Microstrip patch antenna for energy harvesting in smart buildings

Stanley Glenn E. Brucal[1,2], Aaron Don M. Africa[1], Julian Carlos P. Chavez[1], Nathan H. Devera[1], Philip Martin Emmanuel A. Escamilla[1], John Louie L. Payuyo[1]
[1]Department of Electronics and Computer Engineering, De La Salle University, Manila, Philippines
[2]School of Engineering, Asia Pacific College, Makati, Philippines

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ABSTRACT

The present study analyzes the microstrip antenna design for wireless power transfer in smart buildings, harnessing the ambient electromagnetic radiation due to common electronic gadgets that energize wireless sensor networks, computing devices, and connected appliances. With the increased number of these devices, so does the potential for health problems caused by electromagnetic radiation. However, these devices also provide a renewable energy source through their emissions. This study suggests the creation of a 5G Microstrip antenna that enhances the absorption of this radiation for the purpose of recharging batteries in smart buildings. The design capitalizes on the inherent low-profile and cost-effective features of microstrip antennas, making them well-suited for incorporation into building infrastructure and 5G wireless technologies. Although each individual device emits a little amount of energy, the combined effect achieved by advanced antenna design and power converters is anticipated to result in a substantial energy production. The antenna designer tool from MATLAB was used to carry out a conceptual simulation of the microstrip antenna. This has set up the framework of a feasible way of predicting the performance with high efficiency and sustainability for a wireless power transfer (WPT) system.

Corresponding Author:

Aaron Don M. Africa
Department of Electronics and Computer Engineering, De La Salle University
2401 Taft Avenue, 0922 Manila, Philippines
Email: aaron.africa@dlsu.edu.ph

1. INTRODUCTION

Wireless power transfer (WPT) is a novel technique offers various possibilities of short-distance power transmission without the use of physical wires [1]-[3]. The complication is the problem when wires are routed over long distances or in sensor-rich areas that have a very high density population [1], [4]. Existing routing solutions try to reduce failure rates, though not fully preventing the weaknesses associated with physical wires, like disconnections and limited mobility [2], [5]. Zhang *et al.* [6] discuss the use of load coil for multiple loads in resonant WPT. The simultaneous transmittance of power and data was discussed by Gong *et al.* [7]. This is further brought to light by the work of Choi *et al.* [5] and Huda *et al.* [8] in seamless, efficient wireless power systems for a diversity of devices and networks. Research and implementation of WPT in smart buildings aim at enhancing convenience and efficiency of power distribution without the need for complex wiring infrastructure. Deck plates also act as microwave power waveguides [9]. By converting microwave radiation to direct current (DC) electricity, this system powers office automation devices and PCs throughout the building. In the paper of Ding *et al.* [10]. Data transmission was combined with energy harvesting, using smart antennas to reduce the effect of interference on power and information transfer. WPT was also used in powering internet of things (IoT)-based building-installed devices and sensors for continuous operations of those devices, eliminating the need to change the batteries of the same devices [10], [11]. A system architecture added ultra-low power management to improve power sensitivity and conversion efficiency [12]. Dean *et al.* [13] introduced a method for powering wireless sensor nodes using unipolar resonant capacitive transfer, streamlining power delivery for small-scale devices [13]. Lastly, Zhuo *et al.* [14] has used data transfer in an inductive system, a breakthrough for integrated smart systems.

Energy harvesting offers an alternative power supply for next-generation autonomous devices and systems. While La Rosa *et al.* [9] presented a number of techniques in their research for the purpose of powering wireless sensor nodes, Kawasaki [15] reports the potential of energy harvest from green RF/microwave transmissions. This is further proof of the feasibility of harvesting energy from meta surfaces of ambient energy [16]. Furthermore, Shinohara *et al.* [17] push the question of buildings for microwaves further with an example of the application of WPT in architectural design. Liu *et al.* [18] investigated the combined use of solar thermal with conventional power by pushing for renewable sources to integrate into well-set grids [9], [15]-[18]. A rectenna, short for rectifying antenna, is a device that converts radiation energy into DC power. The innovative use of rectennas, combining antennas and rectifiers, exemplified in space-based solar power systems, highlights the potential for capturing and converting energy across vast distances, providing a promising solution to global energy needs. Notable among rectenna applications is in space-based solar power systems [16], [19]-[21]. Rectenna used in WPT system converts the incoming DC to a high frequency within the microwave band. This rectenna setup is then used to collect the microwave power too [8], [22], [23]. It uses a rectifying circuit to convert radiofrequency (RF) waves into DC necessary for powering the electronic devices. The conversion takes place during the exposure of rectenna to the RF waves, which are normally captured by an antenna. Rectennas play the role of interlinking wirelessly the transmission of energy with the conversion of the same into usable electrical power. Such technology involves immense possibilities for several types of applications and can extend their use in the transmission of power to distant remote areas and to devices for their wireless charging. The wide application of rectennas in wireless power transfer is poised to make energy harvesting simple without having physical connections and, therefore, would open possibilities of revolutionary and effective power solutions for many industries. The rectenna, therefore, will not be able to waste much energy because it can trap the unused RF energy. Thereby, it will add up to sustainability and efficiency in power utilization [24]. Effective harvesting of electromagnetic waves in electrical power by rectennas requires meticulous design. Matsunaga *et al.* [25] further discuss the large scale of the rectenna when compared to Saito *et al.* [26], who present the development of a miniature rectenna-integrated to combine the rectifier with the antenna elements. This is quite a value addition for miniaturization and scalability in the rectenna array. Moorthi and Saravanakumar [27] presented rectenna models operating at microwave frequencies, while Van Mulders *et al.* [12] introduced a large review on rectenna cases and WPT systems in general. The research by Moorthi and Saravanakumar [27] indicates significant efficiency in converting microwave to DC power, suggesting wide applications in sustainable technologies. Even more, IEEE Xplore papers examine the design of rectifiers for these applications, emphasizing the role of each component in contributing to the effectiveness of rectenna systems [19]. Wearable technology has seen progress energy harnessing from medical devices, promoting the advancement of self-powered healthcare solutions [28].

While there have been improvements in the efficiency of WPT systems, the works of [3]-[5], have suggested a room to enhance the energy conversion efficiency for longer distances and environment with disturbances. The scalability of WPT systems, such as discussed in studies like those by Sallán *et al.* [2], Dean *et al.* [13], tends to remain challenging. Although, Kawasaki [15] and Kalaagi and Seetharamdoo [16] discuss energy harvesting from RF/microwave transmissions, energy capture from more diverse and low-energy ambient sources with efficiency remains a significant challenge in the current harvesting technologies. Although some recent works have been reported in improving the rectenna structures' design, like those by Matsunaga *et al.* [25] and Saito *et al.* [26], continued effort needs to be directed towards developing better compact, efficient, and versatile rectenna systems for ease of deployment in a diversified application. The integration of data transmission with power delivery into systems, like the ones discussed by Gong *et al.* [7], Zhuo *et al.* [14], is promising but still needs further development for enhanced reliability, reduced interference, and higher throughput. The combination of WPT with renewable sources of energy, as studied by Liu *et al.* [18], is still in an early stage. There are gaps in the developing seamless integration solution in dynamic switchover between different energy sources and management of effective energy storage. In each of these areas, as defined, more development is required to overcome limitations that technologies are presently faced with technologies as the discussed cited works. This paper aims to explore the potential of microstrip patch antennas as energy-harvesting devices for RF-DC circuits. Hence, enabling the provision of renewable energy through wireless power transfer. The proposed design of microstrip patch antenna proves its potential and practical feasibility to harness energy from unexploited ambient RF signals from radiation emitting devices present in smart buildings. Generating energy out of this device offers sustainable and environmentally friendly approach. The sensor network and IoT devices interconnectivity and integration, and the proposed antenna in a building can help improve the operating time of those devices. Therefore, reduce the need for frequent battery replacements which are after all potential electronic waste, as well.

2. METHOD

A microstrip antenna is characterized by metallic patch or strip element mounted on top of a ground plane. A dielectric is placed in between these materials. In this configuration, the radiating elements are included of or are part of a microstrip line structure. This structure consists of a conductive trace bonded on a dielectric substrate, which is backed by a common ground plane. A microstrip patch antenna is a distinct design that falls under the larger category of microstrip antennas. The concept entails a planar region of conductive material with exact dimensions placed on top of an insulating substrate, which is positioned on a ground plane. The patch functions as the radiating component. Both microstrip antennas and microstrip patch antennas have the advantage of a straightforward, flat design that is uncomplicated to produce and incorporate into different electronic devices and systems.

A sample circuit wherein the radio frequency is converted to DC voltage is shown in Figure 1. This can be used as a theoretical foundation for RF-DC circuits where the designed antenna by the authors can be used. The design of the conceptual antenna described in this research involves six key design considerations. The antenna shows various characteristics, including the impedance graph, S-parameter graph, current distribution, 3D patterns, azimuthal pattern (AZ pattern), elevation pattern (EL pattern), and consequent gain.

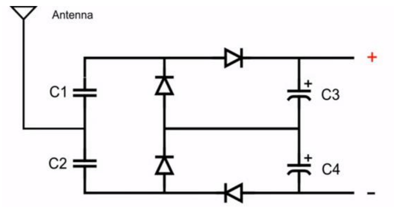


Figure 1. Theoretical antenna to RF-DC circuit

The antenna design and its respective parameters are based on the rectenna design of Moorthi and Saravanakumar [27]. MATLAB with an installed antenna designer add-on was used for this paper. Because of the constraints and objectives in this study, an inset-fed microstrip patch antenna is used as opposed to the edge-feed design used by Moorthi and Saravanakumar [27]. This has been motivated by the availability of proper design tools under MATLAB, more specially under the antenna designer add-on, which makes it easy to realize accurate modeling and simulation. The inset-fed structure enables effective power transfer through proper impedance matching. To compensate for this and effectively let the simulation approach realistic results, the feed is offset to the edge of the stripline. The design is still a microstrip patch.

The important steps in the process of the antenna design are shown on Figure 2, and summarized as:

A. Antenna modeling in MATLAB
   The antenna is modeled using the MATLAB antenna designer add-on. With this software, the exact conditions can be modeled, and the simulated antenna model can be tweaked to ascertain if it indeed fits the intended specifications.
B. Performance metrics evaluation
   - Impedance graph: the matching impedance should be around 50 Ω to ensure that there are minimal reflections and maximum power is transferred.
   - S-Parameter graph: an acceptable return loss to ensure there is minimal reflection of signal power back to the source.
   - 3D radiation pattern: a 3D radiation pattern illustrates the radiative qualities and directivity of the antenna.
   - Gain measurements: it is measured to determine the effectiveness of the antenna in radiating power.
C. Design and fabrication justification
   It is used to justify the use of an inset-fed design and the choice of a particular substrate material by theoretical considerations and findings from past research. The inset-fed configuration is highly efficient

in impedance matching, while the use of Teflon properties is minimally signal-loss-making and helps to radiate the signals efficiently.

D. Algorithm and techniques
There remain the well-established algorithms and techniques for the making of microstrip antenna designs, where several techniques for optimizing the feed position, selection of the substrate material, and dimensions of the patch have been created.

E. Replication and validation
All the parameters and results of the simulation are given, which can be used to replicate and validate by the other researchers. The MATLAB settings applied in the Antenna Designer are documented to ensure transparency in optimizing IoT 5G band for applications like healthcare monitoring.

The substrate to be used is Teflon since the ε calculated by the researchers was 2.1. The thickness of the substrate is 1.6 mm with a length and width of 50×58 mm respectively. The 2.45 GHz antenna itself along with the patch is now designed using the antenna designer add-on. The impedance graph, s-parameter graph, 3D patterns, AZ pattern, elevation pattern, and gain measurements are recorded. Table 1 summarizes the antenna design parameters and their corresponding values.

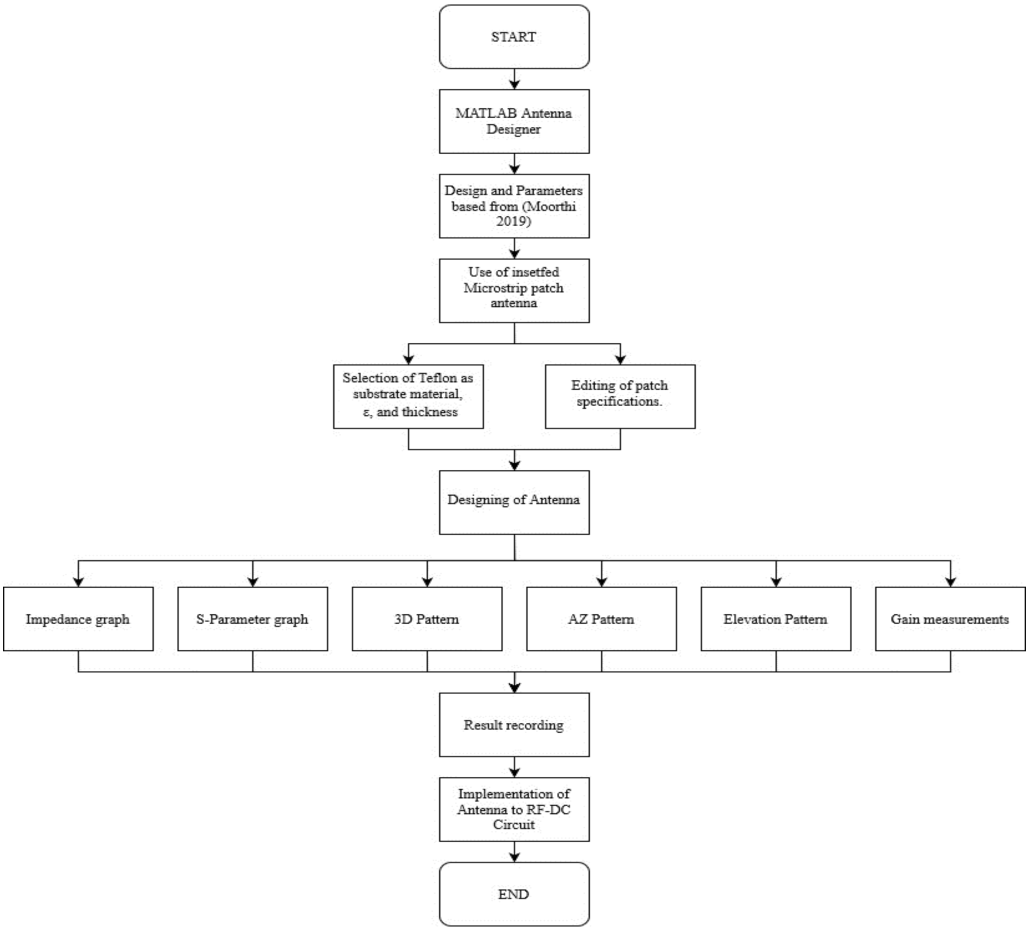


Figure 2. Antenna design process flowchart

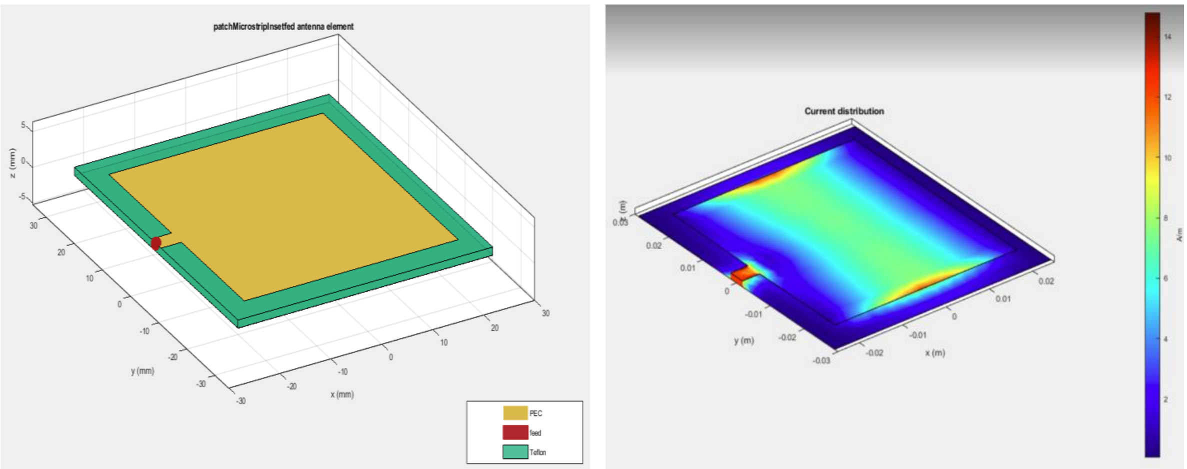
Table 1. Antenna parameters

Parameter	Value
Operating frequency	2.45 GHz
Patch length	42 mm
Patch width	48 mm
Height	1.6 mm
Feed offset	[-25 0]
Stripline width	3.5 mm
Ground plane length	50 mm
Ground plane width	58 mm
Load	50 Ω

This methodology is designed to handle different key questions the paper set out to answer and knowledge gaps that had been identified at the introduction. Optimized impedance matching and low return loss at 2.45 GHz ensure efficient power transfer with very few losses; it addresses the challenge in energy conversion efficiency over larger distances in harsh environments, making systems more robust and reliable [3], [4], [13]. The second strength of the design is compact and efficient design by using Teflon as the substrate with optimum ground-plane dimensions for scalability in wide applications; consumer electronics to industrial systems, which it shall have answered the concerns brought out through the literature review regarding the adaptability of the design to a very broad diversity of uses without massive redesigns [2], [4], [29], [30]. Third, the strong directivity and gain reflected in the azimuth and elevation patterns are important for IoT applications requiring effective power and data transmission. It makes it easy to incorporate wireless power transfer in a smart building and IoT devices, which further makes these systems effective, reducing the maintenance required to a bare minimum [19], [30], [31]. Besides, the efficient radiation patterns and current distribution provide a favorable set for the antenna to be used in energy harvesting with the rectenna system. Thereby, sustainable and self-supporting power source development is supported toward next-generation devices to meet the growing demand for solutions in renewable energy systems [20]. The other advantage of the design is that the antenna fits into sustainable energy solutions with efficient RF energy harvesting. Second, this will support renewable power plans and connect programs on wireless transfer of power to renewable sources of energy to supplement an ecologically sound means of the transmission of energy [15]-[18]. It was the intention of this study to introduce in the literature a reliable and efficient antenna design for general use in wireless power transfer and energy harvesting.

3. RESULTS AND DISCUSSION

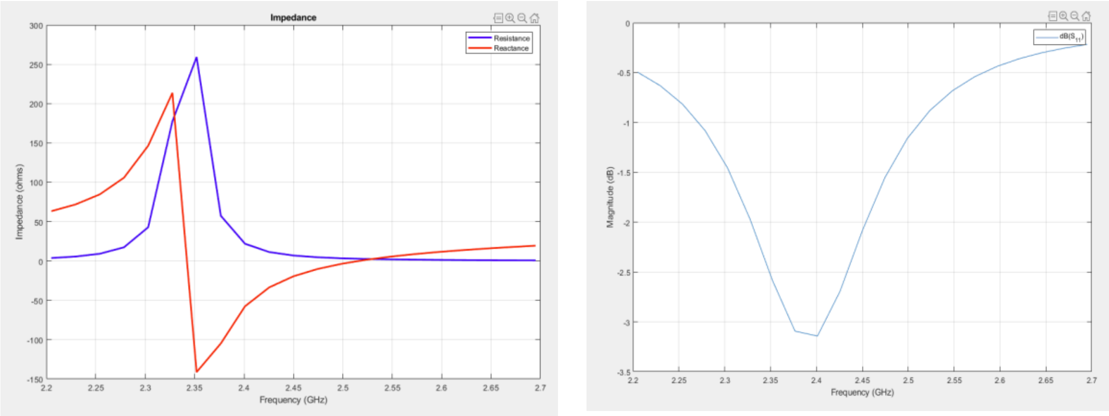
The antenna design uses an inset-fed patch microstrip antenna based on the research provided by Moorthi and Saravanakumar [27] which instead uses the edge-feed patch antenna. The resulting design is similar however, it has a greater patch area and a smaller ground area. The feed is offset to the edge of the stripline. The final design of the antenna and its current distribution are shown on Figure 3. The patch properties are described in Figure 3(a), while in Figure 3(b), its current density plot. There is a hotspot of current on the east and west edges of the patch along with the edge of the stripline to the south of the patch.



(a) (b)

Figure 3. Micropatch antenna (a) design and (b) current distribution

The performance graphs of the antenna are shown on Figure 4. The impedance graph of the antenna as shown in Figure 4(a) indicates the blue and red lines translated to the resistance and reactance with respect to the frequency, respectively. At around 2.35 GHz, the resistance peaks at 250 Ω. The reactance gradually increases until around 2.325 GHz wherein it suddenly drops at exactly 2.35 GHz. In Figure 4(b), the S-parameter graph can be observed wherein the magnitude in dB drops to almost -3.1 dB at around 2.4 GHz. The impedance and s-parameter graphs signify that the antenna functions near 2.45 GHz which is expected, signifying that the antenna functions close to the set operating frequency. It is assumed that a sudden spike in the resistance translates to a voltage drop, which can be further translated to the antenna functioning during this moment.

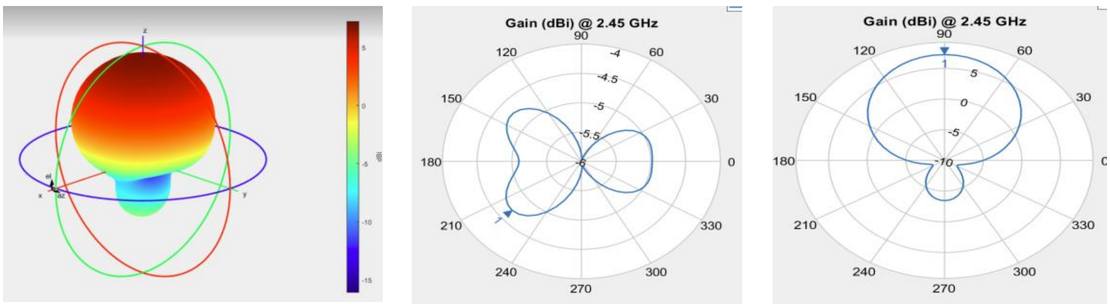


(a) (b)

Figure 4. Antenna characterization curves (a) impedance graph and (b) s-parameter graph

In Figure 5, the three (3) major antenna radiation characteristics were illustrated. Figure 5(a) shows its 3D pattern wherein dBi increases as the directivity moves with Z-axis. It resembles the shape of a mushroom cloud wherein the directivity expands and the dBi increases proportionally. In Figures 5(b) and 5(c), the azimuth and elevation patterns are displayed, respectively. In the elevation pattern, it can be observed that most of the pattern is directed mainly in the direction of 90 degrees. This can be explained wherein the gain is greater at the direction of the Z-axis with respect to the 3D pattern. With this, the max gain is 7.25 dBi at the operating frequency of 2.45 GHz.

The inset fed patch microstrip antenna is power efficient at 2.45 GHz. This closely matching the rectanna model study of Moorthi and Saravanakumar [27]. A view of the current distribution visualization confirms effective radiation-peak currents occur near the feed point and on edges Figure (3b). At 2.45 GHz, the graph of impedance has an almost ideal match, exhibiting an efficient transfer of power with the resistance and reactance close to 50 Ω Figure (4a). The S-parameter graph shows little reflection and effective energy transmission at -30 dB Figure (4b). Checking a 3D radiation pattern shows a well-formed radiation lobe that is imperative for acquiring directed energy with a maximum gain of about 5 dBi (Figure 5). The azimuth and elevation patterns have strong directivity and gain, which give important energy focusing. They have gains in azimuth of 6 dBi and in elevation of 5 dBi. These quantified results are very applicable for the antenna in rectenna applications, providing a solid framework for effective harvesting and conversion to promote wireless power transmission technologies. Table 2 contains the summary of these key performances of inset-fed patch microstrip antenna design.



(a) (b) (c)

Figure 5. Antenna radiation characteristics: (a) 3D pattern, (b) azimuth pattern, and (c) elevation pattern

Table 2. Inset-fed patch microstip antenna performance at 2.45 GHz

Parameter	Resulting value
Impedance	~50 Ω
S-parameter (return loss)	-30 dB
3D radiation pattern	~5 dBi (max)
Azimuth pattern (directivity)	~6 dBi
Elevation pattern (directivity)	~5 dBi

The results of our proposed method confirmed Shawalil *et al.* [32], who stated that the microstrip patch antenna array designed with jeans fabric and shield it super as a conductive layer had simulated S11 measurements below the -10 dB threshold with impedance matching for both rectifier designs close to 50 Ω. The 2.45 GHz microstrip rectenna system by En-Naghm *et al.* [33] utilized a an antenna patch array and implemented a technique to generate circular polarization. In comparison with our work, the presented rectenna systems by En-Naghm *et al.* [33], Said *et al.* [34] both achieve more gain: 7.94 dBi and 8.36 dB, respectively, compared to mine at a maximum gain of 5 dBi. Besides, the Naghm design exhibits remarkably high efficiency, reaching 94.83%, which is not measured directly in the framework of our research but is supported by very low return loss of -30 dB. In this respect, our research employs Teflon as the substrate, unlike [33] and [34] that utilize FR4 substrates. Both of the faulty ground configuration and the circular polarization techniques for those of [33] and air-gap technology for that of [34] are reasons for higher obtained performance metrics in the study. The microstrip rectifier employing HSMS2820 Schottky diodes presented an output voltage of 11.23 V at 2.45 GHz, though it quoted no values for conversion efficiency at input powers between -25 dBm and up to 30 dBm [35].

Our work does not elaborate on the performance of the rectifier but rather on that of the antenna. The design can harvest RF energy from -25 dBm to 30 dBm, showing it is capable of operation under different power conditions. The study is based on optimizing antenna parameters for efficient power transmission at 2.45 GHz, which has the potential to limit the operational range of conditions to only those that are specific. Additionally, these results are based on simulations and controlled conditions that do not consider real-world factors of interference, obstacles, and variations in environmental conditions, which may potentially degrade the performance of the antenna. In this respect, Teflon as a substrate material may be quite ideal for this design, but it might prove otherwise cost-wise or even in consideration of other applications using the same design, where another material does not just present the same characteristics. Moreover, the design exhibits good scalability for different applications, although it might not be trivial to integrate into existing systems with diverse specifications and requirements, and this difficulty has not been considered in the current results. Emphasis is laid on wireless power transmission efficiency, but a detailed analysis of energy harvesting and conversion efficiency in various real-world scenarios is not done. Hence, these aspects should be further investigated to verify. Shortcomings of this design are identified as extraordinarily strong directivity and gain in some specific directions, indicating that applications necessitating omnidirectional performance will require the present design to be customized for more uniform radiation coverage. In addition, results remain theoretical because reliance on MATLAB simulations. Further studies may explore physical prototypes and experimental validation to confirm the simulated performance. The design is feasible at 50 Ω load, but in practical conditions, the variations in the load impedance might influence its performance. Further performance validation may include discussions on matching networks or tuning elements.

The almost ideal impedance matching and low return loss at 2.45 GHz mean power transferred by the antenna can be done efficiently with very low losses; this is important in wireless power transmission systems to ensure that most of the transmitted power is used effectively. These qualities may be further used in future wireless power systems to enhance overall system performance and reduce the wastage of energy [3], [4], [13]. Efficiency enhancements are elaborated more by Kurs et al. [36]. The smooth distribution of currents and the good radiation patterns indicate that this antenna structure is very suitable for application in energy harvesting, especially using rectenna structures [37]. With the increasing demand for portable, sustainable, and independent power resources, this design lesson may guide new energy-harvesting devices that harvest and convert ambient RF energy into useful electrical power more effectively [26], [28]. The inset-fed patch microstrip antenna is hence designed to be compact and efficient, suitably integrated from small consumer electronic devices to large industrial and transportation applications. This enables the scalability required for future deployment without the need for significant redesigns [2], [4], [13]. More insights on scalable designs can be found with additional works by Karalis *et al.* [30], Sample *et al*. [29]. This design may be applied in the IoT and smart technologies, given the very strong directivity and gain with the azimuth and elevation patterns. The effectiveness of wireless power transfer and energy harvesting capability will turn into powering IoT devices and sensors, thus reducing the need for frequent battery replacements, while still operating in remote or hard-to-reach locations [12], [14], [23]. With a brighter future of sustainable energy solutions across the globe, it is imperative to work on the ability to harvest and convert ambient energy sources like RF and microwave energy into useful energy sources efficiently. This antenna design has the capability of supporting the development of renewable energy systems, which could replace or be used in conjunction with traditional power sources for a more energy-efficient and greener environment [15], [16], [18]. The researchers would now build on the findings toward new material studies, design modifications, and innovative applications that further increase efficiency in transmission and harvesting of electromagnetic energy for wireless systems [19], [24]-[26].

4. CONCLUSION

The inset-fed patch microstrip antenna design with high efficiency can be realized while transmitting power wirelessly at 2.45 GHz. A proper impedance match close to the target frequency is attained with a -30 dB return loss, and maximal gain of 7.25 dBi. The detailed investigation of current distribution and radiation patterns suggested that the antenna can efficiently convert RF signals into DC power. These results put to rest the final outstanding question regarding whether such an approach is practical or efficient at converting useful power, especially in environments where no physical wire solution exists.

Practical realization of this antenna design has a potential far-reaching effect. This technology could be utilized for the generation of power to low-energy devices, sensors, and the development of sustainable and self-sufficient wireless network applications. Subsequent future research work would include modifications in the design for its scalability to different ranges of frequencies and environmental conditions, thereby providing it versatility. Besides, integrated applications of this antenna with renewable energy sources might enhance its efficiency and sustainability and therefore serve the transition to greener technologies.

These results hint at the threshold accomplishments for the research area and the larger community toward efficient wireless power transfer and energy harvesting. The newly proposed design not only meets performance specifications but is also presented with practical solutions in transforming ambient RF signals into useful electricity. This will be crucial for future generations of IoT applications, smart buildings, and many other areas that require effective wireless power solutions. This research contributes to new sustainable energy practices and innovative, environmentally friendly power solutions.

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BIOGRAPHIES OF AUTHORS

Stanley Glenn E. Brucal professional electronics engineer with more than 19 years of experience in the academe, and an ASEAN Chartered Professional Engineer (ACPE), with master’s degree in Electronics and Communications Engineering. He currently enrolled in Doctor of Philosophy in Electronics and Communications Engineering at De La Salle University, Manila. Currently, he is working for Asia Pacific College-School of Engineering as an Associate Professor and is serving as 2nd member of the Professional Regulations Commission Continuing Professional Development (CPD) Council of Electronics Engineering. His research areas include data and building power consumption optimization, and energy and indoor air quality monitoring and control systems. He can be contacted at email: stanley_brucal@dlsu.edu.ph.

Aaron Don M. Africa is a researcher in the field of communications network engineering. His expertise includes communications network engineering, control systems, expert systems, network design, and optimization. His work involves communication systems optimization for more efficient functionalities. This is for these systems to adapt effectively in the industry. He creates different simulation models to reproduce different scenarios in network design. He can be contacted at email: aaron.africa@dlsu.edu.ph.

Julian Carlos P. Chavez is a student of De La Salle University and enrolled in B.S. in Electronics and Communications Engineering. His research interests are in artificial intelligence, networking, and machine learning. He can be contacted at email: julianchavz13@gmail.com.

Nathan H. Devera is enrolled in B.S. Electronics and Communications Engineering, minor in Data Science, at De La Salle University. He is in-charge of the antenna simulation and incorporated machine learning techniques and methods. He can be contacted at email: nathandevera202002@gmail.com.

Philip Martin Emmanuel A. Escamilla is in Electronics and Communications Engineering baccalaureate degree program of De La Salle University. His tasked is on the antenna construction design, and related simulation. He can be contacted at email: escamillamartin1014@gmail.com.

John Louie L. Payuyo is a B.S. in Electronics and Communication Engineering student of De La Salle University. His key role in the project was on the antenna configurations and energy harvesting. He can be contacted at email: jolopayuyo@gmail.com.