate of FCC allowed isotropic radiating power should be considered to verify the usefulness of the antennas in practical applications.

F. GREEN WPT

Solar, wind, mechanical, and thermal energy have been the most efficient sources of green energy employed in wireless networks over the last decade. A considerable number of IoT sensors are being deployed in interior environments where natural resources may not be readily available for energy harvesting. The key drawback of such sources is their inability to maintain consistency. Moreover, in context of green energy, it appears that WPT may be damaging to the environment because RF signals are still generated using power originating from traditional power plants. Also, strong electromagnetic radiation if it is not managed, would cause health hazards. Thus, researchers proposed a green WPT concept rethinking the WPT technology [299]. The energy-carrying RF signal will be generated utilizing energy harvested from green resources. The harvest-store-use model can be used to store renewable energy and transmit RF power for the application of wireless charging. Additionally, to increase the transmit power, a stringent limitation can be implemented according to the U.S. Federal Communications Commission. The green WPT is predicted to be one of the

TABLE 15. Historical SSPS concepts.

Proposed by	Concept	Employing Orbit	Microwave Downlink Frequency	Power Supply ability
Solar High Study Group; Department of Energy & National Aeronautics And Space Administration [304]	DOE/NASA SPS reference system concept	Geosynchronous orbit (GEO)	2.45 or 5.8 GHz	Gigawatts
M. Nagatomo et al. [305]	SPS 2000 Japanese concept	Low earth orbit (LEO)	2.45 GHz	10 MW
J. C. Mankins [306]	SunTower concept	Sun-synchronous LEO, middle Earth orbits	5.8 GHz	20-250 MW

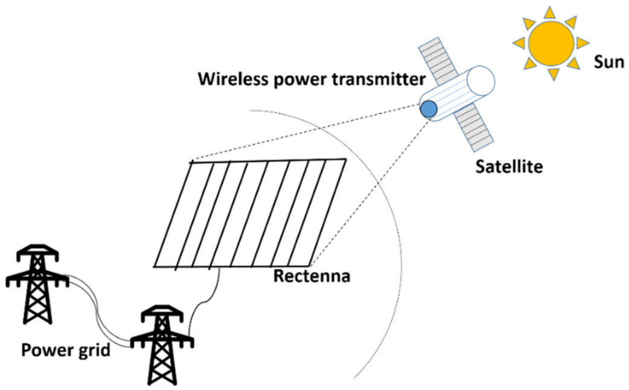


FIGURE 17. Solar power satellite concept [303].

most appealing possibilities for future applications that can serve as a link between natural energy resources and WPT technology.

G. NEXT GENERATION APPLICATION OF WPT TECHNOLOGY

Clean energy can be brought to the earth from sunlight in space which can transform renewable energy resource planning fundamentally. Solar powered satellites in combination with WPT technology have revolutionary possibilities to open new applications in the energy sector. Transferring power to the Earth by microwave beams from power stations in space is a promising technology. Large rectennas can be utilized to capture microwave energy and convert it into electricity [37, 314]. The main idea of Solar Satellite Power Station (SSPS) can be traced back to 1968 when P. Glaser conducted a WPT analysis and proposed the concept of SSPS [301]–[303]. The basic concept is visualized in Fig. 17.

Large solar cell arrays of the satellites located in geosynchronous orbit convert sunlight into electrical energy. That energy will be transmitted to the Earth using a transmitting antenna as RF energy by beaming towards a receiver site on the Earth. Large rectennas will be utilized to receive the RF power, which will be then converted to electrical energy and routed towards electrical power distribution networks. Though this concept has been recognized worldwide as a practical energy solution, it was stated as economically not feasible. Moreover, this technology has been subjected to the consideration of human safety and biological impacts. The program has limited the power density of the 'center of beam' for WPT, $100W/m^2$ to $200W/m^2$ to ensure environmental safety and health. Microwave power density beyond the perimeter of the rectenna will be within permitted public exposure limit.

VIII. CONCLUSION

The performance of a WPT or RFEH system is significantly dependent on the receiving antenna. This paper reports the state-of-the-art and recent progress in antenna designs for RFEH and radiative WPT. This review is intended to help the reader understand the current receiving antenna trends in different circumstances. It started with an introduction of RFEH and WPT, their applications and enveloped a range of topics including wireless charging, the required receiving antenna specifications and state-of-the-art antenna technologies and designs for RFEH/ WPT. Different antennas are reviewed with a focus on design architecture and performance. This study has explored various antenna designs while categorizing them in context of low-profile, multiband, LP/CP and antenna arrays. Performance and advancements of the antennas are compared in light of practical realization of RFEH systems and WPT systems for future applications. This review also covered potential fabrication techniques for receiving antennas, future research scopes and challenges.

The outlined assessment has revealed that low-profile antenna with satisfactory performance still remains a paramount issue. Different antenna fabrication methods including 3D printed, ink-jet printed, textile and on-chip antenna for wireless charging application are highlighted discussing their pros and cons. New fabrication technologies should be considered for rapid prototyping of antennas while keeping the design architecture as simple as possible. In addition to other fabrication methods, 3D printing technology holds great potential. Novel materials and geometry based high gain antenna for a wide frequency range is an important research issue that also needs to be addressed to improve RFEH and WPT efficiency. This survey also reveals that most literatures reported RF to DC rectification efficiency only, making it difficult to determine the amount of RF power received by the antenna being studied. Power delivered from the antenna to the input of the rectifier should be highlighted in-terms of RF power receiving performance of the antennas. Further works can be performed on designing receiving antenna which are easily mountable with planar circuit element. Design and modelling of antennas with the other electronic components of the whole RFEH and WPT systems should be considered for practical applications. Likewise, there are other design challenges that have been highlighted in Table 2. Addressing these challenges with the combination of novel antenna design efforts can make RFEH and WPT promising technology for a future cordless world. Antenna researchers are required to have clear understanding on both the RFEH and WPT systems to achieve optimum performance with reduced size and expense. It is expected that this review will assist researchers working on improving receiving antenna designs for RFEH/WPT, especially for practical applications.

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