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COMPARISON ON MICROSTRIP PATCH ANTENNA MODULES AND RECTIFIER MODULES FOR RF ENERGY HARVESTING

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ABSTRACT

Electromagnetic energy harvesting holds a promising future as an alternative energy in order to power low power devices. RF energy harvesting systems has been carried out by many researches and efforts have been put into converting RF into usable DC. This paper is a comprehensive review paper which covers the antenna modules and rectifier modules which are being utilized in RF energy harvesting systems over the years. Both the antenna modules and rectifier modules are put into comparison and critically analysed. From the comparisons made, the gaps and challenges are further discussed in detail.

Keywords: microstrip patch antenna, rectifier, RF energy harvesting.

INTRODUCTION

In recent times, there has been a vast research interests in radio frequency (RF) energy harvesting/scavenging techniques or commonly known as RF energy harvesting. The concept is to basically convert received RF signals into usable electricity. This method seems to be a promising one as it acts as a solution to power energy-constrained wireless networks.

A basic RF energy harvesting system would consist of an antenna, a matching network, a RF to DC conversion module and a DC load circuit. The antenna is considered to be the heart of the system as the whole system depends on it. In the last few years, many researches have been carried out in designing various types on antennas to meet the purposes that have been proposed for use in RF energy harvesting systems. The reason a microstrip patch antenna being vastly used in this system is due to its low profile, light weight and planar structure. Conventional patch antennas come in circular and rectangular shapes. Variations in this basic design are made in order to meet desired results.

Another important circuit in a RF energy harvesting system is the energy conversion module or known as a rectifier. The main purpose of the energy conversion module is to convert from RF to usable DC. This can be done in many ways which includes voltage double circuits, CMOS technology process, diode charge pumps, RF power detectors and also super capacitors.

A rectifier would mainly consist of diodes. There are various types of diodes in market which have different energy conversion efficiencies. A study has been made on the efficiencies of different types of diodes used in RF energy harvesting system and the efficiency of its energy conversion. The output of the rectifier circuit should be able to power up a DC load circuit.

This paper covers a comprehensive review of antenna modules and rectifier modules implemented in recent RF energy harvesting researches. Comparisons include discussion on existing systems, types of antennas and the bandwidth or gain achieved types of rectifier modules and energy efficiencies achieved. The next section presents a comparison of the existing antenna modules in RF energy harvesting systems. Section III discusses the comparison on rectifier modules and the energy efficiencies achieved. Section IV discusses the gaps and challenges faced in designing an antenna module and a rectifier module for a RF energy harvesting system. Section V concludes this paper.

ANTENNA MODULES

Various types of antennas have been designed over the past years to cater for an efficient RF energy harvesting system. The design of an antenna is often challenged by the need for impedance matching, polarization and also higher order harmonic suppression. An effect of variation in substrate thickness and its permittivity on a microstrip patch antenna was studied [1]. A total of eight cases of antenna characteristics were designed to provide the effect of substrate thickness and its permittivity. Various types of microstrip patch antenna were designed in order to achieve bandwidth enhancement and size reduction. Some of the methods applied are Short Patch technique, Stacked Short Patch, Slot-Loading, and also Slotted Ground Plane techniques [5]. A wide-band E shaped patch antenna was designed and achieved an impedance bandwidth of 32% [4]. A U shaped slot microstrip patch antenna was introduced with a wide operating bandwidth [2]. This antenna achieved an impedance bandwidth of 10-40%. Meanwhile a double U shaped slot microstrip patch antenna was designed [3]. An impedance bandwidth of 44% is achieved. This study shows that the double U shaped slot antenna had a better bandwidth compared to the single slot microstrip patch antenna.

A rectangular microstrip patch antenna was designed based on resonant circuit approach [8]. The microwave filter synthesis technique was applied in order to obtain the resonance at 2GHz. The antenna managed to achieve a bandwidth of 40 MHz. Antennas performed differently under different frequency bands. A dual and triple meander slot antenna was designed for Wireless Local Area Network applications. The antenna can however be simulated to be used for RF energy harvesting. The dual meander slot antenna achieved a bandwidth of

29.48MHz whereas the triple meander slot antenna achieved a bandwidth of 43.01MHz [9].

A multiple slot rectangular microstrip patch antenna was designed in order to achieve enhanced bandwidth [10]. A total of 13 slots were designed and are arranged in parallel with the feeding line. At an operating frequency of 1.6GHz, this multi slot rectangular microstrip patch antenna achieved a bandwidth of 53.3 MHz. Meanwhile, a square microstrip patch antenna was designed via implement a U-slot with metallic rings [11].The antenna's operating frequency is at 5.8GHz. The gain enhancement achieved in via this antenna is 4.3dB.

In order to further improve bandwidth, an L-slotted patch antenna is designed by introducing an annular ring in between [6]. The resonating frequency is greatly reduced by increasing the excited surface current path. This is done without increasing the antenna length. A bandwidth of 100 MHz was achieved in operating frequency of ISM band. A diamond shape microstrip patch antenna was designed for a dual band operation [12]. The antenna operates at a frequency of 7.5079GHz and 10.94GHz and achieved a gain of 5dBi. A rectangular and circular microstrip patch antenna was designed [13]. These antennas are to operate in the X band range of frequency. The circular patch antenna offers about 8% higher bandwidth compared to the rectangular patch antenna. However the rectangular patch antenna shows about 3dB higher return loss compared to the circular patch antenna.

A novel slotted broadband microstrip path antenna was designed [14]. A novel slotted structure was etched on the patch of the new microstrip patch antenna and the ground plane is equipped with strip-line gaps. This is unlike the conventional microstrip patch antenna and it achieved a bandwidth of 1.55GHz which is about 13 times wider than an original microstrip patch antenna. A compact bow shape microstrip patch antenna was designed with different substrates [15]. The antenna has Benzocyclobutene as a substrate and resonates at a frequency of 4.35GHz with a return loss of -19.55dB.

Table-1. Summary of System Comparison on Microstrip Patch Antennas

Reference	Antenna type	Bandwidth Impedance/Gain/Return loss
[1]	Variation in substrate and permittivity	10-40%
[2]	Rectangular U-slot	10-40%
[3]	Rectangular double U-slot	44%
[4]	E-shaped	32%
[5]	Broadband	17.8%
[6]	L-slot rectangular	100MHz
[7]	M-Patch	13%
[8]	Rectangular	40MHz
[9]	Dual and triple meander	29.48MHz/43.01MHz
[10]	Multiple slots	53.3MHz
[11]	Novel square	5.88MHz/4.3dB
[12]	Diamond	5.6dBi
[13]	Rectangular and circular	-21.3dB/-18.3
[14]	Novel slotted broadbaand	1.55GHz
[15]	Compact bow shape	-19.55dB

RECTIFIER MODULES

A rectifier is used in RF energy harvesting system to convert RF to DC. RF signals are naturally AC signals. There are many types of rectifier circuits available. A rectifier's main component is a diode. A diode circuit joined with an antenna is utilized for RF-to-DC power transformation. To change over a greater amount of the antenna surface incident RF force to DC power, high RF-to-DC change effectiveness is needed of the amending circuit. Numerous authors have demonstrated that the effectiveness relies on upon a few variables like Schottky diode sort, harmonics concealment ability, load resistance choice, and the capacity to handle self-assertive polarized incident waves. Some other works have implemented voltage doubler circuits to transform the RF to DC. Schottky diodes are used in voltage doubler circuits as well.

Figure-1 below is a plot on RF energy conversion efficiencies versus the input power [35]. Several trends can be observed from this plot. First and foremost, as power increases, efficiencies tend to increase. This is due to a decrease in the effect of losses due to diode threshold voltage. At high powers, large efficiencies are possible as the energy-harvesting devices are operating in a linear state, far above their diode turn-on voltage. As the power level is reduced, the device efficiency decreases because the diode is "on" for a smaller fraction of the RF wave period. Secondly, as frequency increases, the efficiency of the devices decreases.

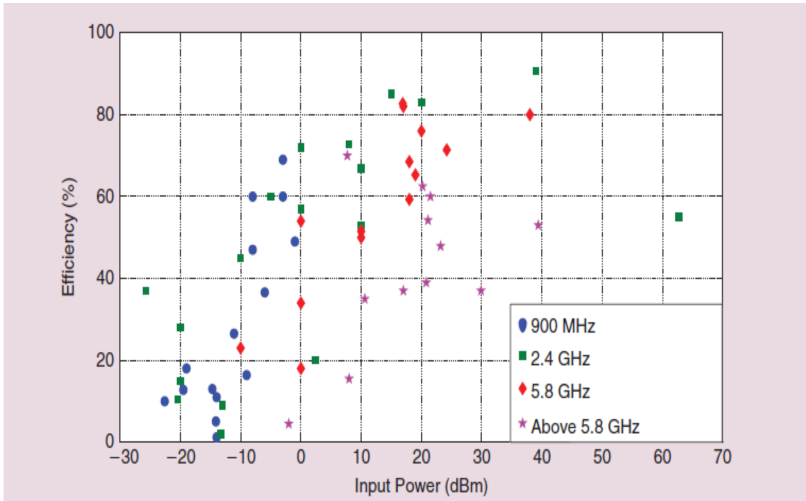

Figure-1. RF conversion efficiency versus input power.

Table-2 and Table-3 shows a comparison for energy conversion devices that has been implemented over time. Some of the device efficiencies are however contributed by the antenna and not only by the rectifier. The device efficiencies use a variety of technologies and varying loads due to their uses in wireless power transfer applications. These works focuses on the GSM 900MHz band and ISM 2.45GHz. In some cases, multiband systems are designed to take advantage of the ambient RF energy from multiple bands. This review presents rectifiers which are being used for single frequency excitation only.

Table-2. GSM 900MHz band energy conversion efficiencies.

Reference	**Input power** (dBm)	**Rectifier element**	**Efficiency** (%)
16	-14	0.3-nm CMOS transistor	1.2
17	-14.1	0.18-nm CMOS transistor	5.1
18	-22.6	0.25-nm CMOS transistor	10
19	-14	90-nm CMOS transistor	11
20	-19.5	0.18-nm CMOS, CoSi2 -Si Schottky	12.8
21	-14.7	0.35-nm CMOS transistor	13
22	-9	0.35-nm CMOS transistor	16.4
23	-19	0.5-nm CMOS, SiTi Schottky	18
24	-11.1	0.18-nm CMOS transistor	26.5
25	-8	0.18-nm CMOS transistor	47
26	-1	Skyworks SMS7630 Si Schottky	49
18	-8	0.25-nm CMOS transistor	60
26	-3	0.13-nm CMOS transistor	60

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Table-3. 2.4GHz band energy conversion efficiencies.

Reference	**Input power** (dBm)	**Rectifier element**	**Efficiency** (%)
27	-13.3	Skyworks SMS7630 Si Schottky	2.01
26	-13	Skyworks SMS7630 Si Schottky	9
28	-20.4	Skyworks SMS7630 Si Schottky	10.5
29	-20	Avago HSMS-2852 Si Schottky	15
30	-20	Avago HSMS-2852 Si Schottky	2
31	-25.7	Silicon on Saphire 0.5-nm CMOS transistors	37
29	-10	Avago HSMS-2852 Si Schottky	45
29	10	Avago HSMS-2852 Si Schottky	55
33	62.7	Thermionic	55
32	0	Avago HSMS-282 *x* Si Schottky	57
29	-5	Avago HSMS-2852 Si Schottky	60
34	10	Avago HSMS-2860 Si Schottky	72
35	20	M/A-COM 4E1317 GaAs Schottky	83

GAPS AND CHALLENGES

Based on the study done, there are still gaps and area of improvement whereby the RF energy harvesting system can be further enhanced by designing an efficient antenna and an efficient rectifier. First and foremost, RF energy harvesting rate is largely affected by the gain of the receiving antenna(s). In order to address this issue, designing a high gain antenna based on materials and geometry for a vast range of frequency is crucial. Gain enhancement for a microstrip patch antenna can be achieved by using multilayer substrates or by integrating electromagnetic band gap (EBG) structures within the microstrip antennas.

Another challenge faced in devising an efficient antenna is the bandwidth. One of the crucial disadvantages of a microstrip antenna is narrow bandwidth. This can be countered in designing the patch antenna with different geometric shapes. For instance, round shapes and round edges allows smoother current flow in which results to ultra-wide band characteristics.

Impedance mismatching occurs when the input resistance and reactance of the rectifier do not equal to that of the antenna. In this context, the antenna is not able to deliver all the harvested power to the rectifier. Thus, impedance variations (e.g., introduced by on-body antennas) can severely degrade the energy conversion efficiency. In most cases, bandwidth limitations are due to impedance mismatch and heavy reactance. This can be countered by designing an efficient impedance matching circuit. Other methods which include in order to improve the bandwidth is increasing the thickness of the substrate supporting the patch antenna

The main factor that determines the RF to DC conversion efficiency is the density of the harvested RF power. Since the harvested power itself is low, improving the RF to DC conversion efficiency is considered to be vital to the RF energy harvesting system. Another countermeasure for this is to introduce a high efficient low power DC to DC converter. This converter would convert a source of DC from a voltage level to another. Besides that, power management tools such as Maximum Power Point Tracking (MPPT) can be implemented for better system efficiency.

Another challenge to be faced in a RF energy harvesting system is the size of the embedded devices. They have to be small enough to be embedded in low-power devices. For example, the size of an RF-powered sensor should be smaller than or comparable to that of a battery-power sensor. As discussed earlier, a RF energy harvesting system would require an antenna to capture RF energy, a matching network and a rectifier. The antenna size has an important influence on an energy harvesting rate. Additionally, high voltage at the output of a rectifier requires very high impedance loads (e.g., 5M), which is a function of the length of the impedance. Hence, this is considered as one of the challenges which has to be looked into in order to further enhance the RF energy harvesting system.

CONCLUSIONS

A comparison and analysis of existing RF energy harvesting systems are discussed. The antenna modules and rectifier modules are put into comparison and discussed. Antennas are considered the heart of the RF energy harvesting system. Various geometry of the antenna yields different results. Main disadvantage in a microstrip patch antenna is its narrow bandwidth which can be countered via different geometric shapes. Rectifiers are a crucial part of the system as well. Schotkky diodes are mainly used in RF energy system due to its low forward voltage characteristics. Based on the review, Skyworks and Avago series diodes seem to yield the highest efficiency. The practical challenges and gaps in the RF energy harvesting systems are also concluded based on the studies done. This gaps and drawbacks can be considered as main objectives for future research.

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