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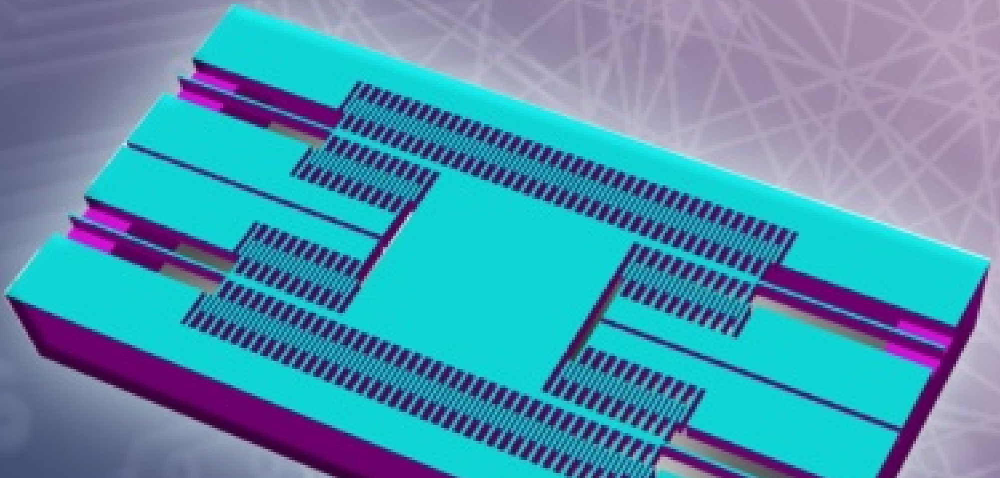

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RF Energy Harvester: Harvesting Power from WiFi Signals for Low Power RFID Application

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Abstract: Radio Frequency Identification (RFID) is a wireless communication technology that enables users to uniquely identify tagged objects or people via radio frequency waves. Active RFID tag has an onboard battery to power the tag which allows greater capability compared to passive tags. However, onboard batteries have limited lifespan and replacement of batteries can be time-consuming and costly. A solution to battery replacement would be to harvest ambient RF energy to prolong the battery life of the active RFID tag. The aim of this research is to harvest energy from WiFi signals using rectenna architecture which consists of a receiving antenna attached to a rectifying circuit that efficiently converts RF energy to DC current. Harvested power will be in the order of microwatt range and utilization of harvested power has to be specific for applications with low power consumption.
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Keywords: Radio frequency, RFID, Energy harvesting, Rectenna, WiFi.

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1. Introduction

Deployment of RFID technology has been strongly advocated by the Malaysian government. Earmarked as an Entry Point Project in Malaysia’s Economic Transformation Program, RFID market is expected to contribute RM1.4 billion towards Malaysia’s Gross National Income and create 4000 job opportunities by 2020 [1].

RFID is a system that transmits the identity of an object wirelessly using radio waves. In general, tags are either active or passive. Passive tags are the most extensively used in RFID applications due to cost and ease of implementation. Unlike passive tags, active tags have onboard batteries, which extend their reading range. These tags are costlier and physically larger due to complexity of design [2]. One barrier in expanding the use of active tag technology is the need for battery replacement. Asset tracking in the oil and gas industry utilize passive tags to eliminate the ongoing need for battery replacement [3]. The significance of active RFID tag technology can be seen in the next ten year forecast from 2011-2021 showing inroads into a wide range of application sectors with strong commercialization potential [4]. In the framework of application development in security documents, energy harvesting technology could be integrated within RFID system to prolong battery lifespan [5].

Table 1 gives a summary of harvester power efficiency from various sources under different conditions [6]. Interestingly, RF energy harvesting records the highest power conversion efficiency at 33 % making it an appealing source for ambient energy harvesting.

Table 1. Efficiency of harvested power from various sources.

Source	Source Power	Harvested Power	Efficiency
Incident Light			
Indoor	0.1 mW/cm^2	10 μW/cm^2	10 %
Outdoor	100 mW/cm^2	10 mW/cm^2	10 %
Motion			
Human	0.5 m @ 1 Hz	4 μW/cm^2	N/A
	1 m/s^2 @ 50 Hz		
Industrial	1 m @ 5 Hz	100 μW/cm^2	N/A
	10 m/s^2 @ 1 kHz		
Thermal Energy			
Human	20 mW/cm^2	30 μW/cm^2	0.15 %
Industrial	100 mW/cm^2	1-10 μW/cm^2	0.001-0.01 %
RF			
Cell phone	0.3 μW/cm^2	0.1 μW/cm^2	33 %

WiFi with a frequency of 2.40-2.484 GHz carries a very strong appeal with ever increasing presence of broadband accessibility in Malaysia and Malaysian Communications and Multimedia Commission has been tasked to expand broadband connectivity throughout the country [7]. Statistics showed an increase of 25 % in the number of hotspot locations in the first quarter of 2011 nationwide as compared to 2010 [8]. With communications infrastructure such as WiFi hotspots already in place, readily available ambient power can be harvested through the rectenna system.

2. Rectenna Architecture

2.1. Conventional Model

Essentially, the rectenna consists of a receiving antenna and a rectifying circuit that rectifies RF energy to DC current. As shown in Fig. 1, a conventional rectenna is made up of an antenna, a matching network, a lowpass filter, rectifying circuit, another lowpass filter for DC path and a resistive load [9]. Incident RF power is converted to DC current by a diode based rectifying circuit through a receiving antenna. Before reaching the resistive load, the DC low pass filter will smoothen the output DC voltage and current by suppressing high frequency harmonics present in the RF signal. Nonlinear rectification process could also contribute to the generation of frequency harmonics.

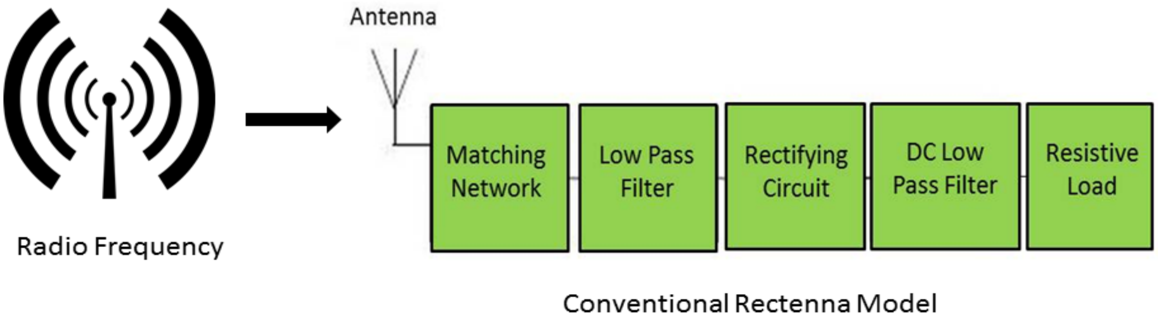

Fig. 1. Diagram showing conversion of RF to DC current using conventional rectenna architecture.

2.2. Rectifying Circuit Topology

Rectifying circuit topology has to be studied for efficient device operation. Common rectifying circuit topologies found in rectennas are the Cockroft-Walton, Dickson or Greinacher voltage multiplier configuration with Schottky diodes being a popular choice. No significant difference was observed between Dickson and Cockroft-Walton topologies [10]. A modified Greinacher topology was utilized by J. P. Curty et al in their rectenna system [11]. It can also be seen that higher DC voltage can be achieved in these topologies when multiple stage configurations are employed [11, 12]. In terms of diode selection, Merabet et al found that low junction capacitance and low series resistance were important considerations under low input RF power for high conversion efficiency [13]. HSMS2860 diode showed highest conversion efficiency with junction capacitance of 0.18 pF and series resistance of 5 Ω.

RF-DC efficiency can be calculated by the following formula

$$\eta(\%) = \frac{P_{DC}}{P_R} \times 100\% = \frac{V_{DC}^2}{R_L \cdot P_R} \times 100\%, \quad (1)$$

where P_{DC} signifies output DC power, P_R indicates power received by the rectifier, V_{DC} symbolizes output DC voltage and R_L represents the load resistance.

Two works involving single stage Cockroft-Walton voltage multiplier performance can be seen in Table 2 with output power ranging from 166 – 470 µW and RF - DC efficiency recorded at 26 % and 47 % respectively.

Table 2. Performance of single stage Cockroft-Walton voltage multiplier.

Ref.	Circuit	Center Frequency (GHz)	P_{in} (mW)	V_{out} (V)	R_{load} (k Ω)	P_{eff} (%)	Output Power (µW)
14	Cockroft-Walton	2.63	0.6	1.35	11	26.0	166
15	Cockroft-Walton	0.925	1.0	1.54	5	47.0	470

However, it is a known fact that a higher DC output voltage can be obtained by adding the number of stages in the voltage multiplier. J. Wang's team investigated multiple stages of a Cockroft-Walton voltage multiplier with RF input of 200 nW (-37 dBm) [16]. Investigation summary is shown in Table 3. The loss of power efficiency is a limiting factor to the number of stages inherently possible.

Table 3. Performance of multiple stages Cockroft-Walton voltage multiplier.

Circuit	Stages	P_{in} (nW)	V_{out} (V)	R_{load} (k Ω)	P_{eff} (%)	Output Power (μW)
Cockroft-Walton	4	200	3.0	$1e^8$	45.00	0.09
Cockroft-Walton	8	200	6.5	$1e^9$	21.13	0.042
Cockroft-Walton	12	200	10.5	$1e^{11}$	0.55	0.0011

2.3. Antenna Design

Antenna design warrants equal attention in our bid to realize an efficient rectenna system. In his dissertation, W. S. Yeoh summarizes different dipole antenna research in the context of a rectenna from different authors working on 2.4 GHz band [14]. By fractalizing an antenna, size reduction can be achieved [17]. A recent study in the area of fractal antennas for rectenna application has already been conducted by S. Sheik Mohammed et al [18]. The ability to minimize the dimension of the antenna while maintaining a high gain would be advantageous for the rectenna system.

2.4. Research Objectives

Requirements for the rectenna system were benchmarked against [19] where piezoelectric vibration was studied as a potential source for active RFID tag application. The active RFID tag studied by Hande et al had a requirement of 18–30 μW average power. The prototype successfully delivered 90 μW of continuous power with 2.5 V output voltage. As such, expected system output should possess minimum system efficiency of 50 %, produces a minimum output voltage of 2 V with low input power below 0 dBm and delivers 18-30 μW of output power.

3. Results and Discussion

Dickson, Cockroft-Walton and Greinacher topologies were simulated using harmonic balance simulation on ADS simulation software by increasing the number of stages to determine minimum requirement for 2 V output voltage. While maintaining center frequency at 2.45 GHz, input RF signal was fixed at 0 dBm. HSMS2860 Schottky diodes were used with load resistance of 1 MΩ. Simulation results obtained from the three different topologies are recorded in Table 4.

Table 4. ADS simulation results of different voltage multiplier topologies.

Stages	Output Power (dBm)			Output Voltage (V)		
	Dickson	Cockroft-Walton	Greinacher	Dickson	Cockroft-Walton	Greinacher
1	-12.053	-12.053	-12.410	0.931	0.931	0.809
2	-12.440	-12.440	-14.008	1.598	1.598	1.184
3	-13.172	-13.172	-15.952	2.096	2.096	1.125
4	-14.060	-14.060	-17.829	2.338	2.338	0.942
5	-15.025	-15.025	-19.488	2.343	2.343	1.184

Simulation results revealed no significant difference between Dickson and Cockroft-Walton configurations for all five stages similar to [10]. A reduction in output power was observed against increasing output voltage by adding the number of stages which agrees with [16]. Compared to the other two topologies, Greinacher topology exhibited lower output power and output voltage for all five stages.

Next, Bessel lowpass filter (LPF) lumped element schematic was added to investigate harmonic suppression between Cockroft-Walton and Greinacher topologies as tabulated in Table 5. RF input signal remained at 0 dBm with 1 MΩ load resistance.

Table 5. Harmonic suppression investigation with Bessel lowpass filter.

Stages	**Output Response**	**Cockroft-Walton**		**Greinacher**	
		With LPF	**% suppression**	**With LPF**	**% suppression**
1	Voltage (V)	1.169	93.94	1.113	94.44
1	1st harmonic (dBm)	4.974		4.812	
1	2nd harmonic (dBm)	-82.08		-86.493	
2	Voltage (V)	1.901	94.47	1.61	96.09
2	1st harmonic (dBm)	4.544		3.841	
2	2nd harmonic (dBm)	-82.21		-89.025	
3	Voltage (V)	2.418	95.52	1.628	98.70
3	1st harmonic (dBm)	3.758		1.21	
3	2nd harmonic (dBm)	-83.92		-93.061	
4	Voltage (V)	2.742	96.83	1.353	98.82
4	1st harmonic (dBm)	2.730		-1.146	
4	2nd harmonic (dBm)	-86.14		-97.487	
5	Voltage (V)	2.794	98.25	1.062	96.85
5	1st harmonic (dBm)	1.551		-3.194	
5	2nd harmonic (dBm)	-88.52		-101.5	

Bessel filters have a smooth response in the passband and attenuation rises smoothly in the stopband [20]. Seventh order Bessel LPF was employed after the rectifying circuitry on the strength that higher order filter will give larger bandwidth for constant group delay [21]. Trade-off for superior harmonic suppression in Greinacher topology comes in the form of lower output voltage which concurs with [22]. According to [22], full wave rectifiers (Greinacher topology) experience more harmonic attenuation compared to half wave rectifiers (Cockroft-Walton topology). Greinacher topology was unable to achieve a minimum of 2 V output voltage in all five stages of multiplication in contrast to Cockroft-Walton topology. The increased number of Schottky diodes introduces more losses which would explain the decline in output voltage after the third stage [10]. Focus was now diverted to Cockroft-Walton topology.

A seven stage Cockroft-Walton voltage multiplication with Bessel LPF was able to achieve 2 V output voltage with an arbitrary load resistance of 1 kΩ under low input RF signal as shown in Table 6.

Table 6. Seven stage Cockroft-Walton topology with Bessel lowpass filter output responses.

RF input (dBm)	**Voltage (V)**	**1st harmonic (dBm)**	**2nd harmonic (dBm)**	**% suppression**
0	3.743	-0.610	-57.023	98.93
-1	3.228	-1.673	-60.263	97.22
-2	2.781	-2.744	-62.777	95.63
-3	2.394	-3.814	-64.838	94.12
-4	2.058	-4.881	-66.663	92.68

Initial Bessel lowpass filter was further optimized with desired frequency response of -3dB at 2.4 GHz as shown in Fig. 2.

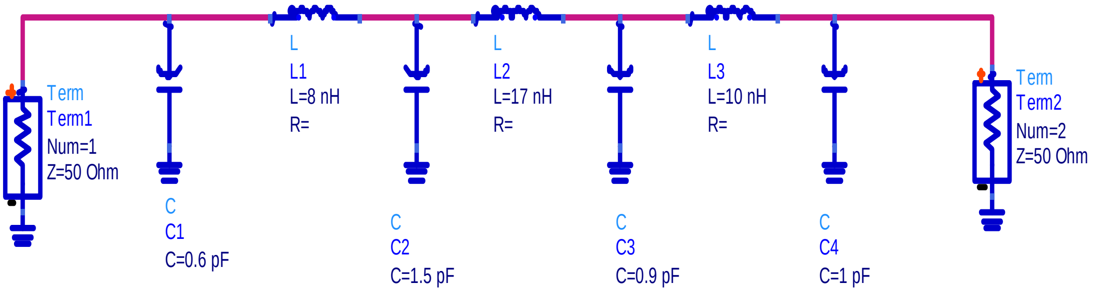

Fig. 2. Lumped element schematic of optimized 7th order Bessel filter.

Lumped element schematic was converted to microstrip dimensions based on cut-off frequency, dielectric attributes and microstrip line width. Laminate substrates taken into consideration were FR4 and RO5880 with the following parameters tabulated in Table 7.

Table 7. Printed circuit board laminate parameters.

Parameter	FR4	RO5880
Laminate thickness (mm)	1.60	0.787
Copper thickness (µm)	35	35
Dielectric constant	4.7	2.2
Loss tangent	0.02	0.002

Simulation was carried out again taking into account parasitic losses from surface mounted component packaging as supplied by manufacturer in order to minimize deviation of measured and simulated results [23]. The parasitic modeling circuit for HSMS2860 chip diode is shown in Fig. 3.

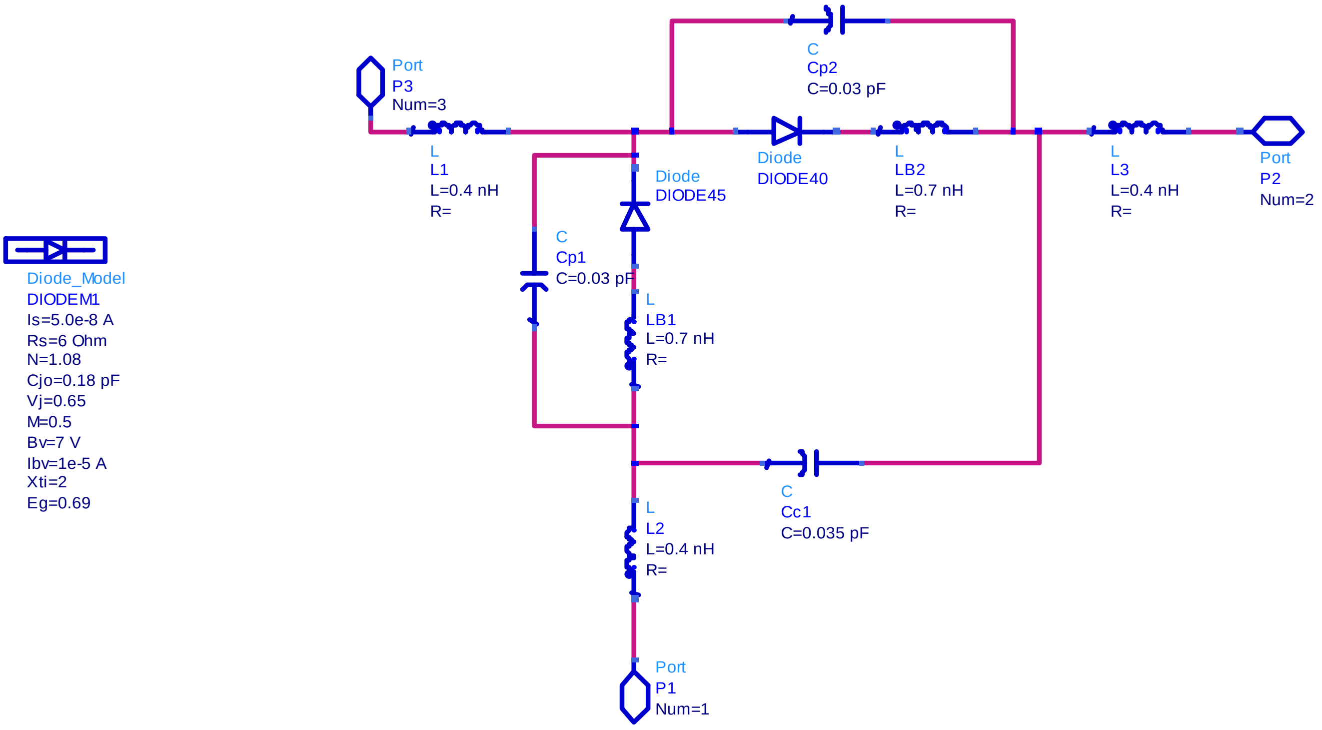

Fig. 3. Parasitic modeling circuit for HSMS2860 chip diode and its packaging.

RF input signal was swept inside ADS simulation from -4 dBm till 0 dBm on seven stage Cockroft-Walton topology with load resistance of 1 kΩ at 2.45 GHz with results shown in Table 8.

Table 8. Simulated results on different laminate material using parasitic modeling.

RF input (dBm)	**FR4 laminate**	**RO5880 laminate**
	Output Voltage (V)	**Output Voltage (V)**
0	2.729	2.729
-1	2.348	2.347
-2	2.018	2.016
-3	1.732	1.728
-4	1.482	1.477

Results show that seven stages Cockroft-Walton topology has the capability to achieve the desired 2 V output voltage with RF input signal below 0 dBm even after taking into account parasitic elements.

4. Conclusions

Clearly, there is much potential in scavenging RF power through the rectenna architecture. A lot of interest has been generated over the last few years in this area of RF energy scavenging even as we move towards promoting green renewable technology. Maximizing power conversion efficiency under low input RF signals would be a priority in evaluating rectenna system performance. The appeal of this research lies in the availability of WiFi signals with statistics showing nationwide expansion on the rise. Knowledge gleaned from this study could eventually be synergized with biomedical engineering expertise particularly ultra low power applications such as pacemakers and hearing aids. Rectifying circuit simulation work show promising results which warrant further investigation into prototype development for experimental validation.

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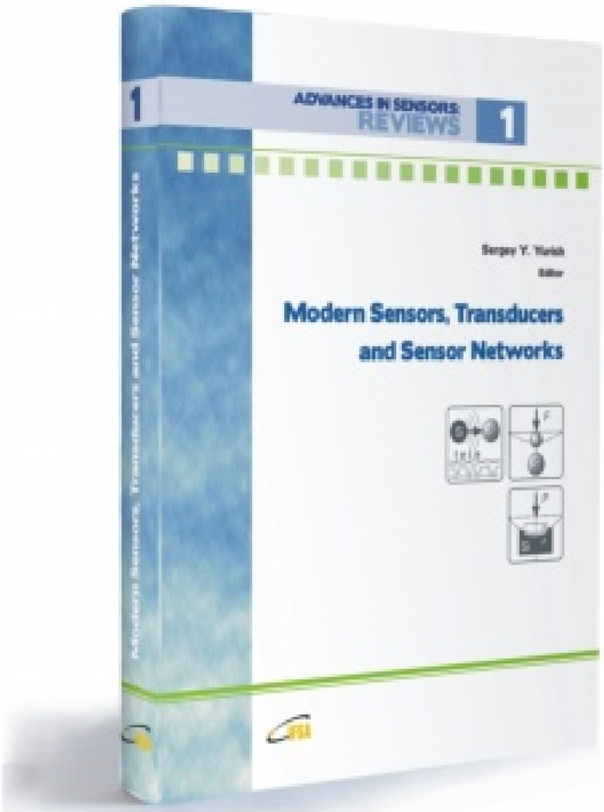

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