IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received April 1, 2018, accepted April 29, 2018, date of publication May 8, 2018, date of current version June 26, 2018.

Digital Object Identifier 10.1109/ACCESS.2018.2834392

Energy Harvesting Using a Low-Cost Rectenna for Internet of Things (IoT) Applications

KINZA SHAFIQUE[1], BILAL A. KHAWAJA[2,3], (Member, IEEE), MUHAMMAD DANIYAL KHURRAM[1], SYED MAAZ SIBTAIN[1], YAZIR SIDDIQUI[1], MUHAMMAD MUSTAQIM[2], HASSAN TARIQ CHATTHA[3], (Senior Member, IEEE), AND XIAODONG YANG[4], (Senior Member, IEEE)

[1]Department of Electrical Engineering, DHA Suffa University, Karachi 75500, Pakistan
[2]Department of Electronic and Power Engineering, PN-Engineering College, National University of Sciences and Technology, Karachi 24090, Pakistan
[3]Faculty of Engineering, Department of Electrical Engineering, Islamic University of Madinah, Medina 41411, Saudi Arabia
[4]School of Electronic Engineering, Xidian University, Xi'an 710071, China

Corresponding authors: Kinza Shafique (kinza.shafique@dsu.edu.pk), Xiaodong Yang (xdyang@xidian.edu.cn)

This work was supported in part by the National Natural Science Foundation of China under Grant 61671349 and Grant 61301175, in part by the Fundamental Research Funds for Central Universities under Grant JB180205, and in part by the International Scientific and Technological Cooperation and Exchange Projects in Shaanxi Province under Grant 2017KW-005.

ABSTRACT Traditionally employed human-to-human and human-to-machine communication has recently been replaced by a new trend known as the Internet of things (IoT). IoT enables device-to-device communication without any human intervention, hence, offers many challenges. In this paradigm, machine's self-sustainability due to limited energy capabilities presents a great challenge. Therefore, this paper proposed a low-cost energy harvesting device using rectenna to mitigate the problem in the areas where battery constraint issues arise. So, an energy harvester is designed, optimized, fabricated, and characterized for energy harvesting and IoT applications which simply recycles radio-frequency (RF) energy at 2.4 GHz, from nearby Wi-Fi/WLAN devices and converts them to useful dc power. The physical model comprises of antenna, filters, rectifier, and so on. A rectangular patch antenna is designed and optimized to resonate at 2.4 GHz using the well-known transmission-line model while the band-pass and low-pass filters are designed using lumped components. Schottky diode (HSMS-2820) is used for rectification. The circuit is designed and fabricated using the low-cost FR4 substrate (h = 16 mm and $\varepsilon_r = 4.6$) having the fabricated dimensions of 285 mm $\times$ 90 mm. Universal software radio peripheral and GNU Radio are employed to measure the received RF power, while similar measurements are carried out using R&S spectrum analyzer for validation. The received measured power is -64.4 dBm at the output port of the rectenna circuit. Hence, our design enables a pervasive deployment of self-operable next-generation IoT devices.

INDEX TERMS Internet of things (IoT), energy harvesting, antenna, rectenna, Wi-Fi, WLAN, universal software radio peripheral (USRP), GNU radio.

I. INTRODUCTION

In our daily lives, numerous small, relatively inexpensive interconnected computing devices are surrounding us, many of which can communicate and perform sensing operations. These devices are called smart objects (SOs) [1], and they cooperate to collect data and provide services to end users in the pervasive computing [1], [2] environment. This leads to the concept of Internet of Things/Internet of Everything (IoT/IoE) [1]–[4]. The IoT can be characterized as the connection of physical devices which do not directly rely on human interaction. Major consumer applications of IoT are in wireless sensor networks (WSNs) and wireless body area networks (BANs) [2]–[4]. The extension of IoT concept for the commercial applications brings us to the advent of industrial-IoT which provides interconnectivity to improve business-to-business services, mainly through machine-to-machine (M2M) interactions [2], [3].

The ever-increasing number of internet-enabled devices in the IoT paradigm like smart cities brings along their own challenges like self-sustainability due to limited energy capabilities. Hence, issues related to self-configuration, power management, and reliability must be addressed, adequately. This paper addresses the power management issues by incorporating energy harvesting [5] technology for the SOs in the next generation IoT applications. In energy harvesting technology, the solar, kinetic, thermal or electromagnetic (EM) energy can be converted to useful DC power which can then be used to recharge the batteries and power up the IoT devices [3]–[5].

In recent years, energy harvesting by using EM waves is used in empowering implantable biomedical devices, WSN nodes, and wireless chargers, etc. Wireless energy harvesting is necessary for biomedical devices, as the replacement of batteries in their tiny structures is tedious especially when they are planted inside the human body. The concept is becoming popular because the environment is full of EM radio waves dominantly from the 300MHz-3GHz ultrahigh-frequency (UHF) band and their applications are commonly found in mobile, satellite and Wi-Fi communications, etc. [4]–[6]. This abundant EM (energy) waves can be picked up and harvested by these self-sustainable SOs for the next generation IoT applications.

Several studies have been conducted and methods are proposed to harvest radio-frequency (RF) energy [6]–[8] which optimally utilized RF ambient energy to power sensors and electronic devices with low power consumption. The canonical method to implement the concept is by using a rectenna circuit comprising of an antenna and an RF/DC conversion unit [6], [8]–[10]. This concept was originally proposed and demonstrated in 1975 [11] when a microwave beam was transmitted through an RF-DC converter at a distance of 1.6km and the efficiency achieved was 85%. For a viable rectenna design, the major work is to propose a suitable antenna for receiving an RF signal and increasing the rectifier's efficiency. The demonstration in [11] opens a new paradigm of research which eliminates the existence of power cables, hence reducing the cost.

In the past, several methods to transfer power wirelessly had been demonstrated [12]–[16]. In the near-field region, inductive power transfer is getting popular for short range applications, typically few millimeters to meters [12], [13]. The concept is successfully implemented in mobile phone chargers, electrical toothbrushes, RF identification (RFID) tags and artificial cardiac pacemakers, etc. The conjugate, capacitive coupling method is also used in low power applications and typically being used in power routing in integrated circuits [14], smart cards and charging portable devices. Whereas, in the far-field region, power transfer using microwaves and lasers are worth mentioning [15]. Microwaves are used for long distance applications in satellite communication, telecommunication and powering unmanned aerial vehicle (UAV) drones [15]. Laser energy transmission is also used for long distance communications as it makes use of atmospheric transparency window in the visible or near-infrared frequency spectrum [15], [16].

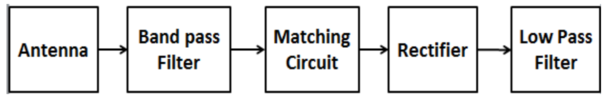


FIGURE 1. Block diagram of the proposed rectenna circuit.

Hence, find its use in the solar-powered satellites, military weapons, aerospace and consumer electronics [15], [16].

In this work, an efficient and low-cost RF energy harvester operating at 2.4GHz ISM band is proposed, designed, optimized, fabricated and characterized. The rectenna circuit comprises of a microstrip patch antenna (MPA), a filter, rectifier and a matching circuit. The MPA is designed using the low-cost flame resistant (FR4) substrate. The measured MPA bandwidth is found in good agreement with the simulated one. Lumped components are used to implement the band-pass filter (BPF) and a low-pass filter (LPF) operating at the 2.4GHz band. A schottky diode is used to implement the rectifier circuit due to its high-speed switching at higher frequencies and low voltage drop characteristics. Transmission-lines and stubs are used for matching and maximum power transfer. The energy harvester is designed and simulated using Agilent advanced design system (ADS) Momentum—a simulator that works on full-wave analysis method-of-moment (MoM) technique [17], [25]. The DC power received at the load is -64.4dBm which can be further amplified to power up next generation IoT devices, smartphones and implantable biomedical sensors.

The rest of the paper is organized as follows: Section 2 discusses the rectenna circuit design and its simulation results. Section 3, presents the parametric tuning study of the designed rectenna circuit. Section 4 compares the simulated and measured results and finally, Section 5 draws conclusion.

II. PROPOSED RECTENNA CIRCUIT

The block diagram of the proposed rectenna circuit is shown in Fig. 1. It can be seen in Fig. 1 that the rectenna circuit comprises of an antenna, a BPF, matching circuit, a rectifier circuit, and a LPF. Each module is matched to the next module using stubs for maximum power transfer [17].

In order to fulfill the rectenna design requirements, the first step is to design the antenna. Here, an MPA is preferred and used which serve as a promising solution for these requirements as they are small, low-profile and easy-to-fabricate whereas their shortcomings such as narrow bandwidth and low-gain characteristics can be improved by using different techniques [18]–[22]. A typical MPA consists of a radiating patch and a ground plane. The radiating patch is characterized by its relative permittivity and height [17]. The fringing-field effect between the ground plane and the radiating patch causes the patch antenna to radiate at a single resonant frequency [17]. For the radiating patch to resonate at multiple frequencies, slots and slits can be introduced in the design which alters the current path on the patch [19]–[22]. The low-cost FR4 substrate is used here with height (h), dielectric constant (ε_r), and loss tangent (δ) of 1.6mm,

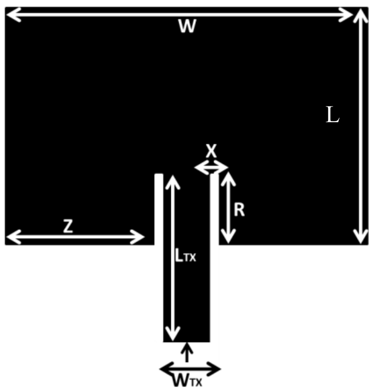


FIGURE 2. Geometry of the proposed microstrip patch antenna.

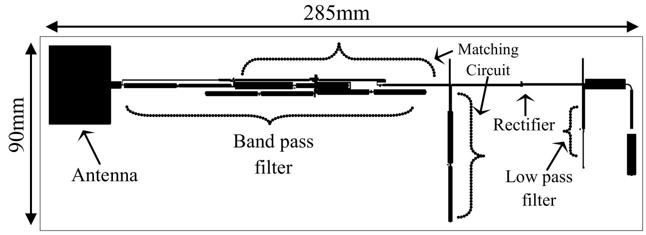


FIGURE 3. Simulated rectenna circuit on ADS.

4.6 and 0.019, respectively. The designed antenna is shown in Fig. 2.

It can be seen from Fig. 2 and Fig. 3 that the overall size of the rectenna system is 285mm × 90mm and the patch antenna is of 54mmx 57mm, respectively. The FR4 antenna is fed by a 3mm × 17mm transmission-line (TL) by using an inset-feed technique. This technique is used, because it is easy to implement and provide a method of impedance control with a planar feed configuration [23], [24]. The antenna was modeled and optimized using ADS momentum [25].

For antenna designing, the resonant frequency (f_r) is selected to be 2.4GHz. The length and width of the patch antenna are calculated using the transmission-line model [17]. When the rectangular patch is first implemented in ADS momentum, the length and width are same as the calculated ones. The length and width of the 50Ω TL are then calculated for the FR4 substrate [17] which are 16.8mm and 3mm, respectively. When these TL dimensions are implemented in ADS, the optimized length is found to be 17mm whereas the width remains the same. The TL is inserted into the patch at 12mm. The distance is found by using mathematical Eq. (1-2) [17], [25]. At first, the inset-feed length is calculated by using Eq. (1) which comes out to be 10.4mm. Later the length was further optimized by using Eq. (2) and the dimension R is found to be 12mm:

$$Z_{in}(R) = \cos\left(\frac{\pi R}{L}\right)^2 Z_{in}(0) \tag{1}$$

$$R = 0.82 \times \frac{L}{2} \tag{2}$$

Where, $Z_{in}(R)$ is the input-impedance set to 50Ω, R is the inset-feed distance as shown in Fig. 2, L is the length of patch antenna and $Z_{in}(0)$ is the input-impedance at the patch edges which is set to 244Ω, respectively [17]. The dimensions of the proposed antenna are summarized in Table 1.

TABLE 1. FR4 Substrate based antenna design parameters (unit: mm).

Freq.	W	L	W_{TX}	L_{TX}	X	R	Z
2.4GHz	37	29	3	25.1	0.1	12	16.9

The simulated reflection coefficient (S_{11}) plot on ADS momentum for the antenna is shown in Fig. 4.

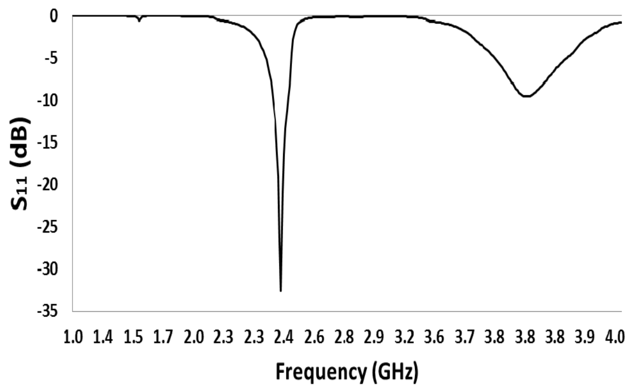


FIGURE 4. Simulated S_{11} [dB] of 2.4 GHz antenna.

It can be seen from the S_{11} plot that the simulated antenna is resonating at 2.4GHz and showing an acceptable bandwidth of 25MHz. Rest of the antenna parameters are summarized in Table 2.

TABLE 2. Simulated results of the proposed antenna.

Parameters	Results
Bandwidth *(MHz)*	25
Gain *(dBi)*	5.6
Directivity *(dBi)*	6.4
Efficiency (%)	82.2
Radiation Pattern	Omni-directional

Next, the signal is passed through a BPF to filter out the noise and undesired frequency components. The BPF is realized by using the *pi* (π) and T models as the passive R/L/C filters are combined in a special way with π and T models to optimize the cost, compactness and performance in RF designs [26], [27]. This paper employs a π model, because it provides more output voltage and ripple-free output as compared to the other proposed filter models [26]. Using the π model shown in Fig. 5, the value of the capacitors and inductors are calculated using the mathematical

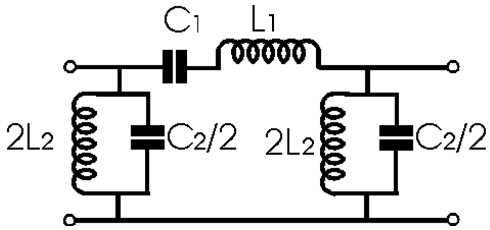


FIGURE 5. *Pi* (π) **model of the proposed BPF.**

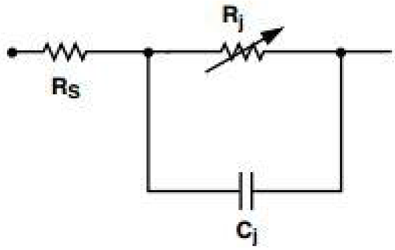


FIGURE 6. **Spice model of the HSMS-2820 schottky diode [28].**

Eq. (3-6) [26], [27]:

$$L_1 = \frac{Z_0}{\pi(f_2 - f_1)} \tag{3}$$

$$L_2 = \frac{Z_0\,(f_2 - f_1)}{4\pi f_2 f_1} \tag{4}$$

$$C_1 = \frac{(f_2 - f_1)}{4\pi f_2 f_1 Z_0} \tag{5}$$

$$C_2 = \frac{1}{\pi Z_0 (f_2 - f_1)} \tag{6}$$

From the above equations, the characteristic impedance (Z_0) and the cut-off frequencies (f_1 and f_2) are 50Ω, 2.3GHz and 2.6GHz, respectively. Moreover, the values of L_1, L_2 and C_1, C_2 are found to be 50.2 nH, 0.2nH and 0.08pF, 20.08pF, respectively.

Next step in designing the proposed rectenna is the matching circuit. Matching is an essential step for maximum power transfer from the BPF to the rectifier [17]. The first step in designing a matching circuit is to calculate the value of Z_{in} and Z_0 using Eq. (7-13) [17]. Z_{in} is the sum of the output impedance of the antenna and the BPF impedance. Whereas, Z_0 is the total impedance of the rectifier, LPF, and the load. The values of the passive components in the matching circuit are then calculated using the L model.

At first, the impedance of the antenna ($Z_{antenna}$) is calculated using the smith chart in Eq. (7) and found to be $50 + j39.5\Omega$.

$$Z_{antenna} = 50 \times (1 + j0.8) \tag{7}$$

Now, the impedance of the BPF is calculated using Eq. (8-11). Here, $\boldsymbol{X_{L2}}$ is parallel to $\boldsymbol{X_{C2}}$ and found to be 3.3Ω. Similarly, $\boldsymbol{X_{C1}}$ is in series with $\boldsymbol{X_{L1}}$ and found to be 1.6KΩ. The total impedance of the BPF is obtained by the parallel and series combination of the above mentioned impedances and is found to be 1.6Ω.

$$X_{L2} = 2\pi f L_2 \tag{8}$$

$$X_{C2} = \frac{1}{2\pi f C_2} \tag{9}$$

$$X_{C1} = \frac{1}{2\pi f C_1} \tag{10}$$

$$X_{L1} = 2\pi f L_1 \tag{11}$$

As stated previously, Z_{in} and Z_0 should be calculated for the matching circuit. Hence, $\mathrm{Z_{in}}$ is found to be $51.6 + j39.5\Omega$. Now, the calculations are made to calculate $\mathrm{Z_0}$. For rectification, the schottky diode HSMS-2820 [28] is used. Its impedance is calculated using the spice model, as shown in Fig. 6 [28]. The values of series resistance (R_s) and junction capacitance (C_j) can be determined from the spice table [28]. The variable resistance depending upon external bias current, saturation current and temperature (R_j) is calculated using Eq. (12). The values of R_s, C_j and R_j are found to be 6Ω, 0.7pF and 1.3KΩ, respectively.

$$R_J = \frac{8.33 \times 10^{-5} nT}{I_b + I_s} \tag{12}$$

Where in Eq. (12), I_b and I_s are externally applied bias current in amps and saturation current, respectively. Now, the impedance of the LPF is calculated. A simple capacitor is used to implement the filter on ADS. Hence, the impedance is calculated using Eq. (13) and found to be 144.5Ω.

$$X_c = \frac{1}{2\pi f_c C}$$

Now, the equivalent impedance Z_0 with 500Ω load is found to be 206.4Ω. Using the values of Z_0 and Z_{in}, the matching circuit is implemented using L model. Hence, L and C are found to be 3.3nH and 0.6pF, respectively.

Rectification is the next step in rectenna circuit design. A schottky diode is employed for rectification, as it has a low voltage drop between 0.15-0.45V compared to the normal silicon diode which has a drop between 0.6-1.7V [9]. Also, schottky diode has a very fast switching action as required by a high-frequency incoming signal, high current density and lower heating losses, hence efficient for applications that are sensitive to accuracy [9].

Low pass filtering is the last step in designing the rectenna circuit as it smoothes the signal and removes any noise present. A simple capacitor is used to implement the filter on ADS. The value of the capacitor is calculated using Eq. (14) and found to be 0.5pF.

$$C = \frac{1}{2\pi f_c R}$$

All the individual modules of the rectenna circuit are then connected together using a matching circuit for maximum power transfer. Hence, input and output impedances of all the modules are considered to calculate the length and width of the TLs for maximum power transfer between the modules. The complete rectenna circuit is shown in Fig. 7.

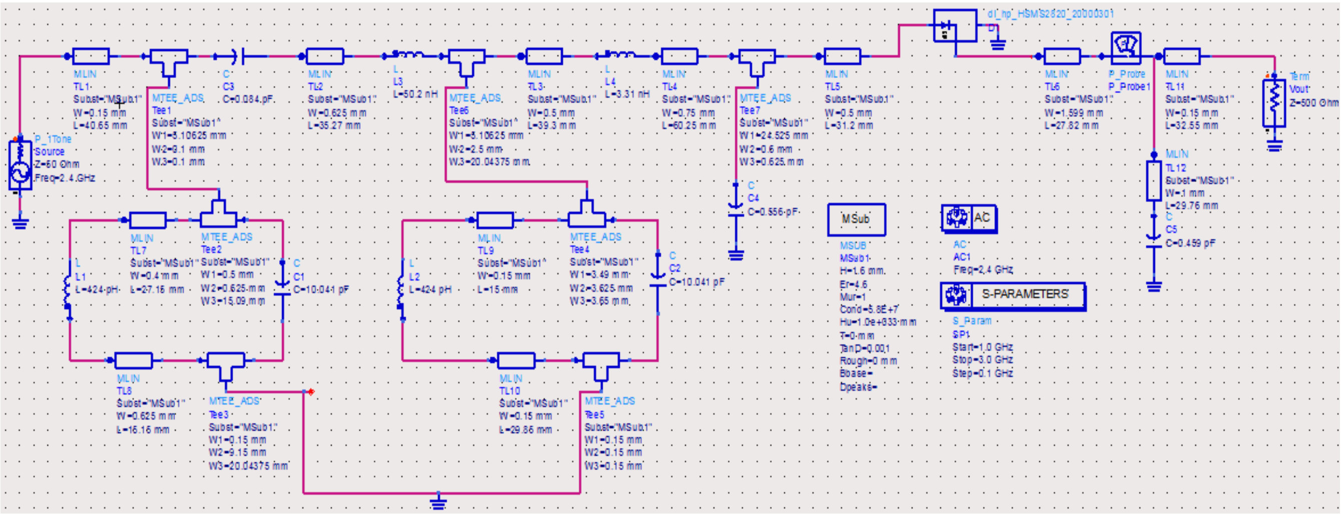


FIGURE 7. Rectenna simulation circuit on ADS.

TABLE 3. Calculated and tuned component values of the rectenna circuit.

BPF	Calculated	Implemented
L_1	50.2nH	50nH
$2L_2$	424pH	400pH
C_1	0.08pF	0.1pF
$C_2/2$	10.04pF	10pF
Matching Circuit	**Calculated**	**Implemented**
L	3.3nH	3.5nH
C	0.6pF	0.55pF
LPF	**Calculated**	**Implemented**
C	0.5pF	0.45pF

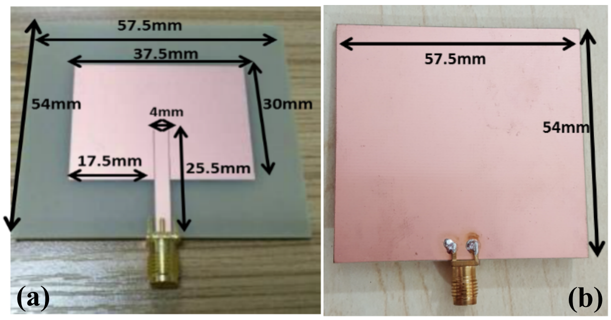


FIGURE 8. Fabricated microstrip patch antenna (a) Front side (b) Back side.

III. PARAMETRIC TUNING STUDY

The rectenna circuit is then further tuned so that the calculated values of all the components match closely with the commercially available component values. The tuned rectenna circuit values are listed in Table. 3.

IV. MEASUREMENT RESULTS AND DISCUSSIONS

A. MPA MEASURED RESULTS

Fig. 8 shows the fabricated antenna with its dimensions. The S_{11} of the fabricated antenna is measured by using Rhodes and Schwarz (R&S) ZND 8.5GHz VNA, and the response is shown in Fig. 9.

It can be seen from Fig. 9 that the S_{11} response of the fabricated antenna is around -30dB at 2.4GHz that is in agreement with the simulated antenna response. The received power by the antenna is also measured using universal software radio peripheral (USRP) [29], [30]. A flow graph shown in Fig. 10 was constructed in the GNU Radio to demonstrate the back-to-back (B2B) system setup. In Fig. 10, an RF tone signal is generated at 2.42GHz from one USRP port and transmitted by using the USRP monopole antenna. The same

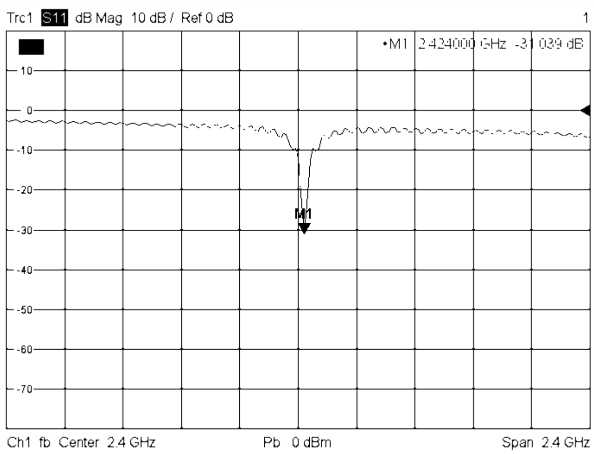


FIGURE 9. Measured S_{11} response of the fabricated FR4 antenna.

signal is received from the other port of the USRP by using the fabricated MPA.

The complete measurement system setup is shown in Fig. 11 highlighting GNU Radio flow graph, the fabricated MPA and monopole antenna connected with USRP.

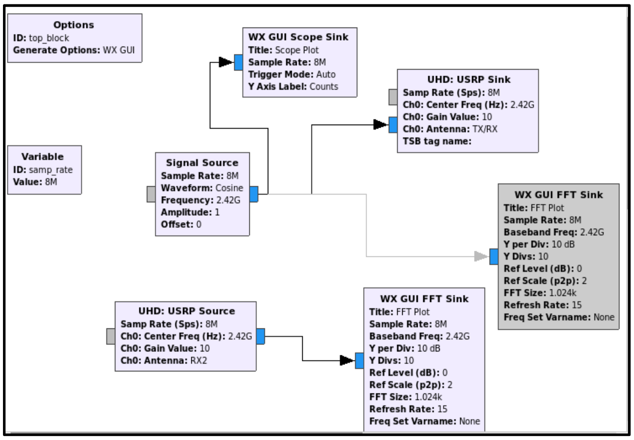


FIGURE 10. Simulation of USRP using GNU Radio.

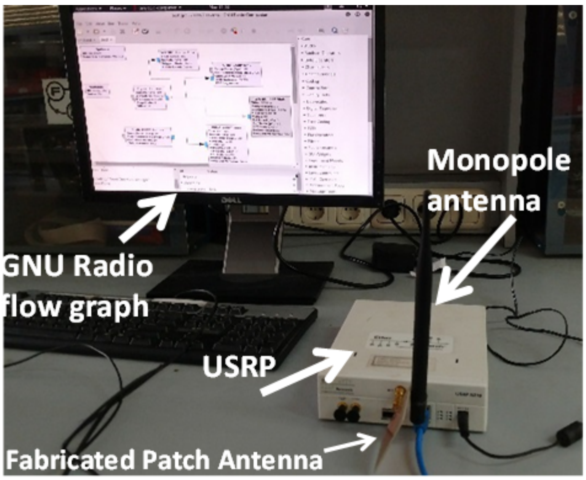


FIGURE 11. B2B system setup to measure the power of 2.4GHz antenna.

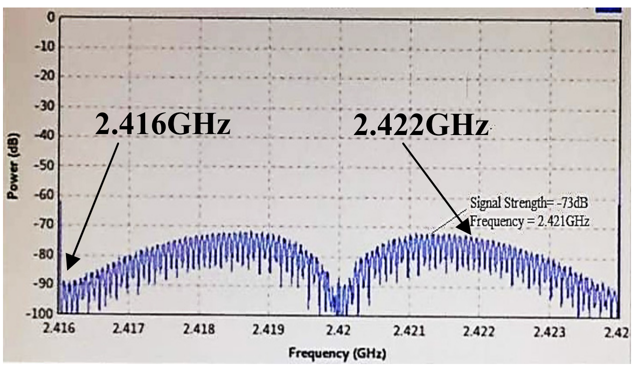


FIGURE 12. FFT plot of the RF signal received by the fabricated patch antenna in the B2B system setup showing the measured signal power.

A transmitted RF tone in the form of fast fourier transform (FFT) plot with −73dBm of signal strength can be observed in Fig. 12. The RF tone follows the monopole antenna signal power typically used by the wireless access points (APs). According to the IEEE 802.11b/g/n standard [31], there are a total of 11 allowed channels having a total bandwidth of 22 MHz. In addition, there are 3 non-overlapping channels and the separation between overlapping channels is 5MHz.

So, in the FFT plot in Fig. 12, channel 1 can be easily observed at the frequency of 2.416GHz, while some part of channel 2 can be seen at the frequency of 2.422GHz. The whole spectrum of the IEEE 802.11 cannot be observed by USRP because the maximum bandwidth of the USRP is 20MHz. Comparison between the fabricated and commercial-off-the-shelf (COTS) antennas are summarized in Table 4.

TABLE 4. Comparison of the signal strength of the designed MPA with COTS available Wi-Fi antennas.

Antenna Type	Signal Strength
Designed MPA	*-73dBm*
COTS Wi-Fi Antenna 1	*-70dBm*
COTS Wi-Fi Antenna 2	*-80dBm*
COTS Wi-Fi Antenna 3	*-86dBm*

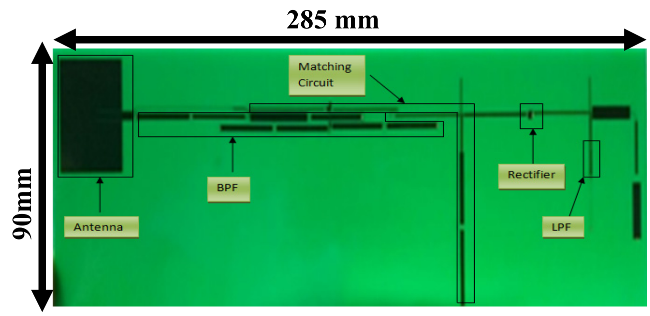


FIGURE 13. Fabricated rectenna circuit showing the designed patch antenna, BPF, matching circuit, rectifier and the LPF.

The results shown in Table 4 suggest that the designed MPA performance is similar or better, when compared with the COTS Wi-Fi antennas that are used at the wireless APs in the Wi-Fi routers at homes. After getting the satisfying results from the antenna side, it is then integrated with the remaining modules of the rectenna circuit.

B. RECTENNA MEASURED RESULTS

The fabricated antenna is then integrated with the rectenna circuit which is then fabricated and is shown in Fig. 13.

The power measured at the output port of the antenna, the BPF, the matching circuit and the rectifier and LPF are shown in Fig. 14 (a-d), respectively. The results are also summarized in Table 5.

Two types of measurement are carried out to assess the performance of the proposed rectenna circuit. Firstly, R&S SMB 100A 6GHz RF signal generator is used with the fabricated MPA resonating at 2.42GHz acting as a transmitter. The antenna is connected to the RF signal generator output port via N-type male-to-SMA female adapter. At the receiver end, the R&S FSC-6 spectrum analyzer is connected to the rectenna circuit via R&S active probe RT-ZS30 to monitor the signal strength at different distances.

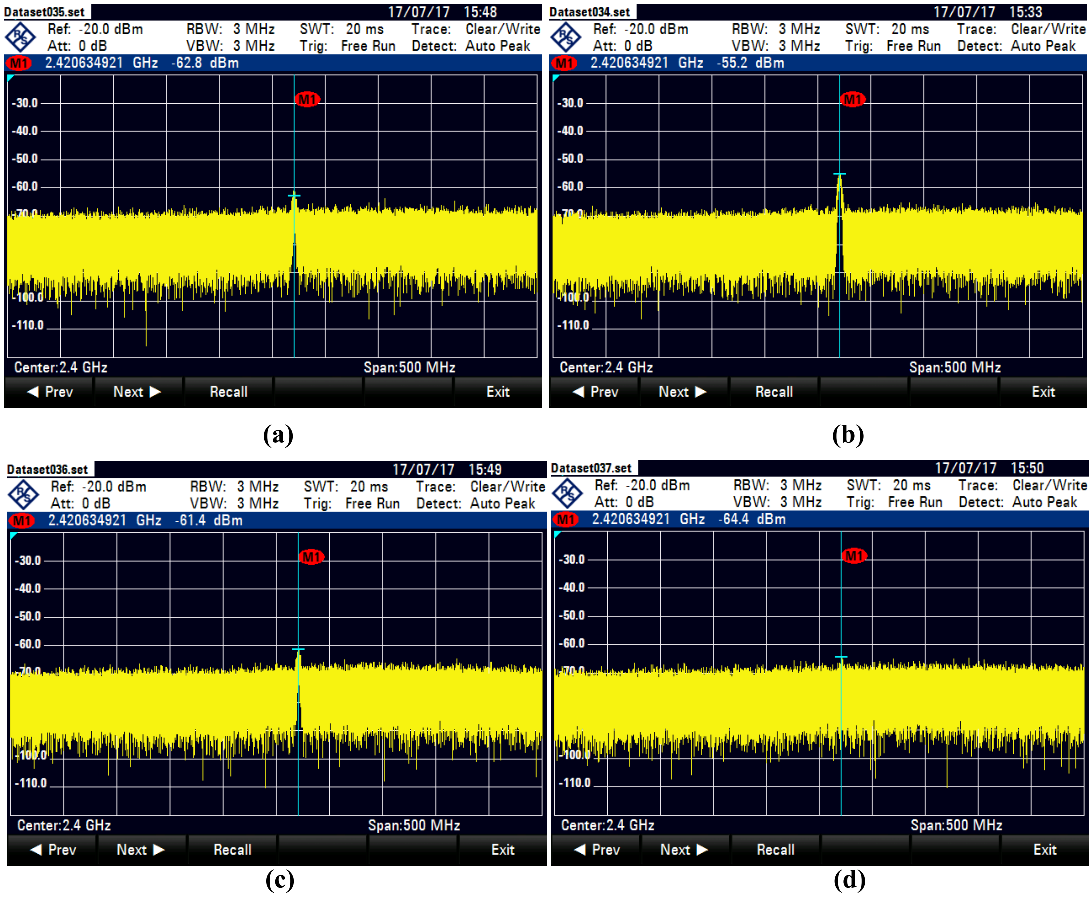


FIGURE 14. Power measured at (a) Output port of the Antenna (b) Output port of the BPF (c) Output port of the matching circuit (d) Output port of the LPF on the rectenna circuit, respectively.

TABLE 5. Summary of the power measured at various points in rectenna circuit.

Measured Position	Power (dBm)
At antenna output port	-62.8
At BPF output	-52.2
At matching circuit output	-61.4
At LPF output	-64.4

Complete measurement setup is shown in Fig. 15, where both the fabricated patch antenna and rectenna circuit are visible with the R&S spectrum analyzer and signal generator. The fabricated rectenna circuit is initially placed close to the RF signal generator to receive the maximum signal strength and then moved away from the RF signal generator with the step-size of 2-inches.

Secondly, similar measurement is carried out, but this time USRP along with the fabricated MPA is used as a transmitter. In this measurement setup, an RF tone signal at 2.42GHz is generated via USRP/GNU Radio and power measurements at different distances are carried out with an step-size of 2-inches. Fig. 16 compares the power vs. distance graph of the rectenna circuit. It can be clearly observed from Fig. 16 that the power is reduced as the rectenna is moved away from the source transmitting antenna. It is also important to note that our designed patch antenna performs better than the COTS 2.4GHz antenna of the USRP as more power is radiated out as depicted in Fig. 16.

The rectenna is also tested at an elevated and depressed level. For this measurement setup, the USRP is initially tuned to 2.4GHz using the GNU Radio. Then, the USRP is placed at an elevated position with respect to the rectenna circuit and the power received on the rectenna circuit is measured. Similarly, another measurement is carried out by placing the rectenna circuit at an elevated position with respect to the USRP and then the power received on rectenna circuit is again measured. The results of these scenarios are summarized in Table 6. It can be seen from Table 6 that the rectenna gives good power in both the cases.

C. DISCUSSION

This paper has proposed, designed and fabricated a low-cost 2.4GHz RF energy harvester (rectenna) for next generation energy harvesting and IoT applications.

For the proof-of-concept, the rectenna circuit is characterized using two different type of measurement setups. The USRP and GNU Radio are employed to measure the

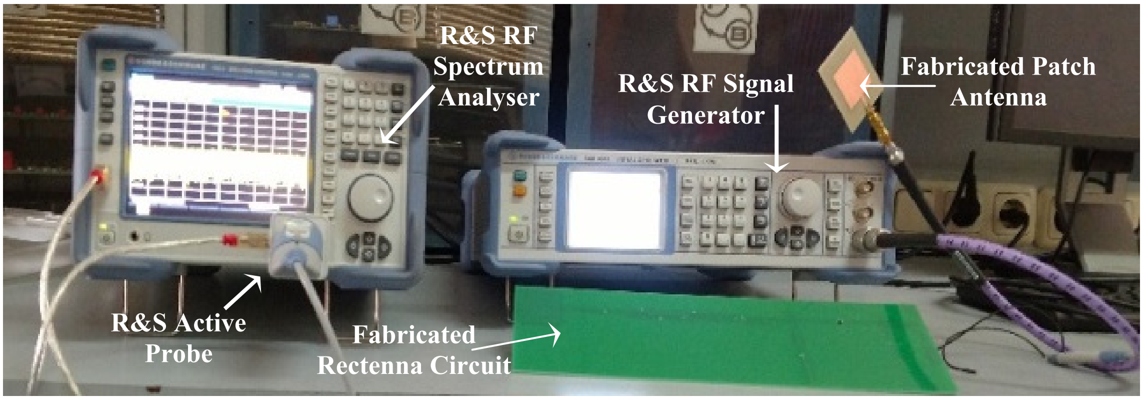


FIGURE 15. Power measurement setup of the rectenna circuit at different distances.

TABLE 6. Rectenna Power measurement at different positions.

Antenna Placement	Rectenna Placement	Power Measured
Ground level	5 inches above	-62.3dBm
Ground level	5 inches below	-57.3dBm

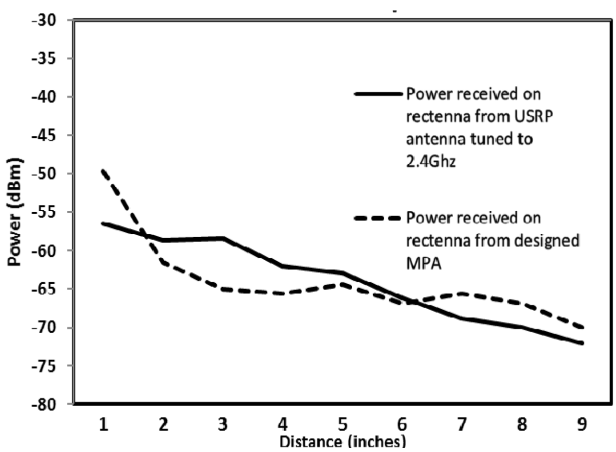


FIGURE 16. Measured power-distance graph of the rectenna's circuit.

received RF power with the help of R&S spectrum analyzer. The maximum received power from the rectenna circuit was in the range of −62dBm (6.31×10^{-7} mW) to −64dBm (3.98×10^{-7} mW). It is important to note that the power level achieved by using the currently proposed rectenna circuit is low but it is enough for the proof-of-concept.

In order to power up an IoT device, the current low-cost rectenna circuit design can be further improved in future for better output efficiency. One way to achieve this is by using two identical rectifiers consisting of voltage doubler topology as proposed in [34]. An alternate method would be to use a low-loss substrate for the rectenna prototype which may lead to a more compact and efficient design. This will be subject to future work.

TABLE 7. Power consumption of different household and personal devices.

Device	Power Consumption	Reference
Smoke detector	55μW	[4]
CO detector	1.5mW	[4]
Gas meter	5.12mW	[4]
LED	60mW	[4]
Smartwatch	31mW	[4]
Wi-Fi Flash memory	210μW	[4]
Wearable device	60μW	[32]
Smartphone	0.5W	[4]

In order to power up an IoT device, it is important to know the power consumed by the sensors which are part of the IoT system. The power consumption of different household and personal devices/sensors which make an IoT system is summarised in Table 7. It can be observed from the data presented in Table 7 that power in the order of tens of microwatts is required for household and personal IoT devices to work properly. Other industrial-IoT sensors may require relatively high power in milliwatts to work continuously.

Even with quite efficient energy harvester devices, it is difficult to continuously deliver sufficient power to an IoT sensor on an ongoing basis. One way to balance the energy harvested with the power demanded by the IoT sensor is to collect energy continuously, but operate the IoT sensor terminal at intervals [33]. This can be implemented in next-generation IoT systems by collecting the generated power in a capacitor and execute sensor operation at intervals, resulting in a method that balances the power generation with the power consumption.

V. CONCLUSION

In this paper, a 2.4GHz RF energy harvester has been proposed, designed and fabricated for the next generation energy harvesting and IoT applications. The proposed rectenna circuit consists of a rectangular MPA, band-pass and low-pass filters, matching circuit and a rectifier. Transmission-lines and stubs are used for maximum power transfer between the individual modules. The rectenna is fabricated using a low-cost FR4 substrate and is found in a good agreement between the simulation and measurement results. The overall size of the FR4 based rectenna is 285mm × 90mm with $h = 1.6$mm. The design is simple, hence can easily be integrated with the existing power-hungry IoT applications which is subjected to future work. The designed antenna is efficient as the RF power of −73dBm at 2.4GHz is received which is similar to thecommercially available Wi-Fi antennas. The proposed rectenna circuit demonstrates a very efficient behaviour as the power received by the patch antenna is −62.8dBm, whereas the available power at the output port is −64.4dBm. These results suggest the rectenna circuit has an overall efficiency of 97.5%. Hence, the rectenna is suitable for driving next generation of energy harvesting and IoT applications. As a future prospect, we propose to make the design more compact. Also, a super-capacitor can be connected to the output port to store DC power for future use [33].

REFERENCES

[1] L. Davoli, L. Belli, and A. Cilfone, "From micro to macro IoT: Challenges and solutions in the integration of IEEE 802.15.4/802.11 and Sub-GHz technologies," *IEEE Internet Things J.*, vol. 5, no. 2, pp. 784–793, Apr. 2018, doi: 10.1109/JIOT.2017.2747900.
[2] A. Costanzo and D. Masotti, "Energizing 5G: Near- and far-field wireless energy and data trantransfer as an enabling technology for the 5G IoT," *IEEE Microw. Mag.*, vol. 18, no. 3, pp. 125–136, May 2017.
[3] A. Zanella, N. Bui, A. Castellani, L. Vangelista, and M. Zorzi, "Internet of Things for smart cities," *IEEE Internet Things J.*, vol. 1, no. 1, pp. 22–32, Feb. 2014.
[4] O. Georgiou, K. Mimis, D. Halls, W. H. Thompson, and D. Gibbins, "How many Wi-Fi APs does it take to light a Lightbulb?" *IEEE Access*, vol. 4, pp. 3732–3746, Aug. 2016.
[5] K. Niotaki, A. Collado, A. Georgiadis, S. Kim, and M. M. Tentzeris, "Solar/electromagnetic energy harvesting and wireless power transmission," *Proc. IEEE*, vol. 102, no. 11, pp. 1712–1722, Nov. 2014.
[6] A. Georgiadis, G. V. Andia, and A. Collado, "Rectenna design and optimization using reciprocity theory and harmonic balance analysis for electromagnetic (EM) energy harvesting," *IEEE Antennas Wireless Propag. Lett.*, vol. 9, pp. 444–446, May 2010.
[7] K. Mimis, D. Gibbins, S. Dumanli, and G. T. Watkins, "Ambient RF energy harvesting trial in domestic settings," *IET Microw., Antennas Propag.*, vol. 9, no. 5, pp. 454–462, 2015.
[8] H. Jabbar, Y. S. Song, and T. T. Jeong, "RF energy harvesting system and circuits for charging of mobile devices," *IEEE Trans. Consum. Electron.*, vol. 56, no. 1, pp. 247–253, Feb. 2010.
[9] H. Sun, Y.-X. Guo, M. He, and Z. Zhong, "Design of a high-efficiency 2.45-GHz rectenna for low-input-power energy harvesting," *IEEE Antennas Wireless Propag. Lett.*, vol. 11, pp. 929–932, Aug. 2012.
[10] S. Ladan, N. Ghassemi, A. Ghiotto, and K. Wu, "Highly efficient compact rectenna for wireless energy harvesting application," *IEEE Microw. Mag.*, vol. 14, no. 1, pp. 117–122, Jan. 2013.
[11] N. Bonifácio, P. S. André, and N. B. Carvalho, "Resonant wireless power transmission," in *Advances in Energy Research*, vol. 8. New York, NY, USA: Nova, 2011, pp. 243–270.
[12] G. A. Covic and J. T. Boys, "Inductive power transfer," *Proc. IEEE*, vol. 101, no. 6, pp. 1276–1289, Jun. 2013.
[13] W. Green and J. T. Boys, "10kHz inductively coupled power transfer-concept and control," in *Proc. 5th Int. Conf. Power Electron. Variable-Speed Drives*, Oct. 1994, pp. 694–699.
[14] J. Dai and D. C. Ludois, "A survey of wireless power transfer and a critical comparison of inductive and capacitive coupling for small gap applications," *IEEE Trans. Power Electron.*, vol. 30, no. 11, pp. 6017–6029, Nov. 2015.
[15] C. R. Valenta and G. D. Durgin, "Harvesting wireless power: Survey of energy-harvester conversion efficiency in far-field, wireless power transfer systems," *IEEE Microw. Mag.*, vol. 15, no. 4, pp. 108–120, Jun. 2014.
[16] B. A. Khawaja and M. J. Cryan, "Study of millimeter wave phase shift in 40 GHz hybrid mode locked lasers," *IEEE Microw. Wireless Compon. Lett.*, vol. 19, no. 3, pp. 182–184, Mar. 2009.
[17] C. A. Balanis, *Modern Antenna Handbook*. New York, NY, USA: Wiley, 2008.
[18] G. A. Deschamps, "Microstrip microwave antennas," in *Proc. 3rd USAF Symp. Antennas*, Monticello, IL, USA: Univ. Illinois, Oct. 1953, pp. 18–22.
[19] K. Shafique, B. A. Khawaja, M. A. Tarar, B. M. Khan, M. Mustaqim, and A. Raza, "A wearable ultra-wideband antenna for wireless body area networks," *Microw. Opt. Technol. Lett.*, vol. 58, no. 7, pp. 1710–1715, Apr. 2016.
[20] K. Shafique, A. A. Razzaqi, M. Mustaqim, B. M. Khan, and B. A. Khawaja, "A 1×2 circular patch antenna array for next generation 802.11ac WLAN applications," in *Proc. IEEE Conf. Emerg. Technol. (ICET)*, Peshawar, Pakistan, Dec. 2015, pp. 1–6.
[21] K. Shafique, M. Mustaqim, B. M. Khan, and B. A. Khawaja, "A thin and flexible ultra wideband antenna for wireless body area networks with reduced ground plane effect," in *Proc. IEEE Conf. Emerg. Technol. (ICET)*, Peshawar, Pakistan, Dec. 2015, pp. 1–6.
[22] A. A. Razzaqi *et al.*, "A triple-band antenna array for next-generation wireless and satellite-based applications," *Int. J. Microw. Wireless Technol.*, vol. 8, no. 1, pp. 71–80, Feb. 2016.
[23] Y. Hu, E. J. Lundgren, D. R. Jackson, J. T. Williams, and S. A. Long, "A study of the input impedance of the inset-fed rectangular microstrip antenna as a function of notch depth and width," in *Proc. AP-S Int. Symp.*, Washington, DC, USA, Jul. 2005, pp. 330–333.
[24] L. I. Basilio, M. A. Khayat, J. T. Williams, and S. A. Long, "The dependence of the input impedance on feed position of probe and microstrip line-fed patch antennas," *IEEE Trans. Antennas Propag.*, vol. 49, no. 1, pp. 45–47, Jan. 2001.
[25] *Planar Electromagnetic (EM) Simulation in ADS*, Keysight Technol., Santa Rosa, CA, USA, 2016.
[26] P. Bhartia and P. Pramanick, *Modern RF and Microwave Filter Design*. London, U.K.: Artech House, 2016.
[27] J. Gabay. (Aug. 2015). *Pi, T Filters Match RF Impedances*. [Online]. Available: https://www.digikey.com/en/articles/techzone/2015/aug/pi-t-filters-match-rf-impedances
[28] Avago Technologies. (Apr. 2010). *Surface Mount RF Schottky Barrier Diodes (HSMS-280x) Datasheet*. [Online]. Available: http://www.farnell.com/datasheets/461156.pdf
[29] *Ettus Research LLC, USRP2, The Next Generation of Software Radio Systems*. Accessed: Feb. 5, 2018. [Online]. Available: http://www.ettus.com/downloads/ettus_ds_usrp2_v5.pdf
[30] A. Nafkha, M. Naoues, K. Cichon, and A. Kliks, "Experimental spectrum sensing measurements using USRP Software Radio platform and GNU-radio," in *Proc. 9th Int. Conf. Cognit. Radio Oriented Wireless Netw. Commun. (CROWNCOM)*, Oulu, Finland, Jun. 2014, pp. 429–434.
[31] *IEEE Standard for Information Technology-Telecommunications and Information Exchange Between Systems Local and Metropolitan Area Networks-Specific Requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications*, IEEE Standard 802.11-2012, 2012.
[32] P. Woznowski *et al.*, "A multi-modal sensor infrastructure for healthcare in a residential environment," in *Proc. IEEE Int. Conf. Commun. Workshop (ICCW)*, Jun. 2015, pp. 271–277.
[33] K. Sekine. (Mar. 2018). Core&Code. *Energy-Harvesting Devices Replace Batteries in IoT Sensors*. [Online]. Available: http://core.spansion.com/article/energy-harvesting-devices-replace-batteries-in-iot-sensors/#.Wq2jKsNubIU
[34] A. Costanzo and D. Masotti, "Design of RF energy harvesting platforms for power management unit with start-up circuits," *J. Phys., Conf. Ser.*, vol. 476, no. 1, p. 012043, 2013.

KINZA SHAFIQUE received the B.E. degree in electronics engineering and the M.S. degree in electrical engineering from the National University of Sciences and Technology at Karachi, Karachi, Pakistan, in 2012 and 2015, respectively. Since 2016, she has been a Lecturer with the Electrical Engineering Department, DHA Suffa University, Karachi. Her research interests include RF circuits and antenna designing/optimization for next-generation wireless systems and body area networks. She is also actively involved in the research related to RF energy harvesting techniques for next-generation Internet of Things devices.

BILAL A. KHAWAJA (M'08) received the B.S. degree in computer engineering from the Sir Syed University of Engineering and Technology, Karachi, Pakistan, in 2002, the M.Sc. degree in communication engineering and signal processing from Plymouth University, Plymouth, U.K., in 2005, and the Ph.D. degree in electrical engineering from the University of Bristol, Bristol, U.K. in 2010. From 2003 to 2004, he was a Software Engineer with Simcon International (Pvt.) Ltd., Pakistan. From 2010 to 2016, he was an Assistant Professor with the Electronics and Power Engineering Department, PN-Engineering College, National University of Science and Technology, Karachi. In 2015, he was a Visiting Post-Doctoral Researcher with the Lightwave Systems Research Laboratory, Queen's University, Kingston, Canada, on the Natural Sciences and Engineering Research Council–Canada CREATE Next Generation Optical Network project on the characterization and measurements of 25-GHz RF signal generation optical comb sources. He is currently with the Faculty of Engineering, Department of Electrical Engineering, Islamic University of Madina, Medina, Saudi Arabia. His research interests include the next generation of millimetre-wave (mm-wave) radio-over-fiber and optical communication systems, mm-wave and THz signal generation mode-locked lasers, and RF transceiver design and antennas design/characterisation for Wi-Fi/IoT/UAVs/FANETs/5Gsystems/UWB wireless body area networks, wireless sensor networks, and millimeter-wave frequency bands.

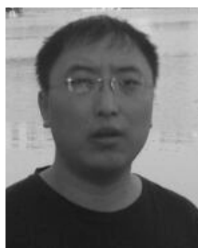
MUHAMMAD DANIYAL KHURRAM received the B.E. degree in electrical engineering from DHA Suffa University, Karachi, Pakistan, in 2017. He is currently with the Electrical Engineering Department, DHA Suffa University. His research interests include RF antennas and rectenna circuit designing.

SYED MAAZ SIBTAIN received the B.E. degree in electrical engineering from DHA Suffa University, Karachi, Pakistan, in 2017. He is currently with the Electrical Engineering Department, DHA Suffa University. His research interests include RF antennas and rectenna circuit designing.

YAZIR SIDDIQUI received the B.E. degree in electrical engineering from DHA Suffa University, Karachi, Pakistan, in 2017. He is currently with the Electrical Engineering Department, DHA Suffa University. His research interests include RF antennas and rectenna circuit designing.

MUHAMMAD MUSTAQIM received the B.S. degree from the University of Central Florida, FL, USA, in 2007, and the M.S. degree in electrical engineering from PAF-KIET, Karachi, Pakistan, in 2012. He is currently pursuing the Ph.D. degree. Since 2010, he has been a Lecturer with the Electronics and Power Engineering Department, PN-Engineering College, National University of Science and Technology, Karachi. His research interests include software-defined radios, wireless networks, and RF and microwave systems.

HASSAN TARIQ CHATTHA (SM'17–M'12) received the B.Sc. and M.Sc. degrees from the University of Engineering and Technology, Lahore, Pakistan, and the Ph.D. degree from the University of Liverpool, U.K., in 2010, all in electrical engineering. From 2005 to 2007, he was a Laboratory Engineer with the Faisalabad Campus of the University of Engineering and Technology, Lahore. From 2010 to 2011, he was a Post-Doctoral Researcher with the University of Liverpool. From 2011 to 2015, he was an Assistant Professor with the Faisalabad Campus of the University of Engineering and Technology. He is currently an Associate Professor with the Department of Electrical Engineering, Faculty of Engineering, Islamic University of Madinah, Saudi Arabia. He has published over 40 technical papers in the leading international ISI-indexed journals and peer-reviewed, reputed international conferences. He is a principal author of the majority of these papers. He did the pioneering work in the design of single element dual-port antennas for diversity and MIMO applications, and his papers on MIMO antennas have been published as featured articles in *IET Electronics Letters* and the IEEE ANTENNA AND WIRELESS PROPAGATION LETTERS. His research interests include MIMO and diversity antennas, antennas for portable applications, reconfigurable antenna systems for 4G and 5G, multiband 5G antennas, UWB and wideband antennas, massive MIMO antenna systems, antenna systems for IoT, and smart antennas. His research paper was shortlisted as one of the best student papers at the International Workshop on Antenna and Technology, Lisbon, Portugal in 2010. He is an active reviewer for many reputed IEEE and IET journals and letters.



XIAODONG YANG (SM'17) has published over 40 peer-reviewed papers in highly ranked journals. His research interests include body area networks, antennas and propagation, 5G, information security, wireless sensing, radar, millimeter-wave technology, THz technology, nanocommunications, biomedical nanoimaging, biomedical communications, visible light communications, calibration of vector network analyzer, machine learning, and so on. He received the Young Scientist Award from the International Union of Radio Science in 2014. He is on the Editorial Board of several IEEE and IET journals, including the IEEE JOURNAL OF ELECTROMAGNETICS, RF AND MICROWAVE IN MEDICINE AND BIOLOGY, and so on. He has a global collaborative research network in the field of antennas and propagation, wireless communications, health informatics, information security, microwave techniques, and Internet of Things.