FUTURE RECTENNA SYSTEMS FOR 5G ENERGY HARVESTING APPLICATIONS

Abstract

This chapter provides a summary of the 5G rectifying antenna and its key components for millimeter-wave (mm-wave) energy harvesting (EH) and wireless power transfer (WPT) applications. The large spectrum accessible to 5G wireless communication bands has sparked substantial interest in a wide range of applications. The power absorbed by a harvesting antenna is proportional to its size. As a result, implementing efficient antenna and rectenna systems at 5G mm-wave is a difficulty.

This chapter outlines current advancements in 5G rectenna systems for various applications at both component and structural levels. The key goals of this chapter are to 1) investigate the possible advancements of mm-wave rectenna structures and the viability of their layouts to achieve the intended features, and 2) give an unbiased examination of performance metrics prevailing rectenna systems.

Keywords: Energy harvesting (EH), Millimeter wave (mm-Wave), Rectenna system, wireless power transmission (WPT)

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I. INTRODUCTION

As wireless technologies such as the Internet of Things (IoT), fifth-generation (5G) cellular systems, human-to-machine, machine-to-human, and machine-to-machine interactions have evolved, the demand for exceptionally great data rates, significant network capacity, and immaculate connectivity have spread universally. 5G communication has been promoted as a promising means of fulfilling energy needs. The main goal of 5G communication schemes is to provide mobile customers with consistency in service quality, reduced power consumption, and improved data rates. The frequency band for 5G has been separated into three bands: upper-band 5G (24.24-52.59 GHz) is a millimeter-wave band, mid-band 5G (3.3-5.0 GHz), and lower-band 5G (less than 1 GHz) [1-3].

The IoT-based smart cities are rapidly expanding, necessitating the utilization of several IoT devices with sensors. This may have an impact on several batteries that must be charged and replaced regularly. Consequently, the design and deployment of sovereign arrangements in the IoT are critical [4]. One method for reaching these objectives is through RFEH (radio frequency energy harvesting). Researchers are now involved in the RFEH methodology due to its distinct advantages over other energy harvesting methods, such as maximal rectification efficiency and environmental autonomy. The rectenna is an instrument made specifically for RFEH use. The critical components of the rectenna system are the rectifier and the antenna [5]. The rectenna was first studied for wireless power transmission (WPT) purposes and afterward for RFEH uses [6]. Due to growing energy demands, the 5G/mmWave bands are actively investigated in the outer atmosphere. As a result, it is desirable to set up 5G mmWave rectennas for mmWave EH/WPT applications. This chapter focuses on the rectennas functioning at the frequency ranges of current interest such as 5GmmWave operating ranges.

II. EH/WPT FEATURES IN 5G MMWAVE COMMUNICATION

Today, 5G is often concerned to as the facilitator of the Internet for everywhere, everyone, and everything. One of the fundamental objectives of 5G technology is to intensify mobile network bandwidth over 4G by a factor of 100, producing a maximum data transfer rate of more than 10 Gb/s [7]. The imperative need for higher information rates and more capacity has led to the investigation of new spectrum utilization strategies, including licensed, distributed, and unlicensed spectra. Sub-6 GHz (0.45–6 GHz) and mmWave (24.25–52.6 GHz) bands are now operated for 5G transmission [8]. Broader coverage and appropriate transfer rates are achieved by using sub-6 GHz bands. At the same time, 4G connectivity will be preserved. The mmWave bands of the 5G technology are intended for extremely high-speed transmission among devices that are close to one another.

Over 35 billion connected devices are expected by 2025, among those more than 20 billion are being machine-to-machine interactions. Consequently, the most important goal of 5G is to empower IoT interactions while also allowing the network to drive autonomously so that services can be accessed without interruption. On this front, energy harvesting is becoming increasingly popular as a viable option. As a result, the perpetual Internet of Things with the layout and realization of autonomous, self-reliant technologies is enormously needed. One method for achieving these goals is the mmWave EH or WPT. Because the federal communications commission (FCC) proposals for admissible generated Effective Isotropic Radiated Power (EIRP) are extended beyond (reaches 75 dBm) those of their relatively low counterparts, mmWave energy, available in the fifth-generation of wireless communication bands (above 24 GHz), found to be a prominent RF scavenging source. This demonstrates 5G's ability to create a functional power grid or wireless power network.

In Sections IV, V, and VI, several design concepts of the sub-6 GHz and millimeter wave EH/WPT-based rectenna system for 5G communication will be explored.

III. RECTENNA DESCRIPTION

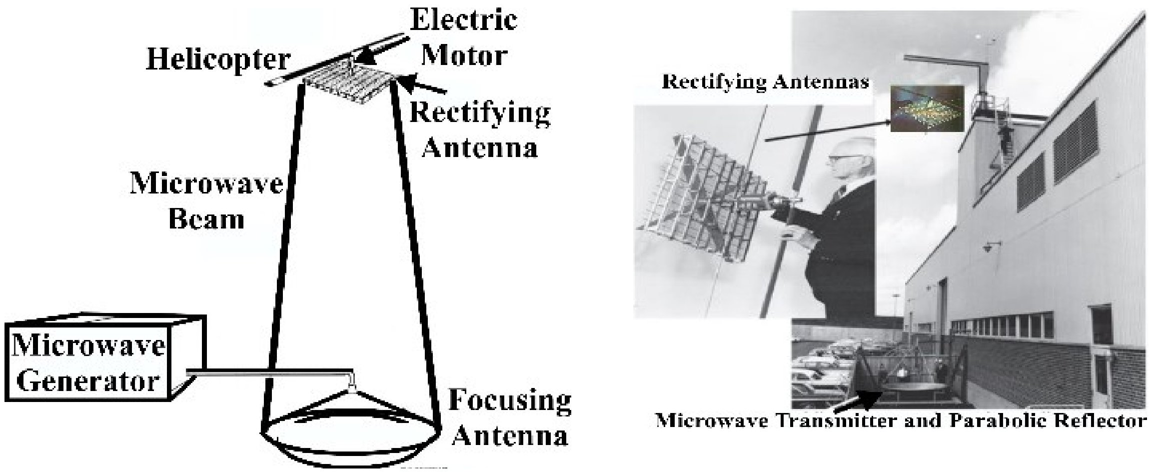


Figure 1: The First Experimental WPT Set-up with the Flying Drone Model [9]

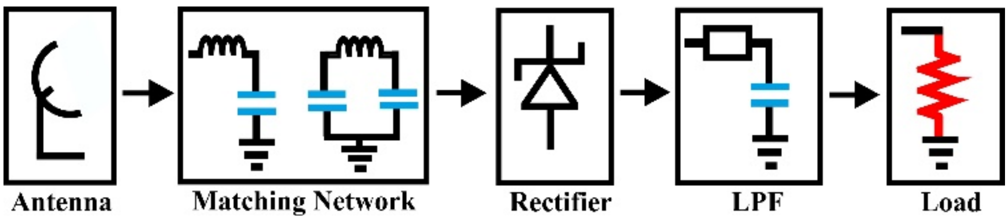


Figure 2: Fundamental Schematic View of A Rectenna System

In the 1960s, W.C. Brown invented the rectenna to operate a model helicopter. A flying aircraft operated solely by a microwave beam has been successfully combined using wireless power transfer and helicopter technology [9-10]. The importance of microwave-powered drone investigation extends far beyond its potential to provide novel and useful expertise in aerospace. It's the first-time microwave beam power transmission has been used, a new technology that's more fundamental and has a lot of potential applications, but it needs a first application to help it expand and get recognition. The microwave-powered helicopter is also an extraordinarily diverse breakthrough that replaces existing charters for a variety of professional, commercial, and government organizations. WPT over great detaches for distant rejuvenate of vehicles or objects without the usage of cables is now possible, thanks to enhanced microwave energy-generation mechanisms at superpower levels. Sensing, implanted devices, self-powered sensors, and other WPT applications are investigated. The rectenna is a device that aids in the performance of various WPT applications.

As shown in Figure 2, a rectenna comprises an antenna, a matching circuit, a rectifier, and a DC pass filter. The quantity of input power to the rectenna can affect on output of the overall rectenna system, which implies that the increase in power input to the rectenna increases the delivered power to a load with an appropriate conversion unit. An appropriate antenna can boost the power output by the antenna, which is feasible due to the antenna's high gain, multi-resonance, broadband resonance, or wide coverage properties. A wide angular coverage antenna may also aid in gathering more ambient radiation from nearby sources.

A rectifier is an significant portion of a rectenna system. The execution of the rectifier is mostly influenced by the choice of a suitable diode and rectifier topology. Due to its low threshold voltage and quick switching speed, Schottky diodes are proven to be appropriate at RF levels. The diode is normally chosen based on the amount of RF power input to the rectifier and the received RF energy's operating frequency. A half-wave rectifier (Series/Shunt), a voltage doubler (VDR), a full-wave bridge (FWBR), and Greinacher rectifiers are all common rectifier topologies.

Table 1: Performance Characteristics of Rectenna System

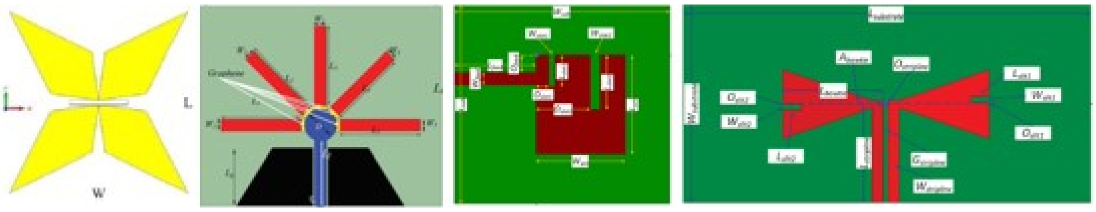
Rectenna System for WPT	Rectenna System for RFEH
An established channel requires a specific source of energy.	Both ambient and specialized energy sources are utilized.
It is preferred to have a directed antenna.	It is preferred to have an omnidirectional transmitter.
Any operational frequency can be used to design the rectenna.	The rectenna needs to be made for a set of frequencies that are most commonly present in the surrounding atmosphere.
Energy density in the surrounding environment does not affect performance.	The level of energy density in the surrounding area affects the performance.
The amount of received RF energy can be determined.	Incident RF energy availability is unpredictably variable.
Highly susceptible to polarization mismatch.	Highly susceptible to polarization mismatch.
Suitable to work with single-band or dual-band applications well.	Ambient RFEH is connected with multiband harvesting; as a result, it can be used in multiband applications.
A high-gain antenna is preferred for the established transmission path.	A large gain antenna is unfavorable since its propagation channel is unsure.
CP rectennas have mostly been suggested for WPT because of their comparatively high susceptibility to being mispositioned.	Due to multi-source harvesting, all polarization rectennas are strongly favored. Dual-polarized antennas help collect the majority of polarized waves from the environment.

Since the Rectenna system's creation, several articles have reported on its use for RFEH/WPT applications. Table 1 summarises the rectenna's basic performance characteristics for RFEH and WPT applications. The next sections go through in depth the various design techniques for mmWave EH/WPT systems for 5G applications.

IV. RFEH/WPT SYSTEMS FOR SUB-6 GHz BANDS

This section shows how RFEH/WPT systems can operate at 5G in the 0.5-6 GHz frequency range using several methodologies. The main objective of any rectenna system is to increase output while obtaining the greatest amount of power from the ambient or dedicated source. This section investigates various classification-based methodologies to fit the RFEH/WPT systems' criteria.

1. Antenna Configurations



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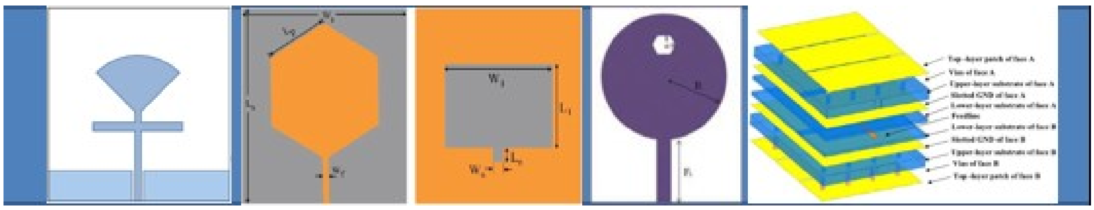


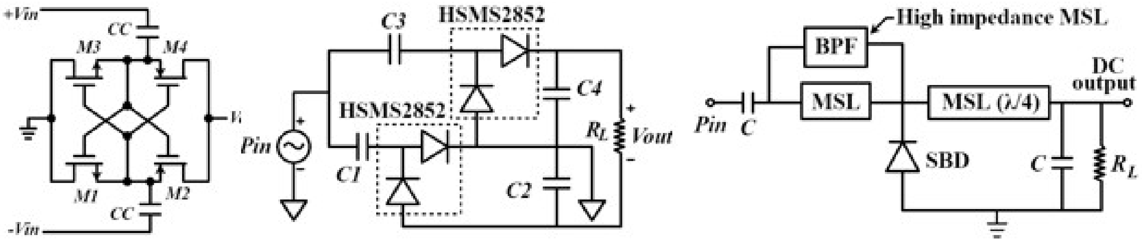
(14) (16) (17) (18) (19)

Figure 3: Various antenna geometries for Sub-6 GHz RF Energy Harvesting applications

For multi-resonance features, including 5G, an asymmetrical diamond-shaped radiator was used [11]. The reconfigurability of a monopole antenna with a circular geometry and evenly spaced rectangular strips has been explored at the operating band [12]. For 5G RFEH applications, a microstrip antenna with a modified E-shape of structure [13], a CPW-fed fan-shape of the antenna [14], and a Bow-tie antenna with loaded strips [15] were used. A slot-loaded approach [16-17] and a slot-embedded circular monopolar antenna [18] were used to increase the operational range of a notch. The patch's back-to-back method aids in achieving broad-angle coverage [19], a tree-shape of printed microstrip patch antenna is implemented in [20].Some of the Sub-6 GHz 5G antenna configurations for RFEH applications are presented in Figure 3.

2. **Rectifier Configurations:** For harvesting applications, a CMOS-based multistage rectifier has been created with two distinct routes for RF input power levels of low and high [21]. A Greinacher circuit was examined for creating dual-band characteristics in [22]. For separating low and high RF power levels, the rectenna system has two separate pathways. [23] designed a high-impedance microstrip line-based shunt diode rectifier. A DC feedback loop was designed to improve the rectifier's performance at low power

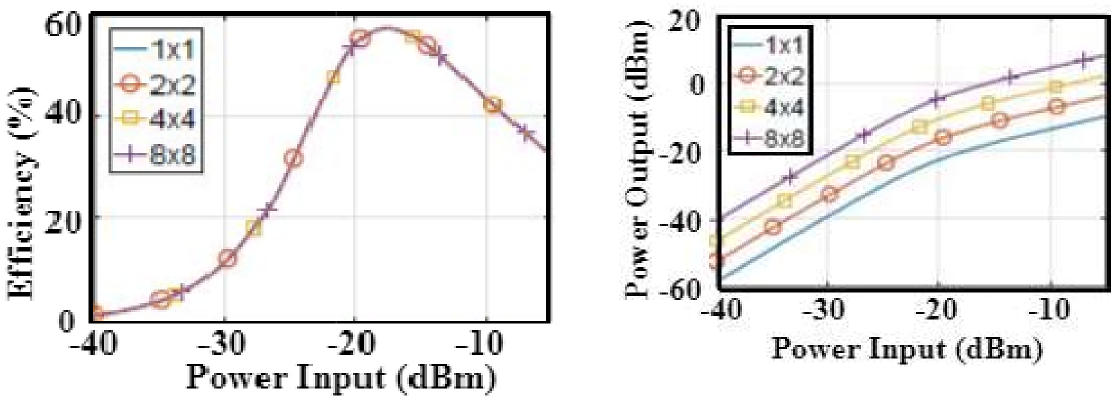
levels while allowing the rectifier to function efficiently over a broad range of designated RF levels. Figure 4 presents some of the 5G-operated rectifier circuits for sub-6 GHz RFEH applications.



(21) **(22)** **(23)**

Figure 4: Various rectifier configurations for Sub-6 GHz RF Energy Harvesting applications

3. Rectenna Configurations



(a) **(b)**

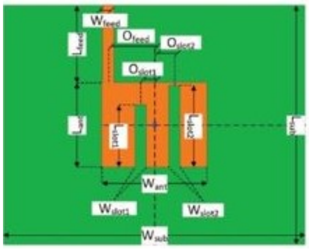
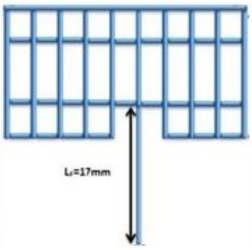
Figure 5: Performance evaluation: (a) Power conversion efficiency and (b) Power output [24]

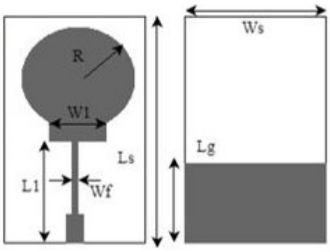
Various rectifier array circuit combinations, such as 1, 2×2, 4×4, and 8×8, were used to investigate the rectenna performance [24]. As demonstrated in Figure 5, the increase in the number of elements in the array does not change the efficiency greatly, but it does raise the output voltage. For IoT applications, a rectenna with a combination of a modified E-shape of a radiator and a voltage multiplier [25] was built, as was an optical rectenna system with a solar cell antenna [26]. The rectenna design [27] featured a flexible keyhole antenna form with a VDR. The rectifier's PCE and output voltage were improved by using two tapered lines connected at the rectifier's core.

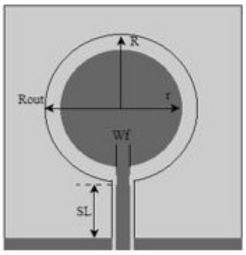
For effective rectenna system functioning, a CPW-fed circularly shaped patch printed on a transparent Poly-Ethylene Terephthalate substrate was explored [28]. A slotted ground with a series-connected rectifier was used to develop a dielectric resonator (DR)-based dual-band rectenna [29].

A rectenna with a half-wavelength shunt rectifier and a stub-loaded planar antenna has been demonstrated [30]. The antenna circuit's working frequency is constrained by the length of the stubs. The rectenna in [31] was designed using a spiral-slot antenna that was integrated into transponder electronics and diplexer.

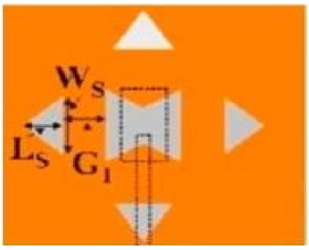
The sub-6 GHz 5G grid allocates for widespread coverage, but it persists in spectrum scarcity, constituting it impossible to support a significant increase in several appliances in 5G and beyond. There is significant attention on deploying 5G mmWave cells under the current sub-6 GHz cells to boost coverage and channel capacity. mmWave has been extensively used for far distance transmission in satellite and terrestrial applications, resulting in extraordinarily high data rates, thanks to their huge resource spectrum at higher frequencies. Due to improved availability and the potential to construct a rectenna system with a tiny size, constructing an EH/WPT system in the mmWave 5G band is extremely attractive.

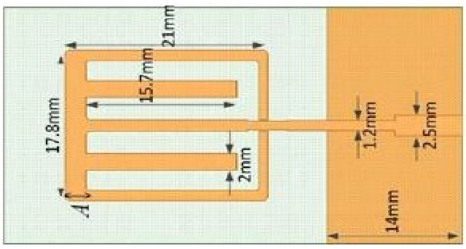



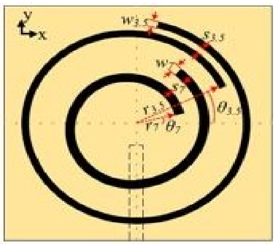




[24] **[25]** **[26]** **[27]**







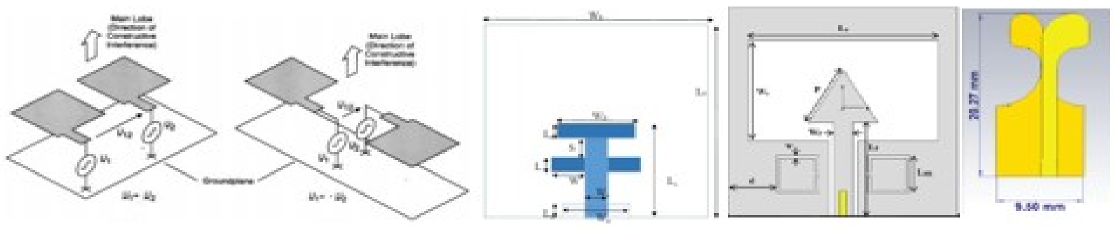
[28] **[30]** **[31]**

Figure 6: Vaious Rectenna configurations for Sub-6 GHz applications WPT/RFEH

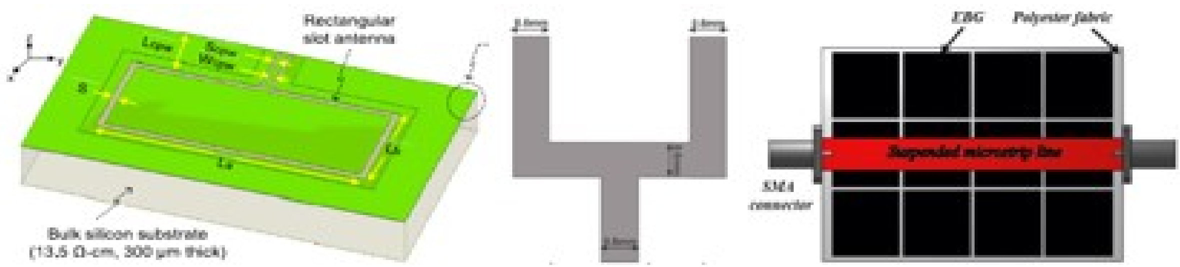
V. ENERGY HARVESTING SYSTEMS FOR MMWAVE 5G

This section examines alternative mmWaveEH system design techniques for 5G mmWave applications.

1. **Antenna Configurations:** For mmWaveEH applications, a dual-patch radiator [32], a two-leg Yagi radiator [33], and a pair of concentric ring slots [34] were examined, as shown in Figure 7. Printing a triangle shape of a patch on a flexible FET substrate is used to create a flexible mmWave antenna [35]. For acquiring multi-resonance characteristics, a defective ground structure (DGS) was used. For harvesting applications at mmWave, a reconfigurable Y-shaped patch antenna [36] and an asymmetric antipodal Vivaldi antenna [37] were developed. [36] achieves reconfigurability by combining two PIN diodes with a microstrip patch. For on-body applications, [38] created a flexible wearable antenna that was incorporated into an EBG structure.



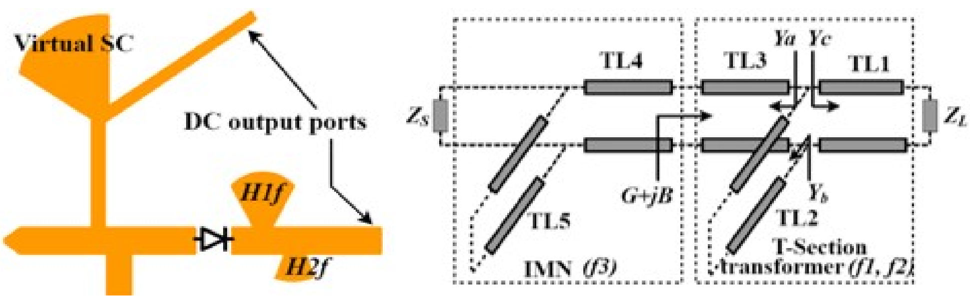
[32] **[33]** **[35]** **[37]**



[38] **[34]** **[36]**

Figure 7: Antenna geometries for mmWaveEH applications

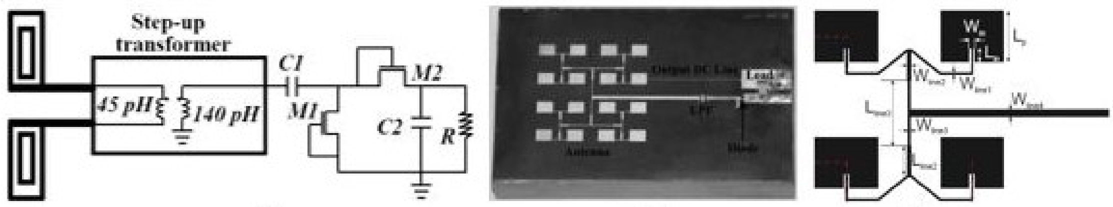
2. **Rectifier Configurations:** Because of its low series resistance (R_s) and low junction capacitance (C_{j0}), a W-band zero bias detector made using Virginia diodes was shown to be appropriate for operation up to 81 GHz [39]. [40] studied the design of a tri-band rectifier using a multi-impedance matching network that included a series-shunt stub and a T-section impedance transformer.



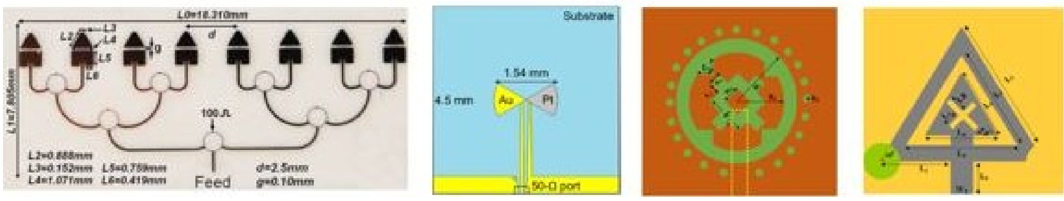
[39] **[40]**

Figure 8: Few examples of rectifier configurations for mmWave EH applications

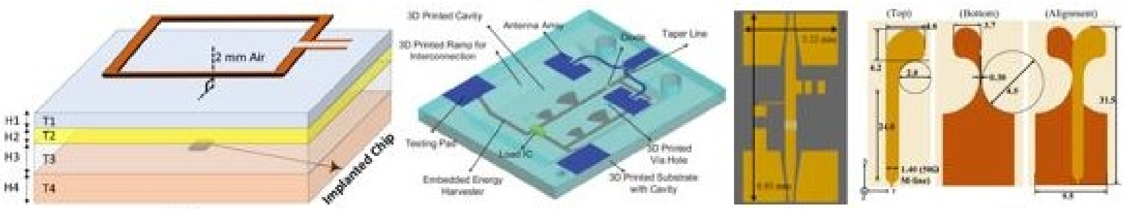
3. Rectenna Configurations



[44] [45] [46]



[47] [48] [49] [50]



[51] [52] [53] [55]

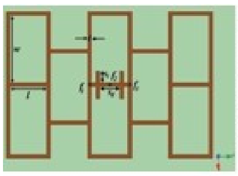
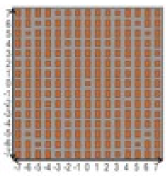
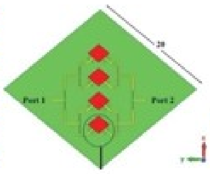
Figure 9: Various antenna/rectifier configurations for mmWave EH applications

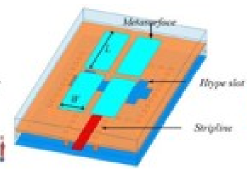
Several arrangements of antenna array cells, including quadrupoles, collinear wire, double dipoles, and mesh, were used to test the effectiveness of the receiving rectifying element (RRE) [41]. With double dipoles and quadrupoles, the RRE performed better in terms of rectification efficiency. [42] used CMOS technology to create a mmWave EH RFID tag. The antenna's gain was improved by using a reflector beneath it. Rectenna with a monopole antenna and a three-stage inductive-peak rectifier were implemented in [43]. With a dipole antenna and a CMOS-based single-stage Dickson rectifier, a rectenna was developed [44]. For designing the rectenna system, an antenna array was examined [45-47], to improve antenna gain, resulting in more power being gathered. Using a metal-insulator-metal (MIM) diode at V-band, improved rectifier PCE performance was reported in [48]. To enhance the rectifier IBW, a graphene FET (GFET)-based rectenna was used [49-50]. Also, when compared to other feasible rectifier topologies, GFET-based rectifiers show less parasitic effects at high frequencies. For biomedical implants, a compact system that is invulnerable to wireless link characteristics and overloading fluctuations has been developed [51]. A 26 GHz packaged integrated harvester system [52] was developed to be incorporated into multilayer adaptable packaging structures made using 3D printing technology. For the first time, a graphene self-switching diode (GSSD) based rectenna was studied experimentally utilizing a patch antenna array [53]. The graphene diode is made to have as much non-linearity in the I-V curve as possible. An antipodal Vivaldi antenna (AVA) and a VDR were used to design a textile-based broadband rectenna for wearable applications at mmWave [54].

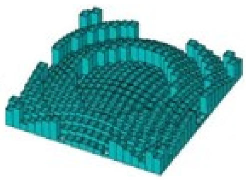
VI. WPT SYSTEMS FOR 5G MMWAVE APPLICATIONS

In recent decades, several mmWave rectenna layouts for WPT systems have been presented. In this, the evolution of rectenna design techniques over time is examined. These methods reduce transmission costs, increase power utility, and complexity, and allow for the establishment of a battery management capacity.

1. **Antenna Configurations:** For mmWave applications, a coplanar stripline (CPS) driven folded dipole antenna was examined [55]. Low diffraction loss was achieved using a lens antenna [56]. The dipole antenna is made up of two folded arms that maximize gain, while the coplanar stripline feed extends the antenna's operational range. For WPT applications, a dual-port electromagnetically linked square patch array antenna was investigated [57]. To eliminate mutual coupling between the elements, the array elements are rotated by 45^0 degrees. Each feedline is connected to a pair of open stub resonators, which eliminates higher-order harmonic components. To produce a high gain, an antenna array approach is investigated in [58-59]. A metasurface superstrate improves the power gathered [60], whereas a metasurface array helps to cover a wide-angle coverage [61]. For mmWave WPT applications, [62] built a microstrip feed-based flexible textile antenna. The inset microstrip feed's broad inset slots ensure that the operating band is properly matched. For 5G applications, a slotted patch with a diamond shape of ground was used [63].





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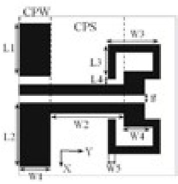
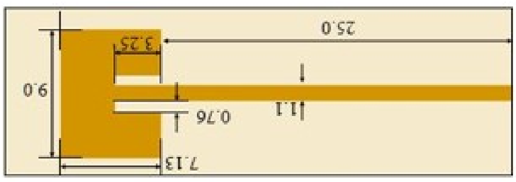
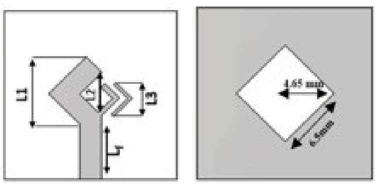


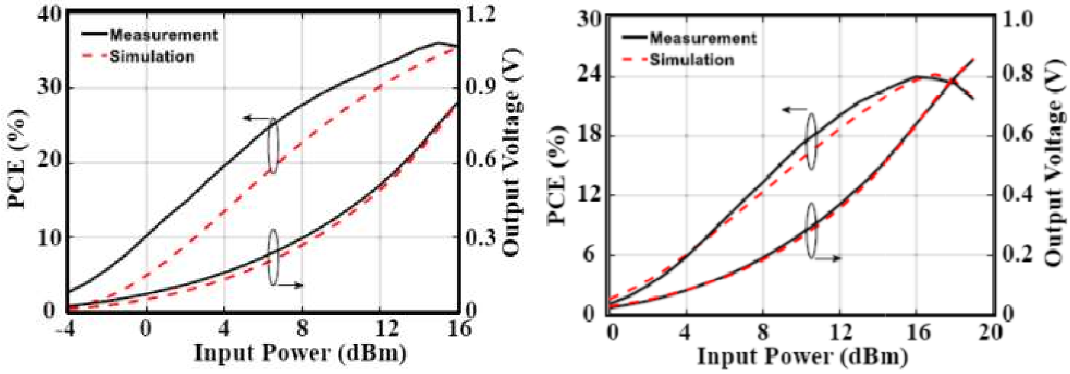




[55] **[62]** **[63]**

Figure 10: Various antenna configurations for mmWave wireless power transmission applications

2. Rectifier Configurations

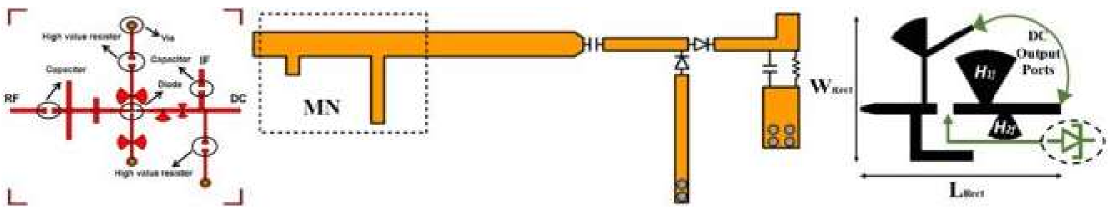


(a) **(b)**

Figure 11: Performance evaluation: (a) 35 GHz, (b) 94 GHz [69]

For WPT applications, a VDR circuit based on microstrip technology was developed [64]. The performance of the VDR with the MA4E1317 diode outperformed the other setups in terms of conversion efficiency. A harmonic harvesting rectifier was built by employing a λ/4 open-circuit (OC) stub resonator to improve the rectifier PCE [65]. To match the antenna and rectifier impedances, transmission line (TL) coupled transformers are utilized [66]. An integrative form of dual tiny microstrip resonant cell (DCRMC) LPF and a CPW feedline using CMOS semiconductor technology was devised to build an extremely tiny rectenna [67]. A TL-based VDR was developed to operate at 28 GHz and 38 GHz frequencies [68]. For WPT applications in the W and Ka bands, a CMOS-based rectifier [69] was implemented. Figure 11 shows the rectifier's performance at two different mmWave frequencies. Improved diode performance is required to increase rectifier performance at sub-THz frequencies, according to [70]. MN's TL-based technique exhibits low loss in the W-band [71]. For input power levels of less than 1 dBm [72], the tunnel diode-based rectifier outperforms the Schottky diode-based rectifier in terms of conversion efficiency (a). A double-stage Dickson charge pump combined with GaAs technology was shown to be useful for performance improvement of the rectifier [73].

3. Rectenna Configurations



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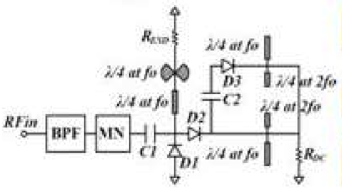
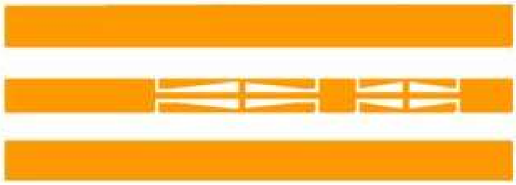
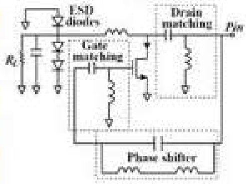
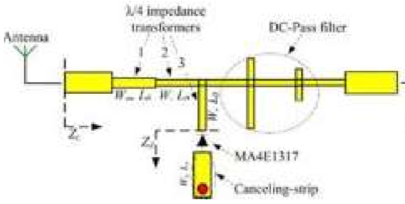
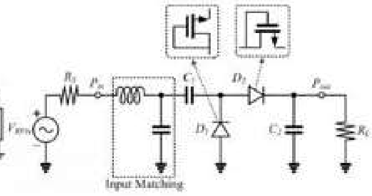


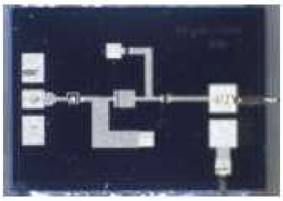




[71] **[65]** **[67]**

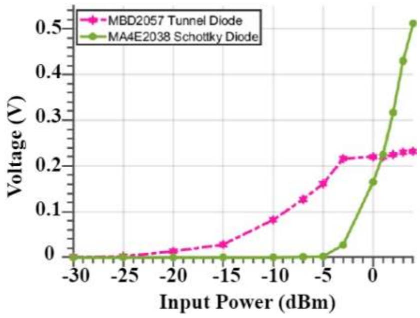


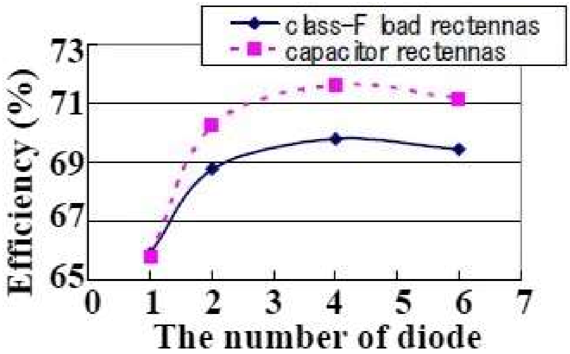




[66] **[69]** **[73]**

Figure 12: Various rectifier topologies for mmWave WPT applications



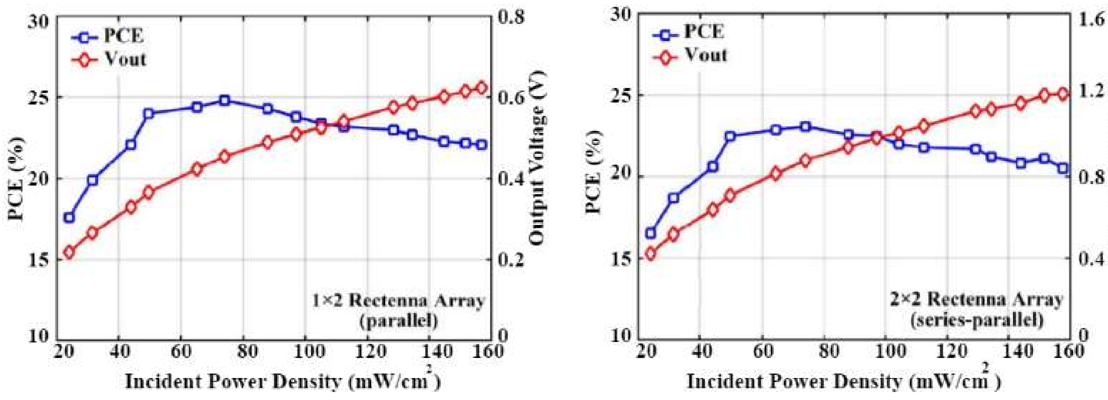


(a) **(b)**

Figure 13: Rectenna system evaluation: (a) V_{out} [72] and (b) PCE [79]

[74] discusses the modelling and advancement of mmWave rectennas and power beaming systems. At 2.45 GHz and 35 GHz, the diode properties were studied [75]. The performance of an array-based rectenna system is superior, and the increase in rectenna output voltage is observed with the increase in the number of antenna elements in the array [76]. In [77], CMOS technology was used to create an FWR-based rectenna with finite-width ground CPW (FGCPW) transmission lines and tapered slots. Harmonic components are reduced using the FGCPW transmission line. The RF-DC conversion efficiency of a shunt topology with an adaptable stub and a resonator after the diode is improved [78]. As illustrated in Figure 13(b), Hatano et al. discovered that a rectenna

with a Class-F load outperforms a typical rectenna using a capacitive load and that its performance advances as the quantity of diode in the rectifier increases [79].



(a) **(b)**

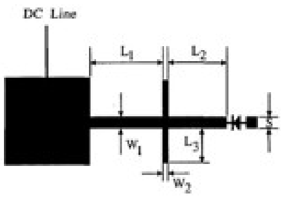
Figure 14: Rectenna array performance variation: (a) 1×2 and (b) 2×2 [92]

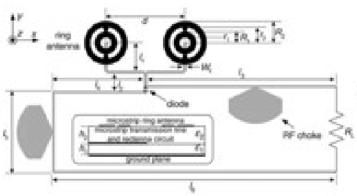
To lower the rectifier dimension and boost the rectifier conversion efficiency, a mmWave rectifier circuit was built as a monolithic microwave integrated circuit (MMIC) [80]. Rectenna design using substrate-integrated waveguide (SIW) technology minimizes losses [81]. A rectenna was created by combining a SIW cavity-backed antenna with a self-biased rectifier [82]. To improve gain and achieve circular polarisation, an array of antennas with SIW cavity-backed antennas was investigated (CP). Two output Class-F DC pass filters and a high-gain Fabry-Perot resonator antenna were used to create a high-efficiency rectifier [83]. A grid-type antenna was combined into a complimentary cross-coupled oscillator-like rectifier to create a rectenna [84]. In [85], a dipole antenna with a single diode HWR was used to create a basic rectenna. In [86], MEMS technology was used to create the rectenna design. To reduce losses, the design method employed a fin-line transfer circuit. In [87], a coupled slotted patch antenna with a MA4E1317 diode-based shunt rectifier circuit was used to develop a 35 GHz rectenna.

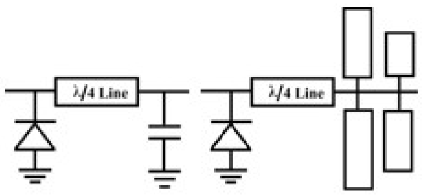
A bow-tie shape of the antenna with a MIM diode was used as a rectenna [88]. A cylindrical patch array was used to construct a flexible rectenna for a conformal plane [89]. For higher gain with adequate isolation between the elements, a slot-coupled patch antenna array with SIW cavity-back feeding was adopted [90]. For increased DC output, the performance of the rectenna array designs was also studied. Rectenna performance was investigated at 24 GHz for two rectifier topologies employing two distinct diodes [91]. The RF-to-DC conversion efficiency was improved with a shunt diode setup using the MA4E2054A diode. To mitigate the losses associated with the microstrip patch, a metallic Fabry–Perot resonator antenna and cavity rectifier-based rectenna are used, resulting in enhanced antenna radiation efficiency [92]. For the first time, a transparent optical rectenna was studied for harvesting purposes [93]. Using a tapered slot antenna and a CMOS switching rectifier, a rectenna was created [94]. The antenna gain and radiation efficiency are improved by the tapered-slot antenna, while the PCE is increased by the CMOS switching rectifier. Figure 14 compares the performance of two rectenna arrays, revealing that the rectenna array with 2×2 antenna elements produces higher output voltage than the rectenna array with 1×2 antenna elements. With the increasing number of rectenna array elements, the same output performance was achieved [95]. The reception antenna was a barbell-type DGS-based four-element SIW patch array, while the rectifier circuit was a parallel-mounted Schottky diode. A free-flight AR-drone was used to test the rectenna system at a height of 800 mm [96].

VII. BEAM STEERING APPROACH FOR 5G MM-WAVE COMMUNICATION

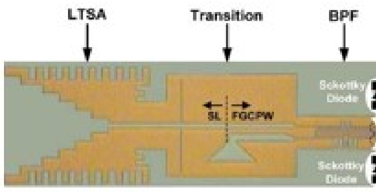
Beam-steering antennas will be required when 5G moves to greater frequency ranges to steer radiated energy from the base station antenna array to the end user while mitigating increased route losses. Beam-steering focuses an input in a specific direction instead of spreading it out across 120 degrees the way it would normally. ESAs govern the signal, allowing for more precise transmission in addition to faster, more secure connectivity than would not otherwise be possible. It reduces transmission loss and broadens the 5G frequency range in the mmWave spectrum. The Rotman lens is a one-of-a-kind and cost-effective solution to accomplish mmWave beam steering.

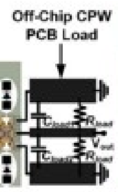


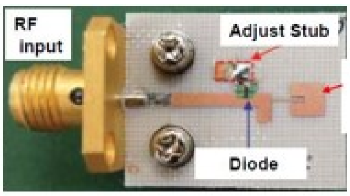


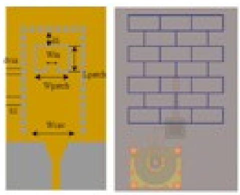


[79] **[75]** **[76]**

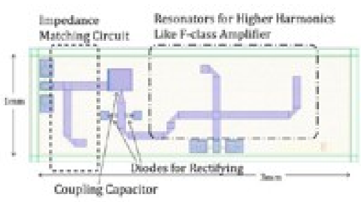


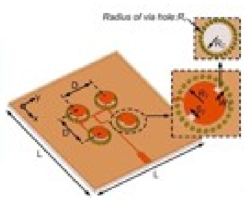


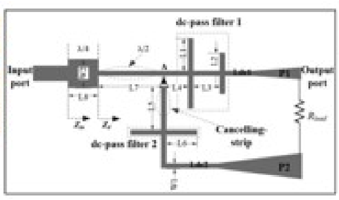


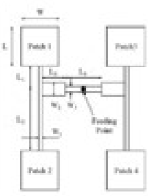


[77] **[78]** **[81]** **[84]**









[80] **[82]** **[83]** **[96]**

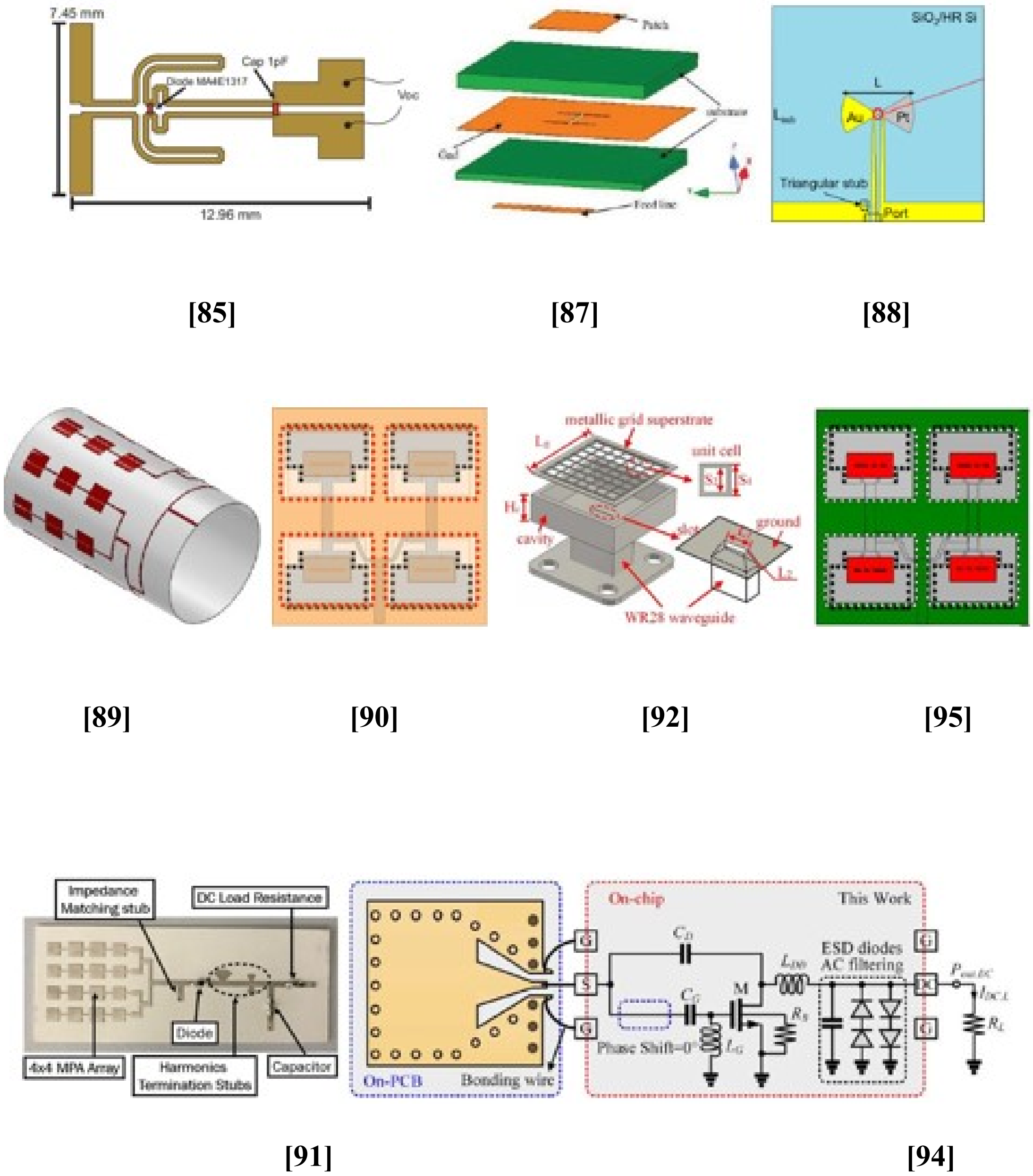


Figure 15: Some rectenna configurations for mmWave WPT applications

The Rotman lens is made up of a lens geometry, multiple input (or beam) ports, and numerous output (or array) ports, all of which are coupled to a radiating component in an antenna array through 'phase correction' lines. When any of the beam ports are activated by the lens, the array generates a slanted beam. The resultant beam can be scanned through the lens's field of vision by switching between input ports. A significant number of beam ports are necessary to achieve a high angular resolution between beams.

Traditional microwave networks may be able to afford equivalent attention and data rates with dense mmWave networks [97]. To create a big gain, advanced beam-forming methods that permit multiuser communication can be applied. For obtaining both huge DC output and wide angular coverage, a hybrid power combining technique that adjusts a beam-forming matrix was developed [98]. For beam scanning and power transmission applications, a 4×4 Butler matrix has been studied [99]. At mmWave frequencies, larger antenna arrays have been employed to achieve higher gain values [100]. To improve the output power of WPT applications, a beamforming network was investigated [101]. To provide concurrent multi-directional full-FoV power transfer, WPT with a scalable array-based passive beamforming technology was examined [102]. A 4×4 Butler matrix and a 1×4 rectifier array were used to make the rectenna. [103] tested various combinations of RF and DC power-combining techniques. The results show that (i) in the four beamforming with DC and RF combining approaches, the output DC power rises substantially as the total number of the antennas within a transmitter/receiver increases, (ii) for DC combining, the optimized beam-forming accomplishes a greater amount of DC energy than the beam forming using the singular value decomposition (SVD), (iii) for RF combining, the SVD-based general receive beamforming outperforms the analogous to obtain beamforming, and (iv) the commonly utilized DC combining technique has no effect on the overall turn-on sensitivity of the rectenna system. A detailed analysis on 5G millimeter wave rectenna systems were presented in [104-107].

VIII. SUMMARY

1. **RFEH/WPT Systems for Sub-6 GHz Bands Applications:** The performance comparison of different antenna configurations for the sub-6 GHz applications has been presented in tabular form in Table 2. It is understood that a bow-tie shape offers better gain, while the bandwidth is narrow. Slotted or partial ground-based structures help in achieving multi-resonance or broadband characteristics with a reason-given value.

Table 2: Performance analysis of 5G Sub-6 GHz antennas for RFEH systems

Ref.	Freq. (GHz)	Bandwidth (GHz)	Gain (dBi)
[11]	1.8/1.9/2.1/2.4/4.9/5.5	(1.53-2.47)/(4.90-5.63)	-
[12]	3.0-7.8	(3.0-7.8)	1.8
[13]	2.6/3.5	(2.62-2.69)/(3.3-3.8)	4.26/2.58
[14]	2.4/5.8	(1.9-2.8)/(3.9-6)	2.05/2.7
[15]	3.5	(3.17- 3.86)	8.6
[16]	1.8/2.6/3.5	(1.70-1.84)/(2.54-2.68)/(2.96-4.64)	6.41
[18]	-	(2.36-2.69)	3.0
[19]	2.1/2.4/3.5/5.8	(2.03-4.08)/(5.73-6.08)	-0.42/0.19/0.91/2.4

Table 3: Performance comparison of different rectifiers for sub-6 GHz 5G RFEH applications

Ref.	Freq. (GHz)	Diode/Transistor	Rectifier Type	Input Power (dBm)	PCE (%)	V_{out} (V)
[21]	0.86-1.96	CMOS	-	-14	10.0	1.0
[22]	2.6/3.5	HSMS285x	Greinacher	6.0	56.1/7.9	-
[23]	-	HMPS282X	Half Wave	27.8	59.0	-

Table 3 compares a few rectifier designs for the sub-6 GHz range that have been published in the available literature. The HSMS-285x family diodes have been proven to be appropriate for sub-6 GHz applications running at medium to high RF input levels. The effectiveness of various sub-6 GHz rectennas is compared in Table 4. According to [26-28], the overall size of the rectenna affects their gain values as well. At 3.5 GHz, higher antenna dimensions increase in gain value. We also see that the HWR has better PCE at low power supply levels.

Table 4: Performance comparison of different 5G rectenna systems for RFEH applications

Ref.	Freq. (GHz)	Volume (mm^3)	Gain (dB)	Type of Rectifier	Input Power (dBm)	PCE (%)	Output Voltage (V)
[24]	0.85	-	-	Half Wave	-17.6	57.4	-
[25]	0.85	295×295×1.6	4.96	Greinacher	−10	-	1.26
[26]	3.5	35×30×0.77	3.5	Half Wave	0	54.9	-
[27]	3.5	27.4×15.6×0.125	2.07	Voltage Doubler	0	43.5	0.93
[28]	3.5	24×24×0.1	1.51	Voltage Doubler	0	42.0	0.9
[29]	3.5/5.8	60×50×1.6	6.41/5.01	Half Wave	5	54.5/ 41.2	1.31/1.16
[30]	2.45/3.8/5.8	56×43×1.6	1.26/0.37/3.32	Half Wave	0	26.8/29.1/43.3	-
[31]	3.5/7.0	35×35×0.6	4.0/3.8	Half Wave	-	-	-

Table 5 compares the effectiveness of various rectenna systems at mmWave frequency. Hybrid and antipodal antenna configurations are constructed to have a wide impedance bandwidth. However, a hybrid system has a lower gain than an antipodal-based system. Table 6 lists a few papers on rectifier circuits for 5G mmWave. MA4E series diodes have been discovered to be suitable for mmWave frequencies. The effectiveness of several rectenna systems built for RFEH 5G mmWave applications is compared in Table 7. It should be mentioned that the HWR circuit is a highly recommended approach at high frequencies. Furthermore, a GFET-based rectenna improves PCE performance and output voltage.

2. RFEH Systems for mmWave Applications

Table 5: Performance investigation of 5G mmWave antennas for EH systems

Ref.	Freq. (GHz)	Bandwidth (GHz)	Gain (dBi)
[33]	60	(56-61)	10.8
[34]	24/40	(20.5–25.5)/(38-45)	-1.0/0
[35]	-	(15.9-19.7)/(22.5-34)	4.8/8.8
[36]	49.8/31.6/31.4/45.45	-	7.8/6.14/ 4.97/6.73
[37]	26/28	(20-30)	6.2/7.0
[38]	26	(25.5-28.1)	6.13

Table 6: Performance investigation of 5G mmWave rectifiers for EH systems

Ref.	Freq. (GHz)	Diode/Transistor	Rectifier Topology	P_{in} (dBm)	PCE (%)	V_{out} (V)
[39]	24/81	MA4E2038 MA4E1317	HWR	5.0	45.0	0.53
[40]	24/28/38	-	VDR	15.6	44.3/42.7/40.6	-

Table 7: Performance investigation of 5G mmWave rectenna for EH systems

Ref.	Freq. (GHz)	Dimension (mm^3)	Gain (dB)	Rectifier Topology	P_{in} (dBm)	PCE (%)	V_{out} (V)
[43]	71	-	-	Three-stage Inductor-peaked	5	8.0	-
[45]	35	21.7×22.6× 1.6	19	Half Wave	8.45	67.0	2.18
[46]	24	13×20×0.18	5.0	Half Wave	18	-	2.5
[47]	61	18.3×7.8× 0.12	13.3	Half Wave	0	49.3	0.05
[48]	36	4.5×4.5× 0.52	4.0	-	-	-	-
[49]	36	3.2×3.2×1.6	8.12	GFET	2.0	80.3	6.38
[50]	24.25	40×40×1.6	7.8	GFET	5.0	83.0	6.8
[54]	24	33×16×0.5	7.41	Voltage Doubler	10	12	1.7

3. WPT Systems for mmWave Applications

Table 8: Performance investigation of various 5G/mmWave antenna configurations for WPT applications

Ref.	Frequency (GHz)	Dimension (mm^3)	ε_r	Bandwidth (GHz)	Gain (dBi)
[55]	35	-	2.33	(33-41)	5.0
[56]	35	100.8×100.8×NS	2.87	-	0.65
[57]	35	20×20×0.63	2.2	(33.9-36.13)	2.4
[58]	60	9×6×0.504	3.2	(57.0-61.5)	2.6
[60]	30	60×60×1.5	2.33	(28-32)	-
[61]	24	20×33.6×1.143	2.2	(23.5-24.5)	16.8
[62]	26	0.59×0.75×0.034	1.95	(24.9-31.1)	8.2

Table 9: Performance assessment of 5G/mmWave rectifier configurations for WPT systems

Ref.	Frequency (GHz)	Diode/Transistor	Topology	P_{in} (dBm)	PCE (%)	V_{out} (V)
[64]	24	HSMS 2862	VDR	40	45	-
		DMK 2790		9	42	
		MA4E1317		20	68	
[66]	35	MA4E1317	HWR	2.5	50	2.92
[68]	28/38	MA4E1317	VDR	15	46/42	-
[69]	35/94	CMOS	-	15	36.5/21	0.7/0.5
[72]	28	MBD2057-E28X	HWR	0	0.23	0.22
[73]	24	-	Dickson Charge Pump	15	51	8.0

The performance of various antenna configurations designed for 5G mmWave WPT applications is illustrated in Table 8. The antennas offer better gain values with compact antenna dimensions. Because of their small size, the rectennas are suitable for integration with implantable devices.

Table 9 discusses the performance of various 5G mmWave rectifier circuits for WPT applications. A voltage-doubler rectifier using a DMK2790 diode exhibits better conversion efficiency over the VDR with other possible combinations of the rectifier circuit.

Table 10: Performance assessment of 5G/mmWave rectennas for WPT systems

Ref.	Freq. (GHz)	Gain (dB)	Diode	Rectifier Topology	P_{in} (dBm)	PCE (%)	V_{out} (V)
[76]	35	4.54	MA4E-1317	Half Wave	10	36	1.73
[77]	35/94	7.4/6.5	CMOS	FWR	29.3	53/37	0.38/0.29
[78]	24	6.8	MADS-001317	Half Wave	16	41	2.0
[79]	24/60	-	MA4E-1317	Half Wave	-	65.6	-
[80]	24	-	-	Voltage Doubler	23.2	47.9	-
[81]	25	-	MA4E2502L	Half Wave	8	17	-
[82]	24	2.6	MA4E-1317	Half Wave	19.5	24	0.6
[83]	35	17	MA4E-1317	Half Wave	18.8	63.8	4.61
[85]	24	-	MA4E-1317	Half Wave	15	35.2	-
[86]	94	1.85	MA4E-1310	Half Wave	20.2	38	-
[87]	35	7.74	MA4W1310	Half Wave	16	61.5	1.83
[89]	24	4.8	MA4E2054A	Half Wave	14	35	-
				Voltage Doubler	14	20	2.4
[90]	35	15	SMA1317	Half Wave	13	21	-
[91]	24	13	MA4E2054A	Half Wave	2.5	46	1.5
				Voltage Doubler		36	1.9
			SMS7621	Half Wave		25	1.1

				Voltage Doubler		20	1.4
[92]	35	15.2	-	Half Wave	19	67.0	4.0
[93]	60	2.6	HSMS 2850	2-stage VDR	30	-	1.447
[95]	35	14.7	MA4E1317	Half Wave	32	49.2	-
[96]	28	4.0	MA4E1317	Half Wave	23.89	55.5	-

The performance parameters of 5G mmWave rectenna systems for WPT applications are shown in Table 10. Because of their low junction capacitance value, MA4E-series diodes are found to be excellent for conversion operations at high working frequencies. At the identical input power level, an HWR design achieves the greatest achievable efficiency of conversion, while a voltage doubler topology achieves the highest output voltage [94, 96]. High input power levels are shown to be more efficient for mmWave rectenna systems than low input power levels. The analytical findings show that substantial gain values are attainable using mmWave communication frequencies.

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