

2.4 GHz Rectifier Antenna for Radiofrequency-based Wireless Power Transfer: Recent Developments, Opportunities, and Challenges

Muhammad Miftahul Amri*, Liya Yusrina Sabila

*Electrical Engineering Study Program, Faculty of Industrial Technology
Universitas Ahmad Dahlan
Kampus 4 UAD, Ringroad Selatan, Banguntapan
Bantul, DI. Yogyakarta, Indonesia*

Abstract

The use of radio frequency (RF) energy for wireless power transfer (WPT) has gained significant attention in recent years due to its potential for powering electronic devices without the need for wires or batteries. A key component of RF-based WPT systems is the rectenna, which converts RF energy into usable DC power. This article provides an overview of recent developments, opportunities, and challenges in the design of 2.4 GHz rectennas for RF-based WPT applications. We have searched major online libraries extensively for studies regarding the 2.4 GHz rectenna. As a result, 35 high-quality studies published between 2010 and 2023 were gathered. In the discussion section, we begin by presenting the basic principles of rectenna design and the key parameters that affect its performance, such as the antenna characteristics, rectifier capabilities, and nonlinearity properties of the rectifier. We then highlighted recent advancements in rectenna design, including novel approaches for improving efficiency and power transfer capability, such as the involvement of hybrid solar cell-rectenna structures, transistor-based rectifiers, and bridge rectifiers. Finally, the article concludes by identifying future opportunities, research directions, and open challenges in the design and optimization of rectennas for RF-based WPT, including the development of compact, low-cost, and high-performance rectennas for a wide range of applications. Overall, this article provides a comprehensive overview of the state-of-the-art of 2.4 GHz rectenna design for RF-based WPT and highlights the exciting opportunities and challenges for this rapidly growing field.

Keywords: 2.4 GHz, rectifier, antenna, rectifier antenna (rectenna), radiofrequency (RF), wireless power transfer (WPT), RF-based WPT, energy harvesting.

I. INTRODUCTION

In the last decade, there has been a massive increase in the number of IoT devices. Thanks to the rapid development of wireless communications technology, IoT devices promise ubiquitous connectivity to support everyday activity. It is expected that there will be 83 billion IoT devices in 2024, increasing from 35 billion devices in 2020 [1], most of which are low-power sensors and low-power communication devices. Unfortunately, the development in battery technology is still lacking behind. Although IoT devices only consume a relatively low amount of power, these devices still need a power source. However, due to the massive quantity, changing those IoT devices' batteries, even once in a while, are impractical (i.e., expensive and inefficient). To complete this difficulty, many of those IoT devices will be deployed in challenging areas (e.g., high altitude, high pressure, high-temperature areas), dangerous zone (war zone, infectious environment, high radiation/radioactive areas), and rural/remote regions, making the battery replacement is not feasible. To this

end, wireless power transfer (WPT) rises as a solution to charge the battery of the IoT devices [2] and even to power the battery-less IoT devices [3] directly.

Since the first proof of the WPT concept by Nikola Tesla in 1901, numerous techniques on WPT have been proposed. Among the most famous and widely used WPT techniques are the capacitive-based and inductive coupling-based WPTs. These techniques have been adopted in many applications, including electric vehicle chargers, electric toothbrushes, and mobile chargers. Capacitive coupling based WPT relies on the metal plate electrode to deliver the electric current to the user equipment (UE). In contrast, inductive coupling based WPT usually transfers the power through wire coils. Both these two techniques can be further developed using two resonant circuits (tuned circuits) to realize resonant capacitive coupling WPT and resonant inductive coupling WPT. In [4], the authors proposed a magneto dynamic coupling based WPT where the power is transmitted between two synced rotating armatures. The armatures are equipped with permanent magnets to generate a magnetic field. These three WPT techniques are among the near-field WPT methods that provide a high-power delivery rate (up to kW order [5]) and high-power transfer efficiency (up to 99 % [6]). However, due to the nature of the electromagnetic (EM) field, the techniques as mentioned above can only cover a very short power transfer range (i.e., in order of

* Corresponding Author.

Email: miftahulamri@ieeee.org

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centimeters [7] and several meters [8], [9]). It is obviously contradictory to the power requirement of IoT devices. As aforementioned, many IoT devices only need a small amount of power (i.e., in the order of μW to mW (See Table 1)). Moreover, due to its various location placement, a short-range WPT might be unusable.

Laser-based WPT offers a significantly longer WPT range than capacitive, inductive, and magnetic ones. However, laser-based WPT depends on the line-of-sight link between the power beacon and the user equipment. In addition, laser based WPT is vulnerable to atmospheric absorption and scattering by rain, fog, and clouds, causing up to 100% power transmission loss. Moreover, the laser transmission link and power level must be carefully designed to avoid radiation hazards.

Radiofrequency (RF)-based WPT, on the other hand, offers hundreds of meters of WPT range [10] and even in order of kilometers [11]. Thanks to the characteristic of the RF waves, the power can still be delivered in a non-Line of Sight (nLoS) condition. However, the wireless transmission level of RF-based WPT is usually constrained to ensure environmental safety. In 2017, the certification of the mid-field RF transmitter of wireless power was first issued by the Federal Communication Commission (FCC) [12]. Later, the FCC granted a license to an over-the-air (OTA) WPT system combining near-field and far-field methods in the 900 MHz carrier frequency in 2021 [12]. RF WPT system must also comply with the specific absorption rate (SAR) requirements. Many institutions (e.g., IEEE, ICNIRP), as well as governing bodies (e.g., Europe, Korea, Japan, US), have issued their own SAR standard (See Table 4).

RF-based WPT also suffers from a high loss over distance. Recent work on RF-based WPT only achieves 20.32% and 0.24% efficiency at distances of 0.5 and 5 meters, respectively [13]. The proposed system achieved a deliverable power of 3.67 mW at a 25 m distance [13]. Nevertheless, the deliverable power in that work is still enough to power the battery-less IoT camera. Hence, RF-based WPT is still considered a promising solution for future IoT networks despite its low power efficiency.

Another reason for utilizing RF-based WPT is that RF is currently used everywhere, ranging from cellular networks to wireless fidelity (Wi-Fi) networks. It is known that the conventional transmitter (e.g., the base station (BS) and Wi-Fi router) always radiates EM signals over time regardless the user's existence. Therefore, several works have investigated the possibility of harvesting energies from such EM waste. In 2015, researchers from the University of Washington proposed power over the Wi-Fi system, which enables batteries to trickle-charging. The researchers also demonstrated the proposed system's capability of powering battery-less cameras and temperature sensors using transmissions from Wi-Fi routers [14]. The power transmission to the battery-less camera and temperature sensor using the Wi-Fi signals can be conducted wirelessly at ranges of up to 20 feet. It was also demonstrated that the Wi-Fi signals could be employed to wirelessly trickle-charge nickel-metal hydride and

TABLE 1. POWER CONSUMPTION OF VARIOUS IOT DEVICES

| Source | Device Type | Power Consumption |
|--------|---------------------|-------------------|
| [18] | Smoke detector | 55 μW |
| [18] | Gas sensor | 5.12 mW |
| [18] | LED | 60 mW |
| [18] | Smartwatch | 31 mW |
| [18] | WiFi flash memory | 210 μW |
| [18] | CO sensor | 1.5 mW |
| [19] | Wearable device | 60 μW |
| [20] | Surveillance camera | A few mW |

lithium-ion coin-cell batteries at distances of up to 28 feet.

Again, low efficiency still needs to be improved in the RF-based WPT. Many authors have investigated methods to improve WPT efficiency. These techniques include the high-efficiency rectifier design [15], high-gain antenna design [16], and even the involvement of reconfigurable intelligent surfaces (RIS) [17]. This article briefly reviews the recent development in 2.4 GHz rectifier antenna (rectenna) research, along with its opportunities and challenges. The frequency band of 2.4 GHz is usually chosen since this frequency is within the ISM band and has been broadly used in the current wireless network (including Wi-Fi). Hence, lots of work on the 2.4 GHz WPT have been done in the last decade. The review is derived from the recent high-quality original research articles, meta-analyses, and selected survey-review papers related to the 2.4 GHz rectenna.

In summary, the contributions of this paper are twofold:

1. We comprehensively present the recent trends and advancement of the 2.4 GHz rectenna development, particularly for the RF-based WPT application. While many existing 2.4 GHz rectenna works exist, the number of comprehensive reviews of the mentioned topic is still needs to be enriched.

2. We briefly discussed the challenges and opportunities of the 2.4 GHz rectenna design for RF-based WPT applications.

Finally, the rest of this article is organized as follows. In Section II, we present the method of this study. Section III presents the results of the study. In Section IV, we present discussions related to 2.4 GHz rectenna. We discussed the reason why 2.4 GHz is preferred in the WPT system. We also discussed the classic challenges of RF WPT, followed by the discussion on the existing 2.4 GHz rectenna design and the challenges in rectenna design (linearity, bandwidth, power limit, and efficiency). We closed the discussion section with the rectenna design metrics consideration (efficiency, bandwidth, gain, and SAR) and the opportunities and path ahead of the 2.4 GHz rectenna for WPT applications. Lastly, Section V presents the conclusion of the study.

II. METHODOLOGY

This article aims to summarize and present the recent development of the 2.4 GHz rectenna for radio frequency-based wireless power transfer applications. In addition, we discuss the present challenges and the attempts that have been conducted to overcome those. We also present a comprehensive discussion on the future opportunities of 2.4 GHz rectenna, particularly in its application for RF-based WPT purposes. This review

was derived from recent high-quality original research papers, meta-analyses, systematic reviews, and selected literature. We extensively searched major libraries such as Springer, IEEE, ACM, MDPI, Nature, and Elsevier for articles related to the 2.4 GHz rectenna for writing this short narrative review. The following keywords were used in the search strategy: radio frequency (RF), wireless power transfer (WPT), 2.4 GHz, and rectifier antenna (rectenna). We did not use Boolean operators (e.g., AND, OR, NOT, etc.). Instead, we included all articles which contain one or more of the keywords as mentioned earlier. We limit the language of search to English. There were no limitations on when the study was conducted [and was published]. As this review is intended only as a narrative one, we manually choose the most appropriate articles describing the recent advancement of 2.4 GHz rectenna, especially in the RF-based WPT area. As a result, 35 published articles were gathered. Published research studies of any type were considered in this paper. However, unpublished data, commentary, opinion articles, and technical notes were excluded.

III. RESULTS AND DISCUSSION

In this article, we have gathered 35 published articles related to the rectenna development on the 2.4 GHz frequency band. We have included articles with experimental validations and excluded articles with only simulation results. The articles were published between 2010 and 2020. Specifically, four articles were published in 2010, 1 article in 2011, 7 in 2012, 5 in 2013, 2014, and 2015, 2 in 2016, and 1 in 2017, 2018, 2019, 2020, 2021, and 2023. Most of the published articles used Schottky Diode as the rectifier component. The collected articles managed to achieve efficiency between 18% and 97.5%. In Table 2, we have presented the summary of the selected studies.

A. Why is the 2.4 GHz Frequency Band preferred in RF-based WPT Applications?

Previous studies have indicated that the 2.4 GHz frequency band is popular for researchers working on RF-based WPT applications. This is mainly due to three reasons. First, the 2.4 GHz frequency band is unlicensed and falls within the industrial, scientific, and medical (ISM) band, meaning that it is available for public use without needing a formal license. This makes it easy for researchers to experiment and test RF-based WPT systems without costly licenses or permissions.

Second, 2.4 GHz has a relatively low absorption rate in most materials, so it can easily penetrate walls and other obstacles. This makes it an ideal frequency band for WPT systems that probably need to transfer power through walls or other obstacles, such as buildings or vehicles. Although higher frequency bands (i.e., sub-6 GHz, 10 GHz, mmWave, and even sub-THz) are preferred for future wireless communications, the path loss and attenuations in those frequencies are often too severe for WPT applications. Moreover, the devices' costs and complexities in such bands are arguably too high for WPT applications. Indeed, previous attempts have been conducted to deploy WPT in lower frequency bands, such as 13.56 MHz [56] and 915 MHz [57]. In

[58], [59], the authors have designed and fabricated a 920 MHz transmitting system comprised of 64 phased array antennas. In [58], the authors demonstrated a maximum output power of 100 W, achieving a maximum power transfer efficiency at 10% for 15 meters distance of WPT. Similar work has been conducted in [59], which realized outdoor RF WPT transmission for up to 50 meters. This work demonstrated the WPT capability to keep alive a sensor device by only using the power received through WPT. The authors achieved 1mW received power at a distance of 50 meters using 11 W of transmitted power. Due to the low-frequency bands, the transmit antenna needed for WPT in both works is considerably large, making the works arguably less practical. Hence, at the current moment, 2.4 GHz is ideal for RF-based WPT applications, considering the costs, complexities, and practicalities factors. Moreover, the 2.4 GHz frequency band has a relatively wide bandwidth, which means that it can support multiple channels and multiple devices simultaneously, which is essential for certain WPT applications (e.g., charging multiple devices simultaneously).

Device compatibility is the third reason. The 2.4 GHz frequency band is widely used in many wireless technologies, such as Wi-Fi, Bluetooth, and Zigbee. This means that a lot of existing knowledge and expertise is available for researchers working on RF-based WPT systems in this frequency band. Additionally, it can leverage the existing wireless infrastructure and easily integrate with other devices operating in the same frequency band.

B. Classic RF WPT Challenges: Limited Power Level & Very Low Efficiency

RF-based WPT is a technology that allows transferring electrical energy from a power source to a device without the need for physical connections such as wires or cords. While RF-based wireless power transfer has the potential to revolutionize the way we charge and power our devices, it also presents several challenges. One of the main challenges of RF-based wireless power transfer is efficiency [21], [22]. RF-based systems typically have lower efficiency than other wireless power transfer technologies, such as inductive coupling and resonant energy transfer.

Another challenge of RF-based wireless power transfer is distance limitations [13]. The distance over which power can be transferred wirelessly using RF technology is typically limited. Due to the nature of radiofrequency, the power transferred decreases with the square of the distance. This attenuation issue is caused by propagation loss. This means that as the distance between the power source and the device receiving the power increases, the amount of power that can be transferred decreases. This can be a major issue for systems that require power to be transferred over long distances, such as electric vehicles or drones. Together with the device design factor, this issue has

TABLE 2. SUMMARY OF THE SELECTED STUDIES

| Ref No | Year | Antenna Type | Rectifier Component | Gain | Efficiency | Power/Voltage | |
|--------|------|---|--|----------------|---------------|------------------------------|-----------|
| | | | | | | Input | Output |
| [21] | 2015 | Dual-polarized suspended square-shaped antenna | Schottky Diode (SMS-7630) | 8 dBi | 25.98% | 200 mW | 1.57 V |
| [22] | 2014 | 2×3 patch antenna array | Schottky Diode (SMS-7630) | N/A | 36% | 5 μW/cm ² | 1.4 V |
| [23] | 2012 | Antenna with shorted annular ring-slot | Schottky Diode (HSMS-2850) | 5.25 dB | 69% | 10 μW/cm ² | 1.1 V |
| [24] | 2012 | Microstrip patch antenna | Schottky Diode (HSMS-282) | N/A | N/A | 2 dBm | 1 V |
| [25] | 2013 | GCPW-fed slot antenna | Schottky Diode (HSMS-2862) | 10 dBi | 72.5% | 34 dBm | 13 dBm |
| [26] | 2012 | T-shape slot dual CP patch antenna | Schottky Diode (HSMS-282) | 8 dBic | 78.45% | 24 dBm | N/A |
| [27] | 2014 | 3×3 CP array antenna | Schottky Diode (HSMS-2820) | 9.14 dBi | 65.8% | 20 dBm | 7.02 V |
| [28] | 2016 | Stacked patch antenna | Schottky Diode (HSMS-2850) | 5 dBi | 63% | 0 dBm | N/A |
| [29] | 2012 | Miniaturized tag antenna | NMOS Bridge | 6.5 dB | 75% | 0 dBm | 560 μW |
| [30] | 2010 | Square aperture coupled patch antenna | Schottky Diode (SMS-7630) | 8.25 dB | 38.2% | 1.5 W/cm ² | N/A |
| [31] | 2016 | Dual CP antenna | Schottky Diode (HSMS-2860) | 7.63 dBi | 78% | 295.3 μW/cm ² | N/A |
| [32] | 2011 | 2×2 planar antenna array | Schottky Diode (HSMS-2852) | 4.5 dBi | 70% | 1 W | N/A |
| [33] | 2012 | SP4T switch-integrated structure antenna | Schottky Diode (HSMS-2860, HSMS-2820) | N/A | 50% | 0 dBm | 2.1 V |
| [34] | 2013 | Microstrip dipole antenna | Schottky Diode (MA4E1317, MZBD9161, MA40150-119) | 3.5, 2.5, 3 dB | 82%, 60%, 70% | N/A | N/A |
| [35] | 2019 | Solar Cell Rectenna - Antenna Array (SCR-AR) | Schottky Diode (SMS-7630) | 6.24 | 18-32% | N/A | N/A |
| [36] | 2010 | LP microstrip patch antenna | Bridge Rectifier (4 × Schottky Diode, non-disclosed) | 4.7 dB | 52% | 10 dBm | 12.6 mW |
| [37] | 2017 | Dipole antenna (rectangular section) | Schottky Diode (HSMS-276) | 2.2 dB | 95.7% | 12.9 dBm | 4.5 V |
| [38] | 2015 | Inductive feed folded dipole | Schottky Diode (SMS-7630) | 7.5 dB | 30% | 1 μW/cm ² | 18.2 μW |
| [39] | 2020 | Microstrip harmonic-rejecting circular sector antenna | Bridge Rectifier (4 × Schottky Diode) | 2.1 dBi | 91.1% | 32 dBm | N/A |
| [40] | 2016 | Rectangular radiation patch | Schottky Diode (HSMS-2862) | N/A | 75% | 19 dBm | 5.2 V |
| [41] | 2015 | Differentially fed-patch antenna | Schottky Diode (HSMS-2860) | 5.47 dBi | 73.9% | 207 μW/cm ² | N/A |
| [42] | 2013 | N/A | MOSFET & Schottky Diode (non-disclosed) | N/A | 60% | 82 mW | N/A |
| [43] | 2010 | LP patch antenna | 2 × Schottky Diode (HSMS-2860, non-disclosed) | 6.2 dB | 83% | 10 dBm | 3.1 V |
| [44] | 2012 | Dual LP patch antenna | Schottky Diode (SMS-7630) | 6 dB | 54% | up to 200 μW/cm ² | 0.1 W |
| [45] | 2023 | Dual-band circular monopole array | Schottky Diode (SMS-7630) | 6.6 dBi | 67.29% | 0 dBm | 1.39 V |
| [46] | 2014 | Dual CP patch antenna | Schottky Diode (HSMS-282) | 7.9 dBic | 82.3% | 0.158 W | 11.42 V |
| [47] | 2013 | Half-wave dipole antenna | Schottky Diode (HSMS-2852) | N/A | 75% | 7.5 mW/cm ² | N/A |
| [48] | 2010 | Cross-shaped slot-equipped square coupled patch antenna | Schottky Diode (SMS-7630) | 7.5 dB | 42.1% | -10 dBm | +90mV |
| [49] | 2014 | Linearly polarized PBG antenna | Schottky Diode (HSMS-286) | 4.29 dBi | 63% | 18 dBm | 1.8 V |
| [50] | 2013 | Microstrip dipole antenna | Schottky Diode (HSMS-282) | 5.2 dBi | 67.6% | 20 dBm | 7.1 W |
| [51] | 2014 | Microstrip patch antenna | Schottky Diode (HSMS-2820) | N/A | 40.1% | 24 dBm | 4.71 V |
| [52] | 2015 | Double-sided planar rectenna | Schottky Diode (non-disclosed) | 9 dBi | 70% | 50 μW/cm ² | 2 V |
| [53] | 2018 | Rectangular patch antenna | Schottky Diode (HSMS-2820) | 5.6 dBi | 97.5% | N/A | -57.3 dBm |
| [54] | 2012 | Microstrip antenna | N/A | 3.6 dBi | 37.8% | 25 dBm | 2.76 V |
| [55] | 2021 | Microstrip patch antenna | Schottky Diode (non-disclosed) | 5 dB | 41% | -10 dBm | N/A |

GCPW: Grounded Coplanar Waveguide

CP: Circular Polarization

LP: Linear Polarization

become the main reason behind the low efficiency of RF-based WPT.

In the higher frequency bands, the attenuation due to the path loss and the shadowing is expected to be more severe [17]. While higher frequency bands offer a better capability of delivering a higher power transfer level, the attenuation factor shall also be considered. Thus, frequency selection is a crucial factor in the RF WPT implementation.

Interference is another challenge of RF-based wireless power transfer [60], [61]. RF-based systems can be affected by interference from other RF sources, such as radio and television stations. This can cause the system to malfunction or efficiency. This can be a major

issue in densely populated areas with many RF sources nearby.

Safety is also a concern with RF-based wireless power transfer [62]. There are concerns about the potential health effects of exposure to RF radiation, although current research suggests that the levels of RF radiation emitted by wireless power transfer systems are generally safe as long as it complies with the safety regulation standards (e.g., SAR standard). However, more research is needed to fully understand the potential health effects of long-term exposure to RF radiation. In addition, this issue has led to people's reluctance to adopt WPT technology. Many people are afraid of the health risks caused by WPT radiation. Hence, active socializations emphasizing the safety of the WPT

technology shall be conducted to increase the confidence of the WPT adopters.

Lastly, as mentioned above, device design has become one of the main factors behind the low efficiency of RF-based WPT [63]. A good design of WPT devices (e.g., rectifier, antenna, rectenna) will improve the WPT efficiency. In this work, we will comprehensively discuss the design factor of WPT devices, particularly for the rectenna design.

In summary, RF-based wireless power transfer presents several challenges, including efficiency, distance limitations, interference, and safety. While these challenges may seem daunting, ongoing research and development are aimed at addressing these challenges and improving WPT technology.

C. Existing Rectenna Design: Which Approach is the Best Rectenna Design Approach?

Generally, the rectenna system consists of the receiving antenna, matching network, filter, and rectifier circuit (see Figure 1). When the antenna captures the incoming RF waves, the waves will go through the matching network (typically 50Ω). The signal is then passed through the filter before being converted into DC power by the rectifier component. This DC power is then stored in the storage element (e.g., supercapacitor, battery) before being depleted by the load.

As presented in Table 2, there are many 2.4 GHz rectenna designs exist, ranging from microstrip antennas, dipole antennas, and array antennas to slot antennas. In terms of polarization, some of the existing rectenna utilizes circular polarization (CP), linear polarization (LP), and dual polarization. However, to the author's knowledge, none of the 2.4 GHz rectenna has managed to reach the commercialization stage, meaning that currently, the rectenna design is still in the research stage, and no rectenna design has been declared 'sufficient' to be marketed.

At this stage, it is rather challenging to assess and decide which rectenna design approach is best. This is due to many reasons. First, there was no standardized measurement setup. Therefore, the measurement setup of the existing studies varies greatly. This factor makes an apple-to-apple performance comparison between one another difficult to conduct. For instance, one study might test their proposed rectenna under a certain transmission distance (e.g., in the order of meters). In contrast, the other tested their rectenna in the centimeters distance or even no distance at all (wired connection).

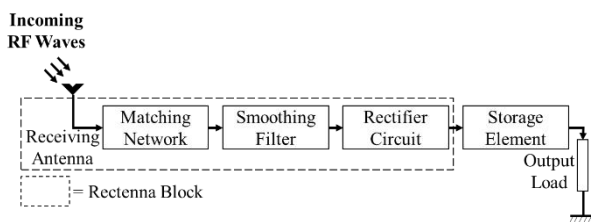


Figure 1. Block diagram of RF energy harvester system utilizing rectenna device.

Having no standardized measurement setup also resulted in different available performance metrics. As observed in Table 2, some studies included complete metrics (i.e., gain, efficiency, and power), while the others did not include all of them. There were many other metrics that we did not present in Table 2 since only a few studies have them. These metrics include insertion loss, directivity, and bandwidth. Even if all studies include complete performance metrics, due to the variation of the performance metrics (and the tradeoff between them), it is rather difficult to evaluate which values are considered 'balanced' and to what extent certain parameters can be compromised. This challenge will only be more difficult since not all studies include all performance metrics.

Lastly, not all studies used the same method to assess their performance characteristics. As observed in Table 2 (column Power/Voltage), some studies used actual power units (dBm or W), while others used power density units (W/cm^2) to measure the input value. Similarly, the unit of the output value varies between dBm and W to V. To add the complexity, every study used different loads. To measure the efficiency, some studies measured RF to DC (end to end) efficiency while others split the efficiency measurement into two different values: RF to RF and rectifier efficiency.

Further, the rectifier component selection variation adds to the performance comparison difficulty. In the WPT research area, it is well known that the rectifier nonlinearity caused significant problems since a long time ago and has not been solved to this date. For instance, depending on the nonlinearity curve, different frequencies and input power will result in different efficiency. Typically, the nonlinearity characteristics of the rectifier (e.g., Schottky diode) have been included in the diode's datasheet. In this work, all selected studies designed their rectenna to work at 2.4 GHz (although several studies proposed dual-band or wideband rectenna), causing frequency-dependent nonlinearity to no longer be a problem. However, the combination of different input power, loads, and rectifier component among the selected studies make the already tough performance analysis more difficult (e.g., due to the nonlinearity).

Due to the factors as mentioned above, in this subsection, instead, we would like to present several rectenna design paradigms summarized from the selected studies. This subsection also presents the Table of the rectifier components used (see Table 3) and their efficiency result. Although, it should be noted that the presented data does not necessarily translate into the rectifier components' performance (i.e., due to the nonlinearity and different experiment setup).

1) Rectenna Design

a) Microstrip Patch Rectenna

Microstrip patch rectenna is among the most used designs for 2.4 GHz rectenna. In [24], a 2.4 GHz rectenna comprising of a combination of a microstrip patch antenna, stepped impedance filter, and zero-biased rectifier is proposed. The authors in [51] demonstrated their microstrip patch rectenna capability in achieving

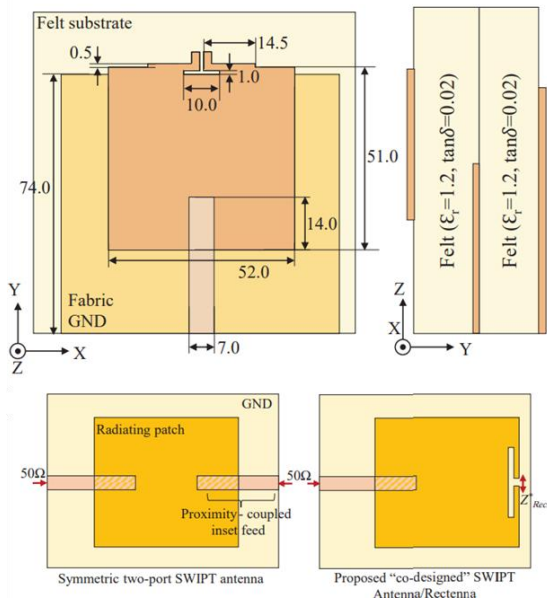


Figure 2. Layout and dimensions (in mm) of the proposed SWIPT microstrip patch rectenna [55].

40.1% efficiency. In [54], the authors achieved a 3.6 dBi antenna gain with 37.80% WPT efficiency using a microstrip rectenna.

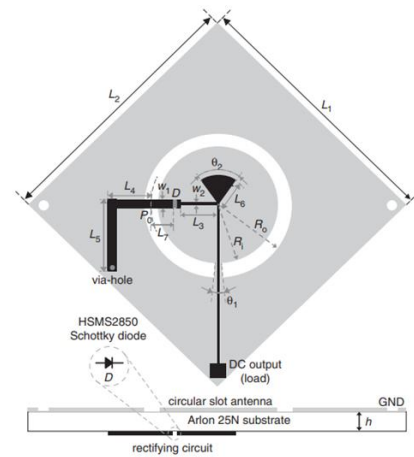
The authors of [55] proposed a 2.4 GHz wearable textile antenna/rectenna for Simultaneous Information and Power Transfer (SWIPT) with microstrip rectenna structure. They achieved 8.9 dBi measured directivity and 41% efficiency at 2.4 GHz. Their proposed rectenna design is depicted in Figure 2.

b) Slot Rectenna

In 2012, the authors of [26] proposed a 2.4 GHz T-shape slot dual CP patch rectenna. This rectenna is designed with circular polarization and equipped with Schottky Diode HSMS-282C. Their proposed rectenna achieved 8 dBi gain with 78.45% efficiency when 24 dBm input power was used. Another 2.4 GHz slot rectenna with an identical Schottky diode (i.e., HSMS-282C) has been proposed in [25]. The authors employed a GCPW-fed slot antenna and achieved a 10 dBi gain with 72.5% WPT efficiency. In [23], the authors proposed a rectenna with shorted annular ring-slot (See Figure 3) equipped with Schottky diode HSMS-2850 as the rectifier element. The proposed design achieved an efficiency of 69% and 1.1 V DC voltage output when a 2500 Ω resistive load at 20 mW/cm² power density was employed.

c) Rectenna Array

Several authors have attempted to design a rectenna array to enhance the antenna gain and efficiency. In [22], the authors proposed a 2 \times 3 patch rectenna array and obtained 36% efficiency under 5 μ W/cm² power density. In 2014, a 3 \times 3 circular polarization array rectenna achieved an impressive 9.14 dBi gain while obtaining 65.8% efficiency when exposed to a 20 dBm illumination [27]. Figure 4 depicts the design of the proposed rectenna. Further, the authors of [32], with their 2 \times 2 planar rectenna array, obtained an even higher



$L_1 = 95$, $L_2 = 95$, $L_3 = 10.1$, $L_4 = 15.5$, $L_5 = 27.3$, $L_6 = 10.4$, $L_7 = 7.9$, $w_1 = 3.5$, $w_2 = 1$, $R_1 = 21.5$, $R_0 = 26.5$, $h = 1.524$, $\theta_1 = 58$, $\theta_2 = 868$ (dimension in mm)

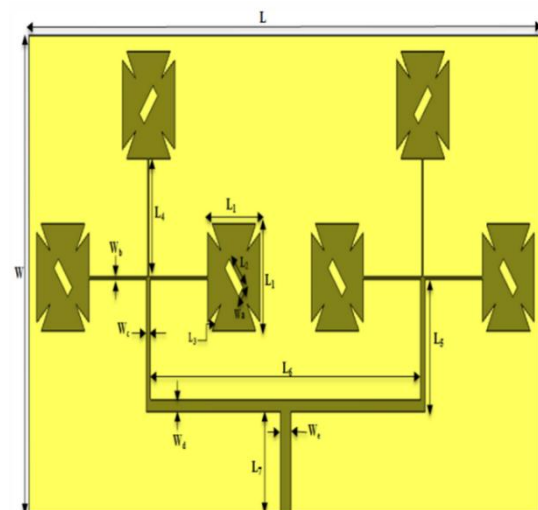
Figure 3. Layout and dimensions (in mm) of the proposed shorted annular ring-slot rectenna [23].

efficiency of 70% under 1 W input power but with a significantly lower antenna gain of 4.5 dBi.

d) SP4T Switch-integrated Rectenna

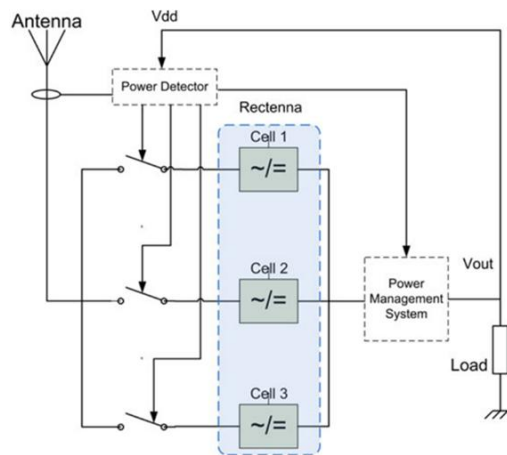
The authors in [33] proposed an unconventional approach where a Single Pole Four Throw (SP4T) switch is integrated into the rectenna structure. By using the SP4T switch, a reconfigurable rectenna was realized. This tunable rectenna can switch between the three possible rectenna circuits according to the rectenna handling capabilities. This approach is proposed to handle various power levels, which has been a tough problem in the RF WPT application (i.e., due to the rectifier nonlinearity)

This work proposed three rectenna topologies (i.e., series-mounted diode, shunt-mounted diode, and bridge rectifier). Each topology is proposed to handle low power levels (<1 mW or 0 dBm), medium power levels (1-100 mW or 0-20 dBm), and high-power levels (>100 mW or 20 dBm). The proposed topologies are presented in Figure 5.

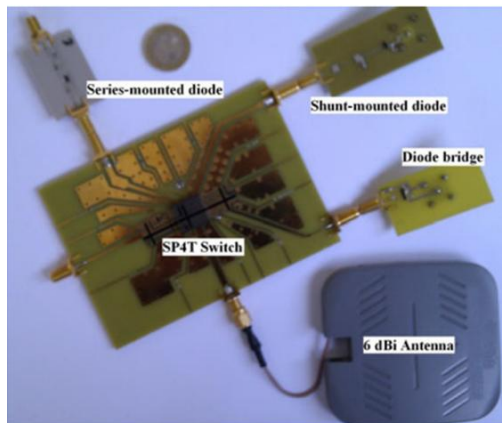


$W = 118$, $W_a = 3.3$, $W_b = 0.704$, $W_c = 2.123$, $W_d = 3.044$, $W_e = 5.12$, $L = 261.8$, $L_1 = 26.52$, $L_2 = 10$, $L_3 = 8$, $L_4 = 29.29$, $L_5 = 33.04$, $L_6 = 137.8$, $L_7 = 33.04$ (dimension in mm)

Figure 4. Layout and dimensions (in mm) of the proposed 3 \times 3 circular polarization array rectenna [27].



(a)



(b)

Figure 5. Proposed SP4T switch-integrated rectenna [33]. (a) Schematic. (b) Actual prototype.

e) Solar Cell Rectenna

The authors in [35] have proposed an interesting approach. The authors proposed a combination of rectenna and solar cells to harvest power from two different types of energy sources (i.e., RF and solar beam) in a complementary manner. As presented in Figure 6, the authors proposed a coplanar antenna array integrated with multi-crystalline solar cells. The rear terminals (aluminum) act as radiators for the antenna array. The antenna managed to achieve 6.24 dBi gain and 8.81 dBi directivity. In terms of efficiency, the proposed system managed to measure 18-32% efficiency under a 3.3k Ω load.



Figure 6. Solar cell rectenna array (SCR-AR) prototype [35].

2) Rectifier Component Selection

As can be seen in Table 2, there was various range of rectifier components used in previous studies. In Table 3, we summarized the type of the rectifier component and the efficiency of the studies using the corresponding rectifier components. Note that the presented data does not necessarily translate into the rectifier components' performance. This is mainly due to the nonlinearity properties, different experiment setups, and the rectenna design. Therefore, Table 3 is intended only to provide an insight into the overall performance of the rectifier components rather than to provide an accurate performance indicator of those components.

As in Table 3, it is observed that most of the rectenna studies used a single Schottky diode as the rectifier component of their proposed rectenna design. There were no significant differences in the average efficiency between one and another Schottky diode. Future research investigating the performance of the diodes under a fair apple-to-apple environment is desired to provide a clear view of the diode performance in the WPT application.

Several studies attempted different approaches in rectifier component selection. For instance, studies [36] and [39] used bridge rectifiers comprised of 4 Schottky diodes. In [42], the authors combined MOSFET and Schottky diode for the rectifier component. The authors of [43] attached two Schottky diodes in their rectenna design.

TABLE 3. SUMMARY OF THE RECTIFIER COMPONENTS VARIATIONS ALONG WITH THE EFFICIENCY

| Total Studies | Rectifier Component | Efficiency | | |
|---------------|---|------------|-------------|---------|
| | | Minimum | Maximum | Average |
| 8 | Schottky Diode (SMS-7630) | 18% [35] | 67.29% [45] | 41.94% |
| 1 | Schottky Diode (HSMS-276C) | 95.7% [37] | 95.7% [37] | 95.7% |
| 2 | Schottky Diode (HSMS-2850) | 63% [28] | 69% [23] | 66% |
| 3 | Schottky Diode (HSMS-2860) | 50% [33] | 73.9% [41] | 67.3% |
| 4 | Schottky Diode (HSMS-2820) | 40.1% [51] | 97.5% [53] | 67.8% |
| 4 | Schottky Diode (HSMS-282) | 67.6% [50] | 82.3% [46] | 76.12% |
| 2 | Schottky Diode (HSMS-2862) | 72.5% [25] | 75% [40] | 74% |
| 2 | Schottky Diode (HSMS-2852) | 70% [32] | 75% [47] | 72.5% |
| 1 | Schottky Diode (HSMS-286) | 63% [49] | 63% [49] | 63% |
| 1 | Schottky Diode (MA4E1317) | 82% [34] | 82% [34] | 82% |
| 1 | Schottky Diode (MZBD9161) | 60% [34] | 60% [34] | 60% |
| 1 | Schottky Diode (MA40150-119) | 70% [34] | 70% [34] | 70% |
| 1 | 2 \times Schottky Diode (HSMS-2860) | 83% [43] | 83% [43] | 83% |
| 2 | Bridge Rectifier (4 \times Schottky Diode, non-disclosed) | 52% [36] | 91.1% [39] | 72% |
| 1 | MOSFET & Schottky Diode (non-disclosed) | 60% [50] | 60% [50] | 60% |
| 1 | NMOS Bridge | 75% [29] | 75% [29] | 75% |

As has been mentioned multiple times in this article, rectifier nonlinearity is a challenging issue in WPT that is difficult to solve. The authors of [33] proposed a clever idea to mitigate this issue by employing three different rectifier structures (i.e., series-mounted diode, shunt-mounted diode, and bridge rectifier). Thus, the rectenna can be tuned by selecting the appropriate rectifier circuit depending on the received signal power.

The authors in [29] have proposed a completely different approach. In that study, an NMOS bridge, instead of a Schottky diode, is employed as the rectifier component. Generally, transistors such as NMOS have a lower forward voltage drop compared to diodes, which can result in higher conversion efficiency. However, transistors may also have higher parasitic capacitance, which can limit their performance at high frequencies. Nevertheless, the proposed system achieved 75% WPT efficiency under 0 dBm input power.

D. Challenges in Rectenna Design for RF WPT Applications: Linearity, Bandwidth, Power Limit, and Efficiency

Wireless power transfer (WPT) using radio frequency (RF) technology has the potential to revolutionize the way we charge and power our devices. However, the rectenna design, which is responsible for converting the RF signals into DC power, poses a significant challenge for RF WPT applications. In this subsection, we will discuss some of the main challenges in rectenna design for RF WPT applications and their implications.

One of the main challenges in rectenna design for RF WPT applications is the tradeoff between efficiency and bandwidth [63]. Efficiency refers to the amount of power that is successfully converted from RF to DC, while bandwidth refers to the range of frequencies over which the rectenna can operate effectively. A rectenna with a wide bandwidth may not be as efficient as one with a narrow bandwidth, and vice versa. This tradeoff can make it challenging to design a rectenna that is both efficient and has a wide bandwidth.

Another challenge in rectenna design for RF WPT applications is the tradeoff between efficiency and size. A rectenna with a large size may result in higher WPT efficiency than one with a small size [60], [63], but it may also be more expensive and less practical for certain applications [60], [63]. On the other hand, a rectenna with a small size may be less efficient, but it may be more practical and cost-effective for certain applications.

A third challenge in rectenna design for RF WPT applications is the tradeoff between efficiency and power handling capabilities [63]. A rectenna with high efficiency may not be able to handle large amounts of power, while one with high power handling capabilities may not be as efficient. This tradeoff can make it challenging to design a rectenna that can handle large amounts of power while also being highly efficient.

A fourth challenge in rectenna design for RF WPT applications is the tradeoff between efficiency and robustness [63]. A rectenna with high efficiency may be fragile and unsuitable for harsh environments, while one

with high robustness may not be as efficient. This tradeoff can make it difficult to design a rectenna that is both highly efficient and robust.

The nonlinearity properties cause another challenge in rectifier design. Nonlinearity challenges in rectenna design arise when the RF signal is too strong, causing the rectifying circuit to behave nonlinearly. This results in harmonic distortion, intermodulation distortion, and other unwanted effects that can degrade the efficiency and performance of the rectenna. One major challenge is designing a rectifying circuit that can handle high input power levels without introducing significant nonlinear distortion. Additionally, the nonlinear behavior of the rectenna may vary with the frequency, amplitude, and phase of the input signal, which requires careful optimization of the circuit parameters to achieve high efficiency over a wide range of operating conditions. Overall, designing a rectenna that can operate efficiently in the presence of nonlinear effects is a complex task that requires a deep understanding of RF circuit design and electromagnetic theory.

In conclusion, rectenna design for RF WPT applications poses several challenges, including the tradeoffs between efficiency and bandwidth, size, power handling capabilities, robustness, and nonlinearity characteristics. These challenges can make it difficult to design a rectenna that is efficient and practical for a wide range of applications. Ongoing research and development aim to address these challenges and improve the WPT technology.

E. Metrics Consideration in Rectenna Design and RF-based WPT: Efficiency, Bandwidth, Gain, and SAR

1) Efficiency

Efficiency is among the most important metrics in evaluating the performance of the rectenna. Generally, the efficiency of RF-to-DC conversion in a rectenna circuit (η) can be calculated as follows:

$$\eta = \frac{\text{Harvested DC Power}}{\text{Input RF Power to Rectifier}} = \frac{P_{DC}}{P_{Rx}} \times 100\%, \quad (1)$$

where the P_{Rx} can be obtained using the well-known Friis equation:

$$\frac{P_{Rx}}{P_{Tx}} = \left(\frac{A_{Tx}A_{Rx}}{d^2\lambda^2} \right) = G_{Tx}G_{Rx} \left(\frac{\lambda}{4\pi d} \right)^2. \quad (2)$$

In (2), P_{Tx} is the power fed into the transmit antenna terminal, P_{Rx} is the power available at the receiver terminal. A_{Tx} and A_{Rx} are the effective aperture area of the transmit and the receive antenna, respectively. d is the transmission distance between antennas, λ denotes the wavelength of the radio frequency, and G_{Tx} and G_{Rx} , respectively, is the gain of the transmit and the receive antenna.

The power level P_L of RF-based WPT can be obtained simply by the multiplication of the load voltage V_L and the load current I_L as [64], [65]:

$$P_L = V_L \times I_L. \quad (3)$$

Practically, the calculation in (1) is naïve and usually does not depict the actual value. The nonlinear characteristics of the Schottky diodes complicate the η calculation via analytical means. Generally, η in most rectifier circuits changes with RF input power, impedance matching, frequency band, and the diode properties themselves (i.e., temperature bias, diode parasitic, breakdown voltage, etc.). The authors in [66] proposed a more accurate model to estimate η by:

$$\eta = \frac{V_D I_{OUT}}{\frac{1}{T} \int_0^T V_{IN}(t) i_D(t) dt}, \quad (4)$$

where T is the input RF signal period, $V_{IN}(t)$ is the rectifier's input voltage, $i_D(t)$ denotes the current flowing through the diode terminals, V_D is the voltage on the DC load, and I_{OUT} is the current flowing through the load ports.

2) Bandwidth

Antenna bandwidth is another important factor that needs to be considered in the rectenna design. Typically, wider bandwidth will result in smaller efficiency and vice versa. Thus, one shall consider this tradeoff and maintain the balance between the bandwidth and the efficiency while maximizing both values. The bandwidth of the rectenna (BW) can be obtained as:

$$BW = 100 \times \left(\frac{F_H - F_L}{F_C} \right), \quad (5)$$

where F_H is the upper frequency, F_L is the lower frequency, and F_C is the carrier frequency. Rectenna bandwidth is typically quoted in terms of voltage standing wave ratio (VSWR), which is expressed as:

$$VSWR = \frac{1+|\Gamma|}{1-|\Gamma|}, \quad (6)$$

where Γ is the reflection coefficient of the rectenna.

3) Gain

Generally, a rectenna is a combination between the rectifier and the antenna. Analogous to the antenna design, the gain parameter is one important factor to be considered in the rectenna design. Generally, one would want to maximize the rectenna gain while maintaining sufficiently high efficiency. The rectenna gain can be calculated as follows:

$$G(\text{dB}) = 10 \log_{10} \left(\frac{4\pi\eta A}{\lambda^2} \right), \quad (7)$$

where $G(\text{dB})$ is the rectenna gain in dB, η is the radiation efficiency, A is the physical aperture area of the rectenna, and λ is the radio frequency wavelength.

4) Specific Absorption Rate (SAR)

Although SAR is not a parameter directly affecting the rectenna performance, SAR is an important metric in the RF-based WPT system. Generally, an RF-based WPT system should be at most the SAR standard. SAR is the time derivative of incremental power dissipated in or absorbed by an incremental mass within a known

density in a particular volume [67]. The SAR value can be obtained as [68]:

$$SAR = \frac{d}{dt} \left(\frac{dW}{dm} \right) = \frac{d}{dt} \left(\frac{dW}{\rho dV} \right). \quad (8)$$

In relation to the electric fields at a given point (e.g., human's body/tissue), (8) can be rewritten as:

$$SAR = \frac{\sigma}{\rho} \times E^2 \left[\frac{W}{kg} \right], \quad (9)$$

Where σ is the conductivity of the tissue [S/m], ρ is the mass density of the tissue [kg/m³], and E is the electric field strength of the RMS [V/m]. In Table 4, we present several existing SAR standards.

F. Opportunities and Path Ahead in Rectenna Design

Despite many existing challenges in the RF-based WPT, particularly in the rectenna design, there are also many opportunities ahead in this area. One of the main yet obvious opportunities of RF-based wireless power transfer is the ability to charge devices wirelessly. This can significantly reduce the need for cords and connectors, making charging devices such as IoT devices, wearable gadgets, and even smartphones and laptops more convenient. It is forecasted that the number of IoT devices will explode soon. Many of these devices are industrial and sensing IoT devices deployed in the area where deploying cords/connectors to deliver

| Classification | | KR [69] | JP [69] | US [69] | EU [69] | ICN IRP [69] | IEEE E [69] |
|---------------------------------|----------------|--|---|--|---|--|--|
| Frequency range (Hz) | | 10 ⁵ ~ 10 ¹⁰ | 10 ⁵ ~ 3X10 ⁸ | 10 ⁵ ~ X10 ⁸ | 10 ⁶ ~ X10 ¹¹ | 10 ⁵ ~ 10 ¹⁰ | 10 ⁵ ~ X10 ⁶ |
| Normal use (W/kg) | Whole body | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 |
| | Head/ trunk | 1.6 | 2 | 1.6 | 2 | 2 | 2 |
| | Limbs | 4 | 4 | 4 | 4 | 4 | 4 |
| Occupati onal user (W/kg) | Whole body | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 |
| | Head/ trunk | 8 | 10 | 8 | 10 | 10 | 10 |
| | Limbs | 20 | 20 | 20 | 20 | 20 | 20 |

*Limbs standard is based on the average value for 10 grams of arbitrary human tissue. Head/trunk refers to body parts excluding the limbs. In Korea and US, the SAR standard for head/trunk is the average maximum value for 1 g of arbitrary human tissue. In Japan, CENELEC, ICNIRP, and IEEE standards, head/trunk is based on the average value for 10 grams of arbitrary human tissue.

KR: Korea

JP: Japan

US: United States of America

EU: Europe

ICNIRP: International Commission on Non-Ionizing Radiation Protection

IEEE: Institute of Electrical and Electronics Engineers

the power becomes challenging (e.g., high pressure, high temperature, high altitude, or radiative areas). Some IoT devices will be deployed in rural/remote areas (e.g., sensors in forests or surveillance cameras in wildlife sanctuaries) and dangerous areas (e.g., warzones), making battery replacement or wired chargers not feasible. Under these circumstances, WPT, particularly RF-based WPT, might be an appropriate solution. In addition, RF-based WPT can also be useful for powering devices that are in motion, such as drones or robots. Therefore, a proper rectenna design is critical to ensure the realization of robust RF-based WPT.

The path ahead of RF-based wireless power transfer includes improving the efficiency of the technology. This can be achieved by developing new rectenna designs and novel modulation schemes. Also, increasing the distance over which power can be transferred wirelessly is an ongoing research area. Additionally, reducing interference from other RF sources is an important research area. Lastly, the WPT robustness and nonlinearity problem is another issue that should be overcome in the RF-based WPT area.

In conclusion, RF-based wireless power transfer has many opportunities, including the ability to charge devices wirelessly, power devices remotely, power devices in hazardous environments, and power devices on a large scale. The path ahead of RF-based wireless power transfer includes improving the efficiency of the technology, increasing the distance over which power can be transferred wirelessly, and reducing interference from other RF sources. With ongoing research and development, RF-based wireless power transfer technology has the potential to revolutionize the way we charge and power our devices.

G. Study Limitations and Recommendations for Future Works

1) Study Limitations

Despite the comprehensive overview of recent developments and challenges in the design of 2.4 GHz rectennas for RF-based WPT applications, this article is not exhaustive and may not cover all the possible design considerations and optimization techniques. The article mainly focuses on the 2.4 GHz frequency band and does not discuss other frequency bands or multi-band rectenna design. Additionally, the article does not comprehensively cover the potential health effects of RF-based WPT systems on human and animal subjects.

Moreover, the article does not systematically compare the performance of different rectenna designs or evaluate their performance under various operating conditions, such as varying power levels, distances, and interference sources. Furthermore, this article does not address the reliability and robustness of rectennas under harsh environmental conditions or long-term usage.

2) Recommendations for Future Works

Future research on 2.4 GHz rectennas for RF-based WPT applications should address some of the limitations mentioned above. Firstly, researchers should explore other frequency bands and multi-band rectenna designs to achieve better performance and compatibility with different wireless devices and applications.

Secondly, systematic comparisons and evaluations of different rectenna designs under various operating conditions should be conducted to identify the most efficient and practical designs for different WPT applications. Additionally, reliability and robustness tests under harsh environmental conditions and long-term usage should be performed to ensure the practicality and safety of RF-based WPT systems.

Another major limitation that must be overcome is the lack of standardization in rectenna design and testing methodologies, making it difficult to compare results across different studies. Future works should establish a standard set of design guidelines and testing procedures to enable more meaningful comparisons of rectenna performance and efficiency.

In this article, rectifier nonlinearity has been mentioned multiple times as one of the main challenges in 2.4 GHz rectenna design. The nonlinear behavior of rectifier circuits can cause harmonic distortion and reduce power conversion efficiency. Future studies should investigate the nonlinear properties of rectifiers in more detail and develop techniques to mitigate the effects of nonlinearity on the performance of rectennas, such as employing adaptive biasing techniques or using advanced signal processing methods to compensate for nonlinear effects.

In the studies collected by this work, none has compared the performance of different rectifier components, such as diodes, transistors, and memristors, for RF-based WPT applications. Different rectifier components have unique properties and characteristics that can affect the efficiency and performance of rectennas. Thus, future works should investigate the performance of different rectifier components for RF-based WPT applications. Rectifier components selection played an essential role in the rectenna performance. For instance, transistors have a lower forward voltage drop compared to diodes, which can result in higher conversion efficiency. However, transistors may also have higher parasitic capacitance, which can limit their performance at high frequencies. Thus, future research should investigate the tradeoffs between different rectifier components and identify the most suitable components for different WPT applications.

Further, the current research is primarily focused on laboratory-scale rectenna prototypes, and there is a need for more practical and scalable rectenna designs for real-world applications. Future works should explore advanced manufacturing techniques, such as 3D printing and nanoimprinting, to develop low-cost and high-performance rectenna arrays that can be integrated into a wide range of WPT systems, from small sensors to large-scale infrastructure projects.

Finally, future works should also investigate the potential health effects of RF-based WPT systems on human and animal subjects and propose guidelines and regulations for safe use. Overall, the research on 2.4 GHz rectennas for RF-based WPT applications has great potential to transform the way we power electronic devices and systems. Further research and development are needed to realize its benefits and address its challenges fully.

Overall, the limitations and recommendations outlined in this section provide a roadmap for future works in the field of 2.4 GHz rectenna design for RF-based WPT and highlight the need for interdisciplinary collaborations between researchers in RF engineering, material science, and manufacturing to achieve practical and sustainable solutions for wireless power transfer.

IV. CONCLUSION

The 2.4 GHz rectenna is a promising technology for radio frequency (RF)-based wireless power transfer (WPT). In recent years, there have been significant developments in the field, which have led to new opportunities for the implementation of this technology in various applications. However, several challenges need to be addressed before widespread adoption can take place.

One of the most significant recent developments in the field is the advancement in rectenna design. Researchers have improved the efficiency of these antennas by using new materials and optimizing the antenna's geometry. This has led to an increase in the amount of power that can be transferred wirelessly, making it more practical for various applications.

Another area of advancement has been in the implementation of WPT systems. Researchers have been able to develop new systems that are more compact, lightweight, and efficient. This has led to the development of new applications for WPT, such as powering various IoT and portable devices.

However, despite these advances, several challenges still need to be addressed before the widespread adoption of 2.4 GHz rectenna-based WPT can take place. One of the main challenges is the limited operating range of these systems. This can make it difficult to implement in certain applications where the transmitting and receiving antennas are far apart. Another challenge is the limited power transfer efficiency. While recent advances have led to an increase in the amount of power that can be transferred wirelessly, the efficiency is still relatively low compared to traditional wired power transfer systems. This can make it difficult to implement in certain applications requiring high power transfer efficiency. Nevertheless, 2.4 GHz rectenna design is still an interesting topic as we believe that 2.4 GHz RF-based WPT is a promising technology for future applications.

DECLARATIONS

Conflict of Interest

The authors have declared that no competing interests exist.

CRedit Authorship Contribution

Muhammad Miftahul Amri: Conceptualization, Methodology, Software, Writing-Original draft preparation, Visualization, Investigation, Supervision, Funding Acquisition; Liya Yusrina Sabila: Data curation, Writing-Reviewing and Editing.

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