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Dual Antenna Power Detector Operating over L, C Bands for Power Harvesting Applications in 3G, and 5G

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ABSTRACT: This paper proposes a circuit for power harvesting using a Wilkinson coupler to combine two patch antennas for dual collecting signals. A voltage doubler is connected through a rectifier stage to double. L-type impedance matching network is applied before non-linear diode for maximum power transfer from source to the load. Design, simulation, fabrication, and measurement results of power harvesting circuit that operates over L, and C bands are presented in this paper. The goal is to scavenge direct current, improve efficiency and sensitivity. From the measurement setup, it was found that the output power obtained is approximately identical with the Friis equation. Therefore, the results are able to employ in the L and C bands for powering 3G and 5G sensors.

KEYWORDS: RF energy harvesting, Wilkinson power combiner, L type impedance matching, Rectenna topology.

I.INTRODUCTION

Energy sources can be solar, wind, vibration, and radio frequency (RF) that have been considered over decades [1, 2]. According to [1-3], ambient light indoor is 0.1 mW/cm^2, outdoor is 100 mW/cm^2, and output power indoor is 10 µW/ cm^2, outdoor is 10 mW/cm^2 respectively. Secondly, vibration/motion of a human is 0.5 m/s^2@1Hz, 1 m/s^2@50 Hz, and industrial source is 1 m/s^2@5 Hz, 10 m/s^2@1 kHz, and the output power is 4 µW/cm^2, and 100 µW/cm^2 respectively. Thirdly, the thermal energy of a human is 20 mW/cm^2, and industrial is 100 mW/cm^2. The output power of the human is 30 µW/ cm^2, and industrial is 100 mW/cm^2. Fourthly, RF source power is 0.3 µW/cm^2, and output power is 0.1 µW/cm^2. The light source depends on the sun, and vibration/motion relied on the movement, but RF continuous.

Hence, researchers have put RF in the priority over other sources due to availability on time and ubiquity [1, 2]. Changing and charging the power supply components pollutes the climate and the result is an unpredictable expiry date. It can lead to a waste of time, and money. For these reasons, also the goal of energy harvesting (EH) is to harness green strategies, and to be powered autonomous.
Consequently, researchers have started to focus on studying the rectifying Wireless Power Transmission (WPT) over decades by [3]. They produce a rectenna concept, it is a process to convert RF signals to direct current (DC). It compromises antenna, and rectifier part including the load stage. It also states some common topologies of the rectifier: A half-wave, and a full-wave. It is also stated that a bridge diode rectifies the signal from positive and negative. An extra topology, the voltage multiplier, is presented by [3], it is a special form of rectifier circuit that converts and boosts AC input to DC output. The declared DC output can be improved by packaging single rectifiers into the series. Other research by [4] designed antenna is received AC then rectifying into DC. The method is divided

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the RF, after that it feeds various rectifying sections. The result is single-input, single-output rectifier. Their input is 17 dBm, PCE = 53.3% at frequency 2.1 GHz. The model has presented a framework used for obtaining an ideal antenna impedance by [5]. They used voltage doubler placed on the rectifier stage, and the frequency operates for 850 MHz to 1.94 GHz. Their results are in the distance 25 m, efficiency is equal to 60% at 980 MHz, and 17% at 1800 MHz, voltage is 3.76 V for open circuit and 1.38 V is across for load 4.3 kΩ.

A rectifier consisting of two stages L-type matching networks, operating at 2.4 GHz, and employing SMS7630 Schottky diodes is proposed in [6]. They obtained 0.17 V at the rectifier output, and the rectenna prototype scavenge DC current of about 3µA at the RF input power of -10 dBm. Another state-of-the-art design rectifier uses a 3 dB Quadrature hybrid coupler (QHC) for a wireless energy transfer system. The isolated port is connected to a load and coupler outputs are connected with two matching networks. Two sub rectifier circuits used four diodes SMS7630 [7].

From the state-of-the-art, there are still challenges EH such as input impedance power, unbalanced frequency. The desire is to contribute to the improvement of DC, sensitivity, and efficiency. Therefore, this paper focuses on designing a circuit for rectifying sufficient DC for powering the applications until 5G sensors. Also, the low power level is considered to improve the sensitivity and efficiency of the rectifier. The aim of this research is utilizing available source that ubiquity for powering telecommunication devices. Therefore, it enhances a sustainable power source via collecting signals for devices consumption, and green strategy. The implement of our work is in the following sections.

II. DESIGN AND FABRICATION

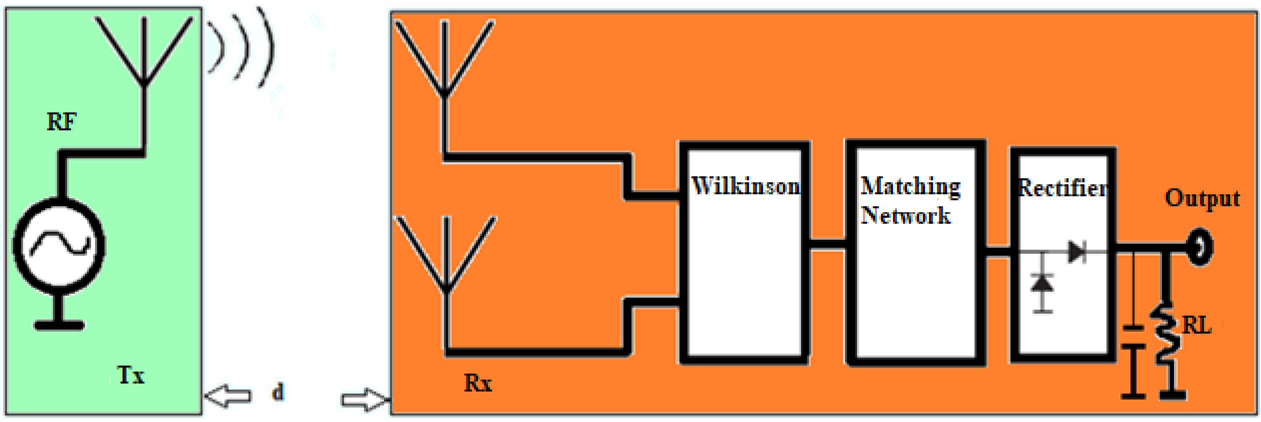

Fig. 1. Diagram of RF to DC for EH.

There are core parameters that are required to be contributed such as DC voltage, sensitivity, and efficiency. For these reasons, this paper designs the circuit from RF to DC for EH is shown in Figure 1. It employs a Wilkinson to combine two patch antennas to hook up as a trap for RF signals. Choosing a Wilkinson coupler is for their features, such as high isolation between ports, matching, and wideband. Substrate RO4350B has been used for printed circuit board (PCB).

The first step starts with the design of two rectangular patch antennas required to feed the inputs of the Wilkinson. Patch antennas are easy to fabricate, light weight, and can be used as an integrated array to increase the gain. The antenna's size is obtained by the equations of length and width in (mm) of the rectangular patch antenna [8].

$$\text{Width } (W\_antenna) = \frac{C}{2f\sqrt{(\text{Er}+1)/2}} = 17.28 \text{ mm} \quad (1)$$

Substitute frequency = 5.8 GHz, speed of light with dielectric constant ε_r = 3.48, and the thickness (h) = 1.52 mm, which are desirable for designing. When W/h>1, $\frac{17.28}{1.52}$ =11.368, then effective dielectric constant ($\varepsilon reff$), which is usually close to ε_r, then substitute the $\varepsilon_r, \text{h}, \text{W}$ in the equation 2: $\varepsilon reff = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[1+12\frac{\text{h}}{\text{W}}\right]^{-1/2} = 3.336$ (2)

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Effective length, it is assumed by equation 3: Leff $= \frac{c}{2f\sqrt{\varepsilon reff}}$ = 14.160 mm (3)

$\Delta L = 0.412\ \frac{(\varepsilon reff+0.3)\left(\frac{W}{h}+0.264\right)}{(\varepsilon reff-0.258)\left(\frac{W}{h}+0.8\right)}$ = 0.465mm (4)

Length_$antenna$ = Leff – 2 . ΔL=14.160+0.93=15.09 (5)

The second step is to design a Wilkinson power combiner [9] to connect patch antennas which are fit especially for bandwidth issue. The transmission lines are microstrip type to integrate all components into the same substrate. A computer aided design optimisation using Advanced Design Software (ADS) is performed to improve the original design parameters of two patch antennas.

A: Three ports are configured by equivalent transmission lines (TL), which needs width, and length of physical ports. The Z_o = 50 Ω, effective electrical length of the line (EL) = 90º, top cladding metal thickness (T) = 17.5 µm, loss tangent=0.004 mm. ADS tool calculates the dimensions of Wilkinson accurately.

B: Arrangement two curves of transmission lines to connect the ports, each curve is $Z_o.\sqrt{2}$ = 70.71 Ω, length of transmission line (L_TL) =λ/4, width of the TL is less than the three TLs of the ports.

C: Connect port 2 with port 3 by resistor for high isolation, and lossless, due to the ports are matching, and identical.

R = 2Z_o = 100 Ω (6)

Radius of Wilkinson $=$ L_TL.$\frac{2}{\pi}$ (7)

Patch antennas are connected with Wilkinson inputs by impedance transformers for matching purposes [7-9]. As well as it is required for impedance matching network. The tuning is an essential technique in order to obtain an ideal simulation of parameters such as S11, gain, and directivity. There is also a space considered λ/2 between the central of two antennas to avoid coupling between two patch antennas and direction of the energy.

Figure 2 illustrates the layout of Wilkinson with two antennas connected to its inputs, including the dimension. This circuit is integrated in one layer for performing the purpose of power scavenging.

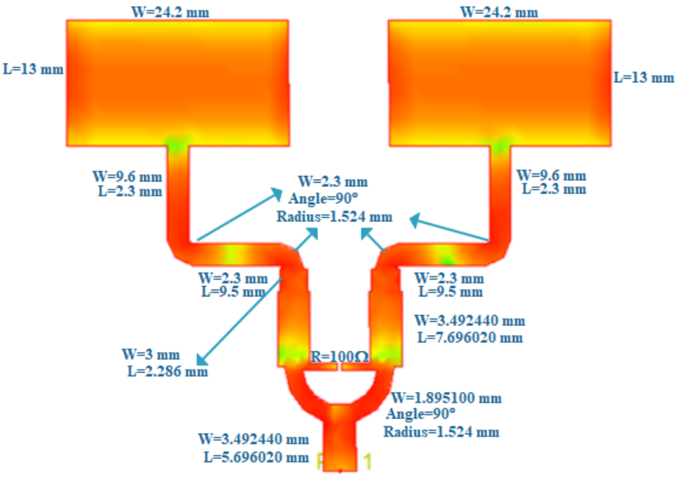

Fig. 2. Wilkinson and two antennas for radiation pattern.

The top view of the radiation distribution of the polar plots in Figure 3 is increasing. Thus, due to the by connecting dual source both rectangular patch antennas in the distance for all directions. An array patch antennas is affecting the directivity, gain, and the efficiency. The ideal radiation occurs when two antennas radiate at the same time, which leads an increase in the directivity and boost the gain.

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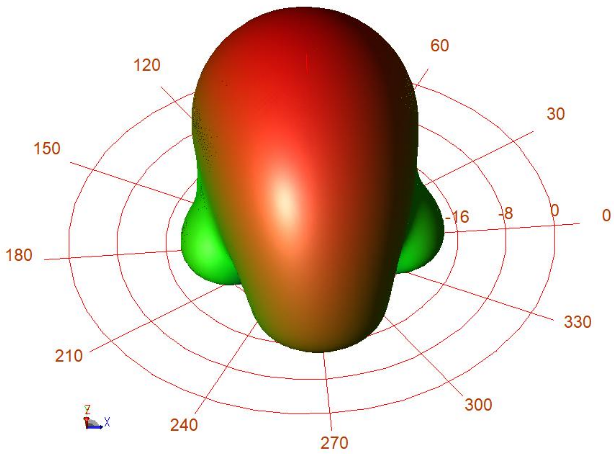

Fig. 3. Simulated result of 3D radiation pattern (rectangular two patch antennas with Wilkinson coupler).

In Figure 4, the directivity is reached 10 dBi, and the gain is greater than 8 dBi. The gain in single patch antenna is improved by combining two patch antennas.

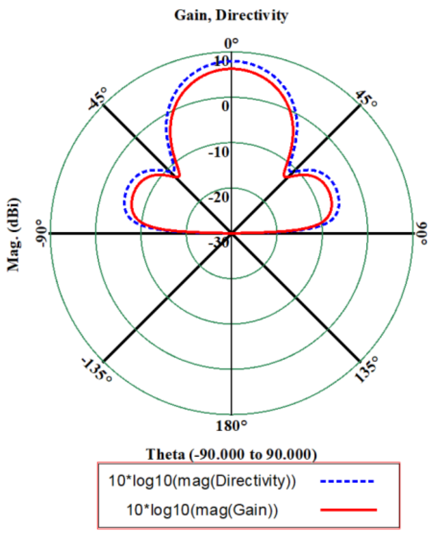

Fig. 4. Gain and directivity (rectangular two patch antennas with Wilkinson coupler).

Step three is the design of the Impedance Matching Network (IMN). The IMN adapts to maximize power transmitted from source to the load [10]. Unlike mismatching circuit leads to leakage through transmission line that causes deficient power. This paper uses the much simpler L type of Matching Network, and the source with RL are characteristically static values. Figure 5 displays in series inductor 1 connected with capacitor 1, and connected inductor 2. This circuit is located before the rectifier stage to ensure the highest power transmitted to the load stage.

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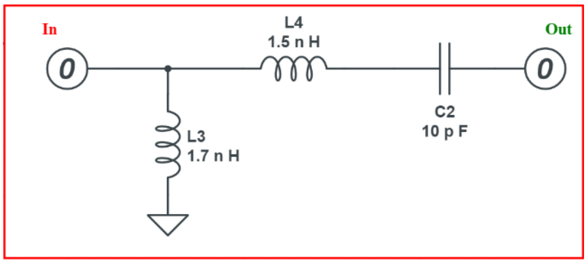

Fig. 5. Sketch of impedance matching network.

Step four is following up through the same line, voltage doubler is placed in rectifier stage. Its candidate for twice peak the voltage amplitude, for using a diode converts RF to DC via an auxiliary capacitor. This work employs' Schottkydiodes model SMS7630-006LF as shown in Figure 6 to fix the low power incident [11]. The features of this diode are low-barrier diodes and zero-bias detectors.

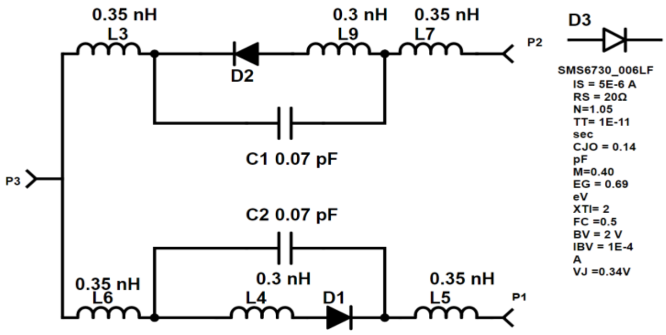

Fig 6. Schematic of Schottky diode.

The load stage consists of a capacitor = 1 µF for eliminating ripples, a resistor load = 5 Ω, and SMA female connecter. The matching simulation results (S11, S22) are observed in Figure 7 under -10 dB ranging from 1600 MHz to 2000 MHz, from 4100 MHz to 4600 MHz, and from 5600 MHz to 5900 MHz's. It obtains multiband over L, and C bands, due to increased thickness of substrate, Wilkinson matching, and considering the step equations of the component's parameters. Subsequently, achieving more bandwidth, leads more collecting signals, which is enhancing EH from output powering.

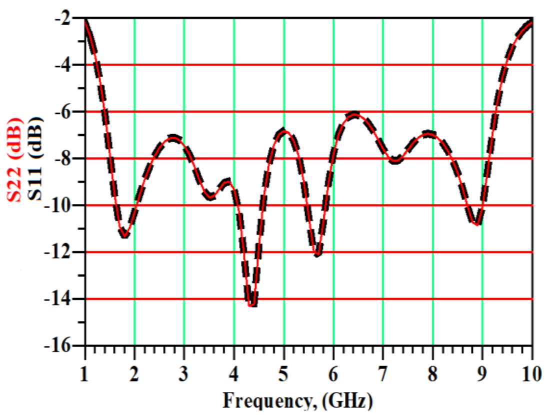

Fig. 7. S11, and S22 simulation.

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In power harvesting, parallel sources of RF design are enhancing the gain to reach efficiencies that plot in Figure 8 is 57% in an input power level 0 dBm. Also, the sensitivity metric is known as the lowest amount power necessary to power an integrated circuit. It is prompted around 1.325% in an input power -25 dBm through the simulation as detected.

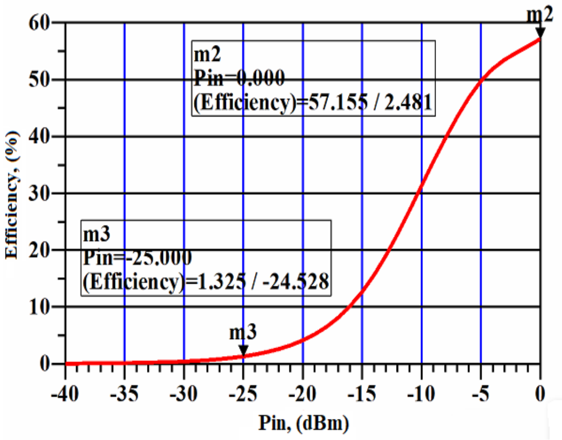

Fig. 8. Simulation of efficiency versus input power.

The DC Vout is 2.435 V for a power incident of 0 dBm, which is depicted in Figure 9 (at 0 frequency).

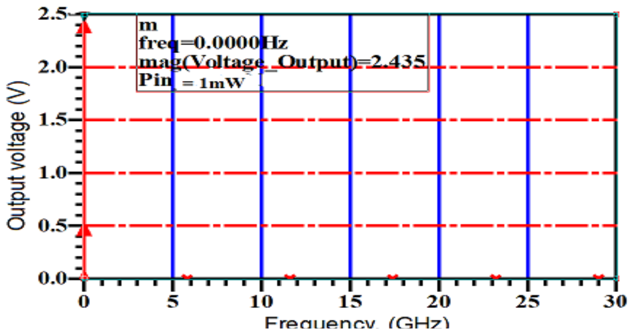

Fig. 9. Shows the Vout versus frequency.

Table 1 illustrates Vout at different input powers; the result is triggering of the diode and dramatic increase the Vout as shown at 0 dBm. In spite of some challenging such as changing the frequency or input power level, however, the result is proper due to persisting matching of Wilkinson combiner [12].

Table 1. Illustrates Vout versus Pin of Wilkinson combines two antennas.

Pin (dBm)	Vout (V)
-30	0.007
-20	0.066
-10	0.522
0	2.435

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The equation (8) of the output power linear from 0 to 30 GHz frequency uses for the linear output DC power in dBm [13]. These factors are affecting the valuable results, especially for DC output from the load stage that displays in Figure 10 linear output power in (dBm) at (ADS) subtract 20.

$$Pout = 10\,.log^{10}.\frac{\text{Vout}^2}{\text{Rl}}\,.10.\log^{10}.\frac{1}{100} = \text{-2.27(dBm)}. \quad (8)$$

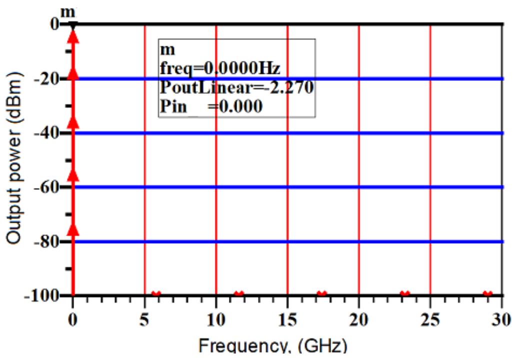

Fig. 10. Displays the Pout in linear.

In Figure 11 illustrates the fabricated circuit (7.5 x 7.5 cm). Physically, the circuit is simple, and smaller when compared with other works. It is appearing as a Printed Circuit Board (PCB). As well as the items are available, cheap, and the Rogers company provides the substrate.

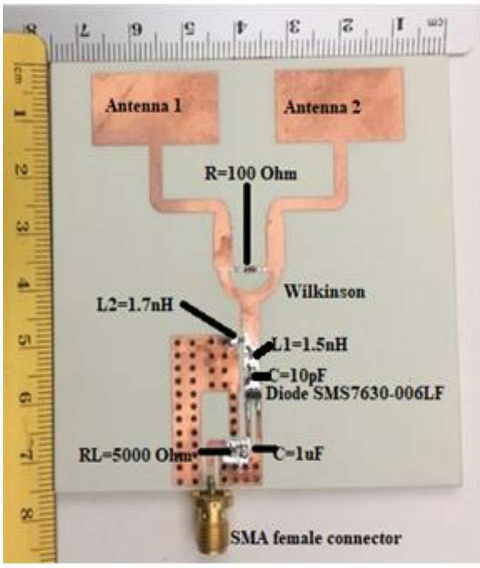

Fig. 11. Physical of the fabrication circuit prototype.

III. MEASUREMENTS

Friis equation is applied in the measurement process. The representative setup of the near field and far-field of WPT classification is based on Figure 1. The equation (9) is used to calculate the receiver power (Prx) at the load of the proposed circuit.

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$$Prx = Ptx\,.\,Gtx\,.\,Grx\left(\frac{\lambda}{4\pi D}\right)^2 = -19.6938\text{ dBm}. \tag{9}$$

By applying the values of power transmitter (Ptx) = 7 dBm, the gain of the transmitter (Gtx) = 7 dBi, the gain of the receiver (Grx) = 8 dBi, the distance between transmitter and receiver 50 cm, and π, a received power with the value of -19.6938 dBm has been obtained.

Equation (10) is used to find the: Path Loss $= Gtx\,.\,Grx\,.\left(\frac{\lambda}{4\pi D}\right)^2 = -26.687\ dBm.$ (10)

The demo is conducted in the INRS Lab Montreal. On the receiver side, Agilent 34401A, 6½ Digit Multimeter device is connected with the receiver circuit is collecting RF and converting RF to DC. The output power result illustrates in Table 2. It is determined the unit of input/output power is in dBm, frequency (*f*) is in MHz, and *D* is the distance between transmitter antenna and receiver circuit is fabricated. Related to the simulation in Figure 7, Friis equation, and measurement setup process, there is an approximate agreement of results.

Table 2. Transmitter input power = 7 dBm, and the measured results of output power.

D (cm) / (MHz)	100	75	50	25
	Output power (dBm)			
1760 to 1930	(-32.356) – (-40.665)	(-26.551) – (-40.303)	(-22.456) – (-35.657)	(-18.865) – (-24.652)
3020 to 3160	(-34.725) – (-41.331)	(-19.435) – (-27.215)	(-17.562) – (-22.432)	(-15.765) – (-21.864)
5320 to 5700	(-35.230) – (-44.212)	(-27.711) – (-40.434)	(-21.798) – (-30.675)	(-17.342) – (-28.231)
6000 to 6060	(-36.866) – (-45.264)	(-34.331) – (40.230)	(-24.543) – (-30.439)	(-19.547) – (-29.275)

IV.CONCLUSION

This paper presents Wilkinson combines two patch antennas for collecting more energy. In addition, it is twice the value of voltage due to the configuring the voltage doubler topology. It boosts the results of DC voltage, efficiency and sensitivity by employing the full-wave topology rectifier. The efficiency of the circuit is 57.155% at 0 dBm in simulation under the Rl = 5 KΩ, and the sensitivity 1.325% at input power -25 dBm.
In measurement, a 7 dBm input power provides the output power with a wideband frequency at multi peaks of output power fluctuates based on the frequency versus the distance from -45.264 dBm to -15.765 dBm (shown in Table 2) where the power consumption of the sensors is less than the power provided by the proposed rectenna.
Accordingly, the power harvesting circuit could be used for 3G, also 5G that will launch in 2020 over L and C bands frequencies. Consequently, the voltage crop of the circuit proposed has come up as expected from the work.
The future work will be expanded to combine RF in triple before rectenna to accumulate more RF. Also, it might concentrate on some aspects that contribute to improving the result.

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