Increase the Efficiency of IoT Devices by Using the Wireless Power Transmission in the Industrial Revolution 4.0

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Abstract—Today's world is evolving toward creating a smart house where a multitude of Internet of Things (IoT) devices and sensors are interacting to deliver plenty of useful information. Essential to the implementation of this IoT is the design of energy-efficient solutions aiming toward a low-carbon-emission, namely green, society. Many R&D studies are working on a long-range distance wireless charging that will send microwave energy to powered IoT devices wherever it is in the room and without cords. Wireless power transmission technology is the diffusion of RF power without using any physical support. The vision of future technology is to make the IoT devices charging and powered wirelessly. The objective of the work scope is to combine the wireless power technology with smart IoT and IIoT devices and reduce the turnoff of devices due to battery depletion. In this research paper, we designed and realized a wireless charging device using the fundamentals of microwave radiation. The proposed electronic device takes all parameters above to deliver sufficient energy to charging any IoT devices wirelessly with a maximum power of 5W.

Keywords—RF harvesting energy, Wireless Power Transmission, loop antenna, Internet of Things, RF-to-DC converter, Industrial Internet of Things

1 Introduction

Nowadays, it is commonplace for cities to be equipped with free WiFi hotspots, real-time traffic information, and safety surveillance, to mention a few. In this respect, creativity-driven and farsighted governments are playing a crucial role in speeding up the city's technological evolution [1–3]. From technological innovations, products and services will become ubiquitous in future smart cities depending on the IoT technology [4] [5]. IoT technology thereby revolutionizing a broad range of applications in a variety of domains, such as healthcare, home automation, transportation, intelligent energy management, and smart grids [6]. With ever-increasing services and cloud connectivity, IoT devices set to permeate all aspects of our daily lives [7]. Nevertheless, electricity distribution to power it still relies on cables for its delivery. To increase the performance of the IoT devices, we will implement a combination between the Wireless Power Transmission (WPT) and the Internet of things (IoT). The wireless power tech-

nology will become a cornerstone in the design of new and grown human settlements in industry 4.0. In this paper, we propose the wireless power technology to charge any IoT devices in the smart district, as shown in Figure 1.

Fig. 1. 3D picture of a smart house without wire

The RF energy generated by a local Microwave Power Station (MPS) [8–10]. Although, still in an early stage, long-range wireless power transmission is gaining momentum. Both industrials and academic know us well that the WPT will be the solution of battery autonomy and running off [11–15].

Fig. 2. IoT devices powered and charging wirelessly

This research is toward creating smart IoT devices powered wirelessly to reduce the running out of the battery of the devices, as shown in figure 2. In this study, the portable microwave station already exists and will use in the testing phases.

2 Design of the Circular Loop Harvester Antenna

Wireless power harvester devices emphasize lightweight, compact, and low cost to be merged into IoT devices. The efficiency of this antenna depends upon their geometry shape and physical dimensions [16, 17]. Circular loop antenna rises like the right receiver meeting these requirements. This is due to its versatility of possible geometry

and pure integrity with any IoT and IIoT devices, as shown in figure 3. In this research work, the size of the antenna is a significant parameter for harvesting more energy from different angles and directions. Typically, useful over a range of frequencies relative to the diameter of the wavelength, especially it's hidden inside IoT devices [18, 19]. The ratio of the radiation intensity is related to the beamwidth of the loop antenna. Where:

The operating frequency $f_r = 2.45\,GHz$

Speed of light $C = 3 \times 10^8\,m/s$

2.1 Dimension of the receiver antenna

This antenna works in the UHF range (up to 3 GHz). The currents through this circular antenna will be in the phase. The EM field will be perpendicular to the whole loop carrying the current. The radius is (a) and is assumed to be much smaller than a wavelength ($a < \lambda$). A small loop is by definition a loop of constant current. Its radius must satisfy:

$$a < \frac{\lambda}{6 \times \pi} \approx 0.053\lambda \tag{1}$$

In fact, to make sure that the current has near-constant distribution along the loop, a tighter limit must be imposed:

$$a \cdot < 0.03\lambda \tag{2}$$

Here, we give only the far-field components of the loop, the axis of which is along z:

$$\underline{E_\theta} = (\eta\beta^2) \times (IA)\frac{e^{-j\beta r}}{4\pi r} \times \sin\theta \tag{3}$$

$$\underline{H_\phi} = (-\beta^2) \times (IA)\frac{e^{-j\beta r}}{4\pi r} \times \sin\theta \tag{4}$$

It is obvious that the far-field pattern:

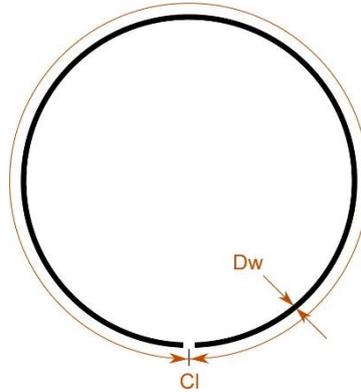$$\overline{E_\theta}(\theta) \cdot = \cdot \sin \cdot \theta \tag{5}$$

Radiated power:

$$\varPi = \frac{1}{12\pi}(\eta\beta^4)(IA)^2 \tag{6}$$

Radiation resistance:

$$R_r = \eta \frac{8}{3} (\pi)^3 \left(\frac{A}{\lambda^2}\right)^2 \approx 31171 \left(\frac{A}{\lambda^2}\right)^2 \tag{7}$$

Equation (7) gives the radiation resistance with one circular loop.

Fig. 3. The geometry of the proposed circular loop antenna

Tabulated values using the above equations shown in Table 1.

Table 1. Overview of the antenna specifications

Description	Value
Operating frequency	2.45 GHz
Wire diameter (DW)	1 mm
Copper conductivity	5.8 e7 S/m
Circumference Loop (Cl)	137 mm
Radius (a)	21.80 mm
Antenna impedance (Rin)	50Ω

The optimized parameters of the designed antenna shown in Table 1 and the performance results will be studied and analyzed in the following subsection.

2.2 Simulation and discussion

The layout of the antenna created using the ADS Keysight software, and it is further validated by confirming these results utilizing Microwave Studio soft- ware (CST). We affected many parameters like: Directivity, Reflection coefficient, Smith plot, Radiation pattern 3D, and the Current distribution.

Directivity: The simulated Gain for the designed antenna was 4.78 dBi at 2.45 GHz, and the Gain was 4.97 dBi at 2.25 GHz, as shown in figure 4.
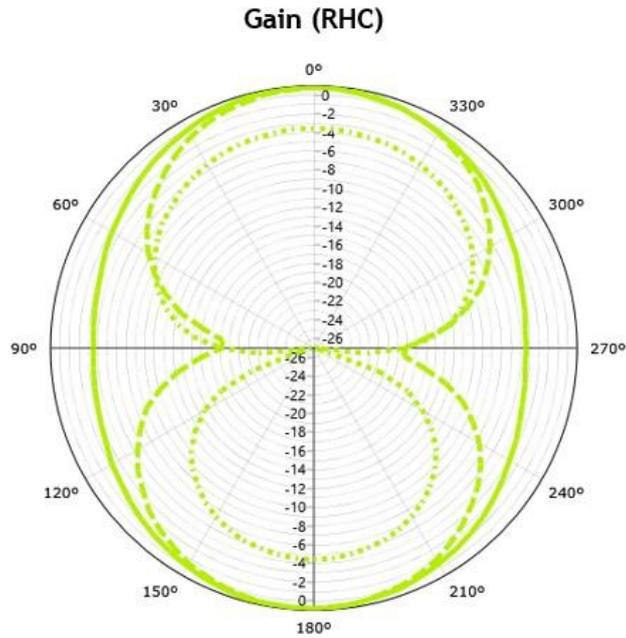
Gain (RHC)

Fig. 4. Directivity of the proposed antenna

Reflection coefficient of the antenna: Return loss (S_{11}) presented in Figure 5, and we obtain a very high return loss, -31.21 dB at the operating frequency. The bandwidth of the receiver antenna is 16.93%.
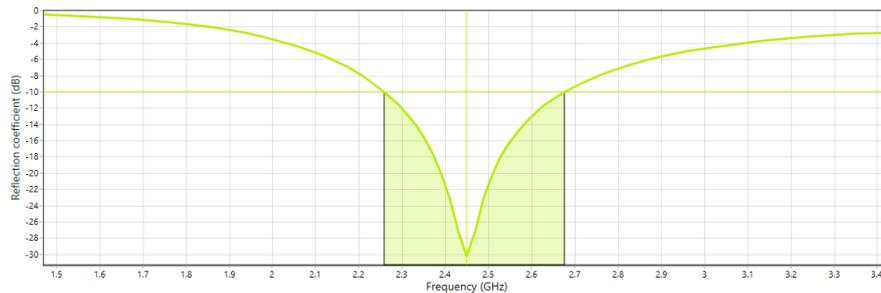

Fig. 5. Antenna Return Loss vs. Frequency

VSWR: A VSWR approaching 1.0 is desired for the loop antenna design at the resonant frequency. At 2.45 GHz, the simulation yielded a VSWR around 1.17, as shown in Figure 6.

Radiation pattern 3D: Figure 7 shows the 3D radiation pattern of the pro- posed antenna, which indicates that there are proper lobes and a maximum Gain of -3 dB.
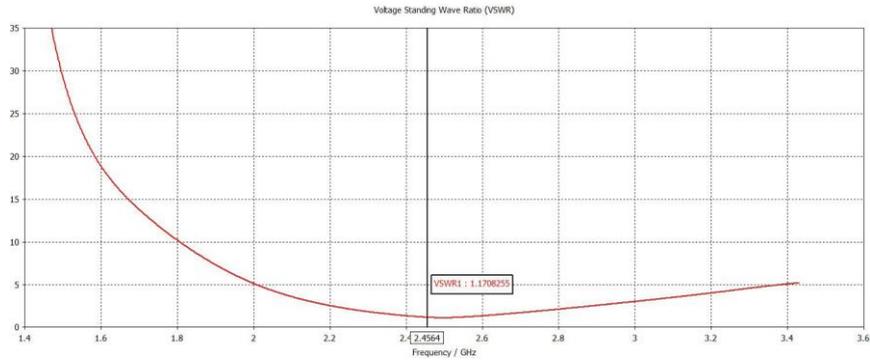
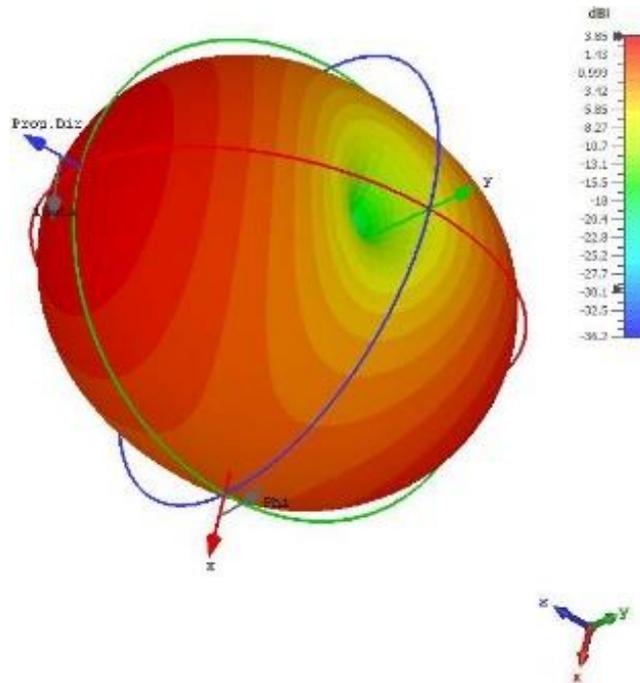**Fig. 6.** Antenna VSWR vs. Frequency

Fig. 7. Radiation pattern of the presented antenna for 2.45 GHz,

E-field distribution: Figure 8 shows the simulated E-field distribution of the antenna for different frequencies, as well as 2.45 GHz. The E-field intensity 185(V/m).
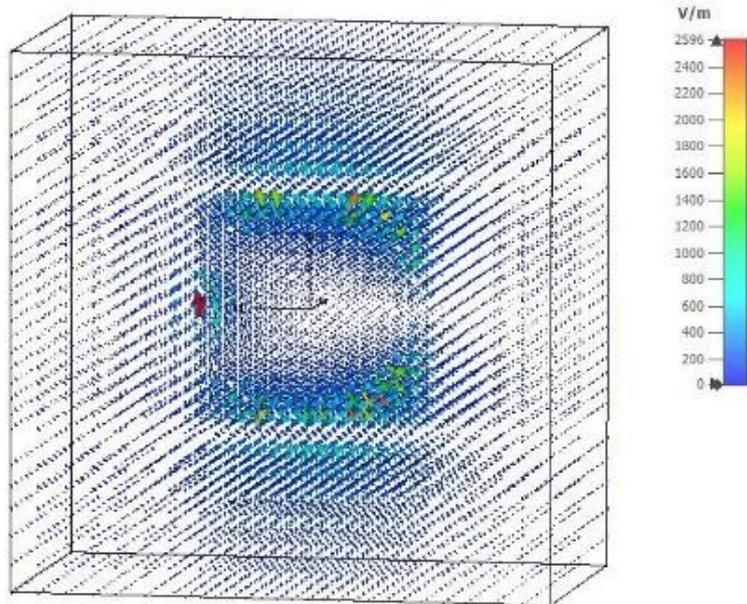
Fig. 8. E-field intensity of the proposed antenna

Current distribution: The 3D current distribution plot gives the relationship between the co-polarization (desired) and cross-polarization (undesired) components. Figure 9 shows the current distribution of the loop antenna.
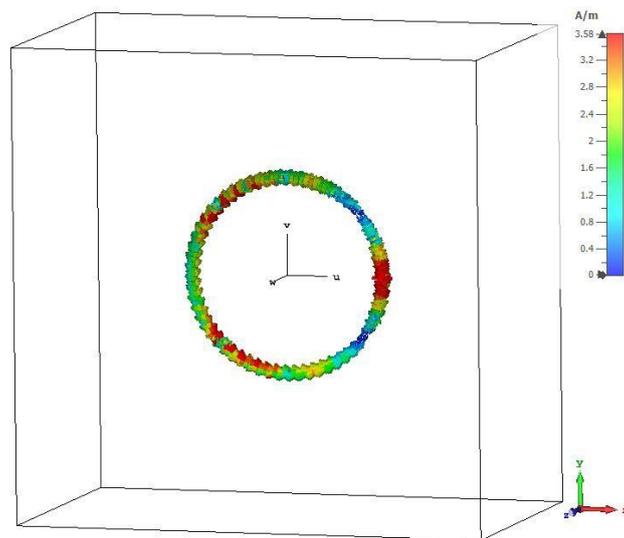

Fig. 9. Surface current distribution of the antenna

Precisely, the designed antenna has a simulated gain of 4.78 dBi, the directivity of 3.849 dBi, the input power of 495 mW, and the radiated power of 565 mW at f_r =2.45 GHz.

3 Energy Harvester Design at 2.45 GHz

This microwave signal is transferred to the 7-stage charge pump rectifier through an impedance matching circuit, to convert into DC power, which is additional accumulated in a storage element. The rectifier is a Schottky diode in which impedance is matched to the antenna by a low pass filter [20–22]. The topology design contains three main subsystems, each having specific purposes. The receiver antenna captures electromagnetic radiation from the MPS. The receiver signal is then efficient via the rectifier circuit that utilizes BAT63 (Infineon) Schottky diodes. A final subsystem acts as a backup system by storing power in the battery. The first storage device stores and accumulates charge from the rectified DC signal outputted by the rectifier circuit. As for the rectifier topologies, the choice of the rectifier, it will be studied and analyzed in the following subsection. All the requirements to install a harvester device hidden into the IoT devices should be proved, as shown in Figure 10.
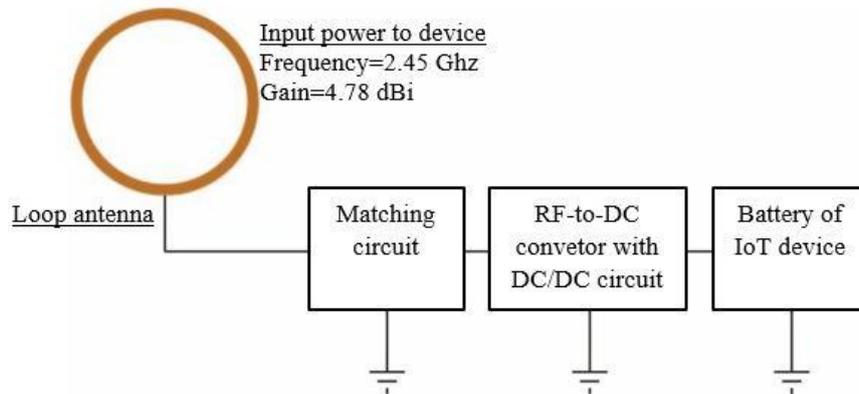

**Fig. 10.** Block diagram of the proposed harvester circuit

3.1 Matching circuit

In the phase testing, the VSWR at 2.45 GHz is 1.17 to reduce to 1. The matching circuit ensures the maximum power distribution from the antenna to the rectifier circuit [23].

3.2 Rectification subsystem

In this part, the RF-DC conversion circuit using seven stages charge pump uitilize Schottky diodes. The input impedance of the rectifier is connected to the matching cir-

cuit's output to maximize the power harvesting and decrease the signal reflected from the load [24]. Knowing the receiving is designed to operate at 2.45 GHz with the output impedance of 50Ω. Figure 11 shows the schematic de-sign of the rectification subsystem circuit. Figure 12 shows the simulation result of the 7-stage charge pump rectifier using diode BAT63. The below simulation shows the output voltage (V) of the rectifier circuit.
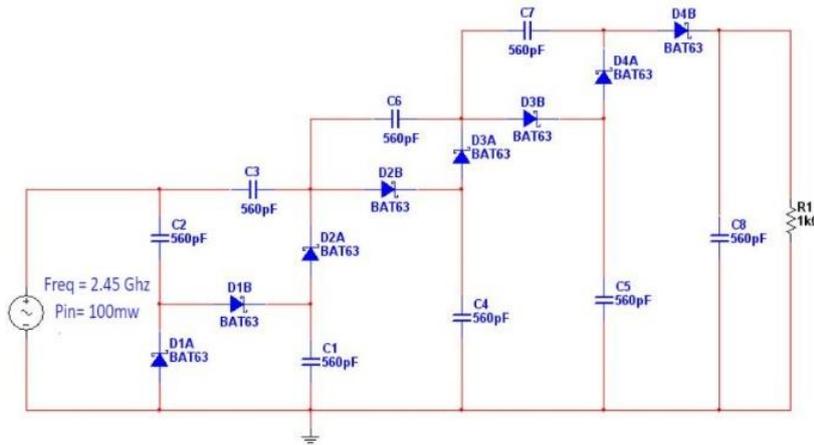

Fig. 11. Schematic diagram of microwave harvesting circuit with BAT63 diode
(Agilent ADS and Multisim)
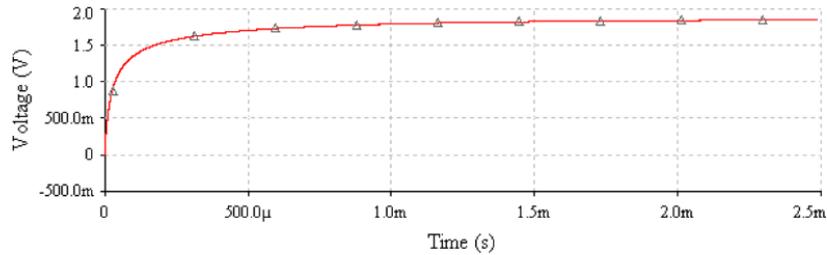
Fig. 12. Transient Analysis for 2540 MHz Charge Pump Design (100mW)

4 Prototype Result and Discussion

The microwave output power of the microwave station is $P_{out} = 55\,W$. We create the antenna using high-quality copper. The antenna prototypes are successfully built and measured using the S3101 Antenna Analyzer. Then, the loop antenna is ready to be tested with a vector network analyzer machine VNA. The measured S11 graph is depicted in Figure 13 in the Magnitude plot. It was around -24.65 dB from 2.455 GHz, and it is not the same simulation results. Also, our loop antenna can reach a maximum gain of 4.78 dBi.
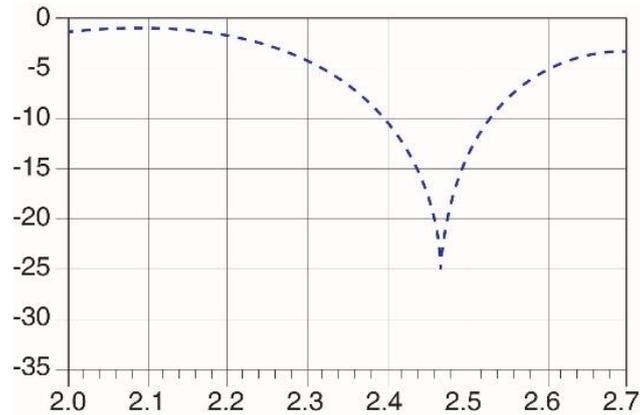
Fig. 13. Measured return loss (S11) results of antenna

The radiation efficiency is 47.23%. All the antenna parameters have been tested and optimized to deliver high-performance receivers. The results are satisfactory and show the advantage of using a loop antenna for acquiring microwave energy. In summary, all the simulated and real measurements indicate that the harvester device has a good performance. The energy acquiring device of the present work is capable of receiving microwave power from the S-band, and con- vert the received signals into electrical energy. An examination of the prototype in Figure 14 and Figure 15, respectively.

Actual test, it can be observed the efficiency of the harvester circuit changes according to the distance. The amount of power received change according to the gap between the microwave power station and the harvester circuit, as shown in table 2.

5   Conclusion and Perspectives

In this research paper, we tested, and we approved that we could produce electricity from S-band frequency to charge any battery of electronic devices. We made sure to easily install the harvester circuit into any IoT devices. The antenna achieves a reflection coefficient in a real test of -21.351 dB and the maximum gain direction at 4.80 dB at the operating frequency. All these performances measured results make this antenna suitable for S-band. High power and high-efficiency RF-to- DC convertor fabricated using Schottky diodes BAT63.
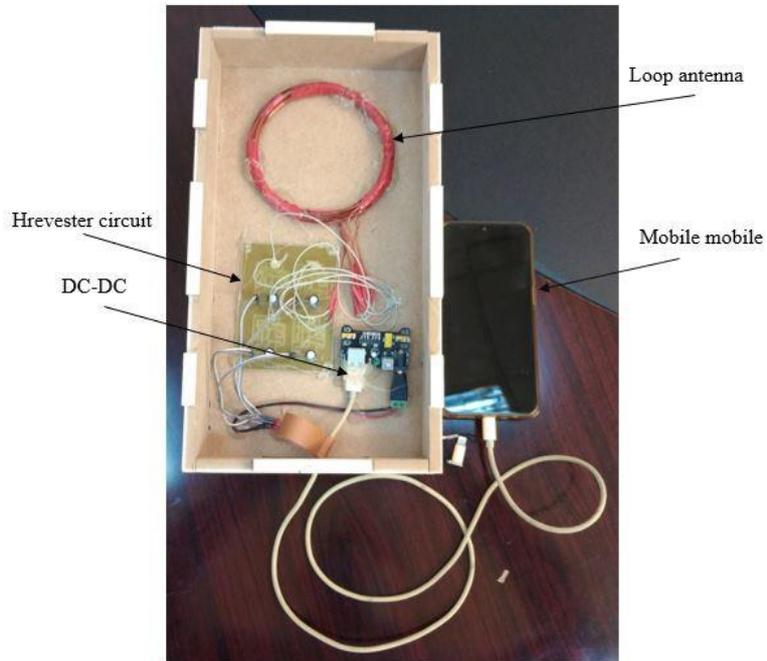
Fig. 14. Photograph of the receiver prototype (Photograph of the microwave harvesterdevice connected to a mobile phone to charge it)
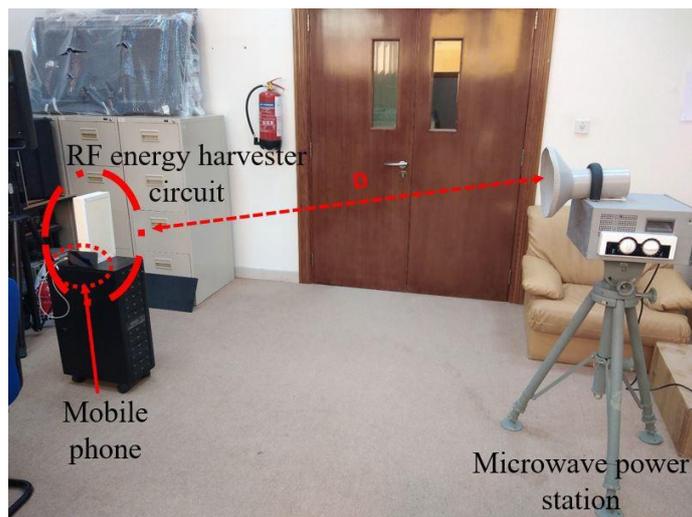
Fig. 15. Photograph of the experimental setup with a prototype

The circuit achieves high output DC voltage and good conversion back into electricity efficiency. Theconversion efficiency of 27% was achieved at S-band at an input

power level of 14.77 W a distance 10 m. In this research, we approved that we could change the strategy of the future industry 4.0 using the wireless power technology to keepall IoT devices full charge and can working a maximum of the time. In the future should be all IoT and IIoT electronic devices powered wirelessly. For the next work, different types of miniature antenna can be used in this application. We will also change the topology of the rectiier circuit and check the efficiency of the RF-to-DC circuit.

Table 2. The efficiency of the harvest circuit depends on the gap distance between the RF emitter and receiver IoT device

Distance between emitter and the Harvesting circuit (m)	Power at the receiving point (W)
10	14.77
15	13.58
20	10.23
25	8.01
50	6.55

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