Optimization and Analysis of WLAN RF Energy Harvesting System Architecture

Syeda Wajiha Munir[1], Osama Amjad[1], Engin Zeydan[2], and Ali Özer Ercan[1]

[1]Department of Electrical and Electronics Engineering, Özyeğin University, Istanbul, Turkey 34794.
Email: {wajiha.munir, osama.amjad}@ozu.edu.tr, ali.ercan@ozyegin.edu.tr
[2]Türk Telekom Labs, Istanbul, Turkey. Email: engin.zeydan@turktelekom.com.tr

***Abstract*—This paper presents the design, analysis and optimization of Radio Frequency (RF) energy harvesting system for Wireless Local Area Network (WLAN) source operating at 2.4GHz and 5.8GHz. The system architecture comprises of RF Wireless Local Area Network (WLAN) source, wireless channel, an efficient dual band microstrip patch antenna, an impedance matching network, 4-stage voltage rectifier and a storing circuit. Matching network ensures the maximum power transfer from source to load. HSMS-2850 Schottky diodes are used in rectifier design, which provide low forward voltage and low substrate leakage. The proposed designed system is used to analyze the effect of distance on RF power obtained at receiving side. The selection of storing capacitor is done carefully such that it can store maximum charge and takes reasonable charging time. Moreover, the circuit parameters are varied to optimize the designed circuit that provides the maximum efficiency of 40%. Simulated results show that for received RF power of 5dBm; the designed system can provide 1.3mW of power across 10kΩ load which can be enough to energize the low power devices. The voltage supplied by the harvesting system can be increased further by increasing the number of stages in voltage rectifier at the cost of parasitic losses.**

Keywords*—*energy harvesting, microstrip patch antenna, Schottky diode, matching network, rectifier.

I. Introduction

Recently, there has been rapid growth of wireless devices in many applications such as wireless sensor nodes (WSN) and Internet of Things (IoT) sensor network. These sensors require low power but since they are large in numbers so it necessitates a green design, more preferably perpetual operation without the need for replacing batteries. Moreover, battery maintenance is a crucial problem when wireless networks are deployed at hard-to-reach places such as remote rural areas, within concrete structures, and within human body [1]. This leads to an upsurge of research interests in scavenging energy from different environmental sources such as solar, thermal, chemical, Electromagnetic (EM) and dedicated Radio Frequency (RF) sources [2]. RF energy harvesting [2] is considered as revolutionary technology because of ubiquitous availability of RF signals compared to other conventional sources, moreover it also helps to develop the energy efficient wireless networks.

Energy can be harvested from different analog and digital RF sources such as FM (88-108 MHz), AM (540-1600 kHz) GSM900 (880-960 MHz), GSM1800 (1710-1880 MHz) WLAN (2.4 GHz, 5.8 GHz) and DTV broadcasting (470-810 MHz) [4]. Although RF harvesting scheme may not be perceived as a reliable source of energy because limited amount of energy can be harvested from these RF sources. However, as the RF energy harvesting systems become more efficient, it may be possible to energize low power sensor devices, which can solve the problem of replacing the batteries [1] [2]. Above all, there exist critical challenges that need to be tackled such as design and implementation of RF energy harvesting systems [3].

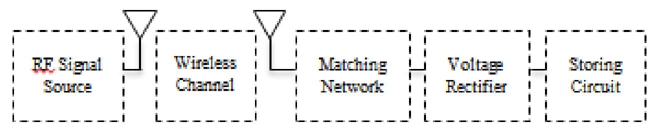


Fig. 1: General Architecture of RF Energy Harvesting

Fig. 1 shows the general architecture of RF energy harvesting system. The transmitted RF signals are received by antenna via wireless channel which are converted to DC power by the voltage rectifier block. The matching network ensures the maximum power delivery from antenna to voltage rectifier. The storing circuit allows uninterrupted power delivery to the load even when external energy is not available [4]. In the field of RF energy harvesting, remarkable work has been done ranging from efficient antenna design to scavenge enough RF signals to power the devices like wireless sensor nodes. More specifically, Global System for Mobile Communications (GSM) and WLAN energy harvesting gains much attention as their signals are present everywhere. Authors presented the experimental setup of RF energy harvesting system from GSM cell towers in [4] [5]. In [6] and [7] dual band RF energy harvesting system along with efficient receiving antenna for GSM and WLAN signals are designed and analyzed respectively. In [8] and [9] energy harvesting from 2.45 GHz indoor Wi-Fi signals are discussed. Within short distances small amount of energy can be harvested from a typical WLAN router (transmitting power is in the range of 50-100 mW) [10]. WLAN is a continuous source of renewable energy in an indoor environment and size of resonating antennas is in the order of 10-50 cm^2 [11]. For greater distances, large gain antennas with high transmitted power level are required and in most of the cases 3G/4G mobile stations and broadcast radio towers are used as RF sources [4].

In our proposed work, an optimized circuit for WLAN RF energy harvesting is designed on Agilent Advanced Design System (ADS) software. Compared to other existing solutions in the previous work that only consider receiving subsystem of RF energy harvesting, in this work RF signal transmission from WLAN source to receiver at a distance ranging from 1 m to 40 m via wireless channel is considered while considering realistic channel conditions like path loss and terrain information. Additionally, dual band microstrip patch antenna is designed which can operate at both 2.4GHz and 5.8GHz simultaneously. In simulation environment, the designed antenna is used at receiving side in order to scavenge energy from WLAN's Wi-Fi routers. The matching network is designed for WLAN 2.4 GHz operating frequency which is composed of inductive and capacitive elements using Smith Chart Utility [12]. Small alterations in the matching circuit parameters can change the frequency range over which the power transfer is maximum. It should be noted that increasing number of multiplier stages yields higher voltage at the load, but reduces the current through the output resistive load. Therefore, in our proposed system, the designed circuit is optimized to attain the maximum efficiency in terms of power delivered at the storing circuit and the load side.

The rest of the paper is organized as follows: In Section II, the system architecture of energy harvesting systems is explained. Section III includes the RF harvesting components such as antenna design, impedance matching and voltage rectification. Section IV presents and interprets the results of corresponding designed antenna and overall RF energy harvesting system. Finally, Section V concludes our findings and analysis.

II. System Architecture

The overall RF energy harvesting system architecture comprises of two sub-systems namely RF signal transmitter/source and RF signal receiver. RF source generates and transmits the signal to the receiver via path loss channel and signals are then incident on receiving antenna [13]. In this presented work, WLAN signal source is used which generates RF signal with carrier frequency of 2.4GHz and different values of source power (P_s) is chosen such as 1W, 200mW and 100mW for analysing the results. Wireless channel with Rayleigh fading model and typical office environment is used which not only considers the path loss but also terrain information. The received RF power is then matched with the remaining circuit to deliver maximum power to the load. Signal is then fed to voltage rectifier which consists of stage capacitors and silicon based HSMS-2850 Schottky diodes [13]. In storing circuit optimum capacitor is used which can store maximum charge and has more charging time. The designed circuit in Fig. 2 is used to analyze the effect of distance on RF power obtained at receiving side, where range of distance from source to receiver is from 1m to 40m and corresponding power obtained is considered as mentioned in Table I.

TABLE I: RF Power Obtained In Indoor Environment

Distance(m)	P_s=1W	P_s=200mW	P_s=100mW
1	4.3	-2	-5.67
5	-9.67	-16.64	-19.67
10	-15.68	-22.68	-25.7
15	-19.2	-26.2	-29.2
20	-21.7	-28.72	-31.7
25	-23.65	-30.64	-33.67
30	-25.23	-32.20	-35.23
35	-26.57	-33.55	-36.57
40	-27.74	-34.72	-37.73

III. RF Energy Harvesting Circuit Components

RF energy harvesting circuit comprises of an efficient antenna to receive EM waves of particular frequency and a rectifier which converts RF signal to Direct Current (DC) output. The detail work and analysis is mentioned in the following subsections.

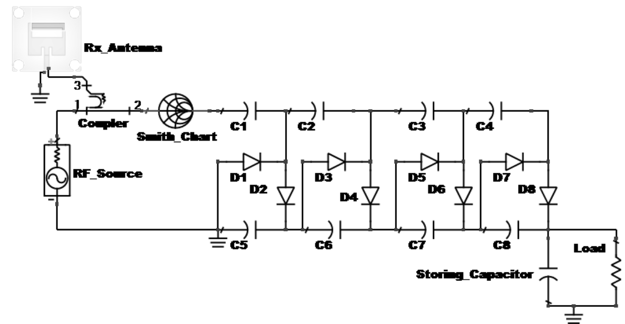


Fig. 2: Schematic Diagram of 4-Stage WLAN Energy Harvesting System

A. WLAN RF Source

The system uses 1W WLAN RF power source operating at 2.4GHz as shown in Fig. 3. The source power of the transmitter and the distance between the transmitting and receiving antenna greatly affect the harvesting rate [1]. Within specific range of distance and at certain time instant, the values of power obtained at antenna can be used to energize the remaining circuit. In order to utilize the information of channel conditions and power incident on receiving antenna across a range of distance, circuit shown in Fig. 3 has been used. Whereas proposed antenna is integrated at receiving side which has been designed to scavenge energy from 2.4GHz signal as shown in Fig. 3 to better analyze and optimize the design. Moreover, single frequency power source is used to energize the receiving side according to the received power information obtained from designed circuit in Fig. 3.

B. Receiving Antenna

The proposed antenna in this paper is microstrip fed patch antenna with a rectangular slot to operate at WLAN dual frequencies i.e. 2.4GHz and 5.8GHz. The antenna can be designed to operate on either single or multiple frequency bands, in which the device can simultaneously harvest from a single or multiple sources [1]. Previous research motivation on RF energy harvesting was restricted to single band which was not much efficient [8]. However, recently much focus has been concentrated on design and implementation of dual band and antenna arrays for RF energy scavenging [7] [14].

Antenna has been designed on ADS and Sonnet Suites software. Fig. 4 shows the top and bottom view of designed antenna. The slot dimensions are optimized such that maximum efficiency can be achieved in terms of return loss. Fig. 5 shows that antenna has two operating bands around the center frequencies of 2.4GHz and 5.8GHz. Moreover, it shows that ADS and Sonnet results are in well agreement with each other.

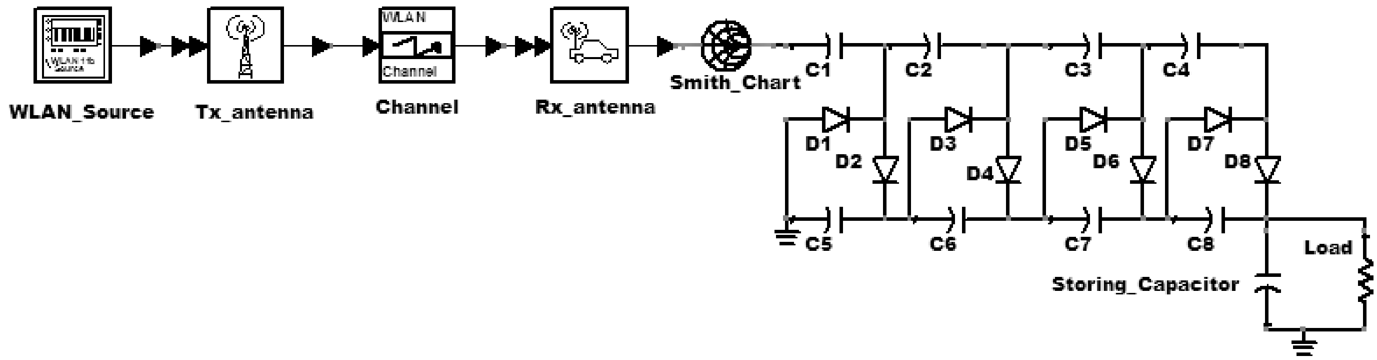


Fig. 3: System Architecture of Proposed System

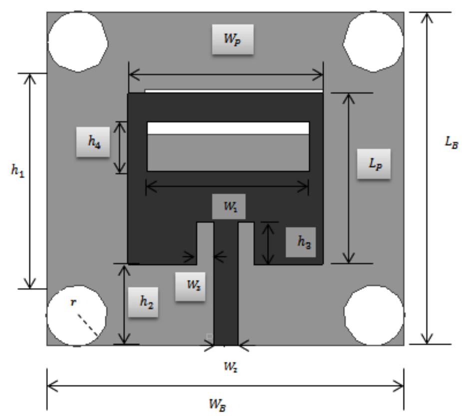


Fig. 4: Top and Bottom View of the Proposed Dual Band Antenna

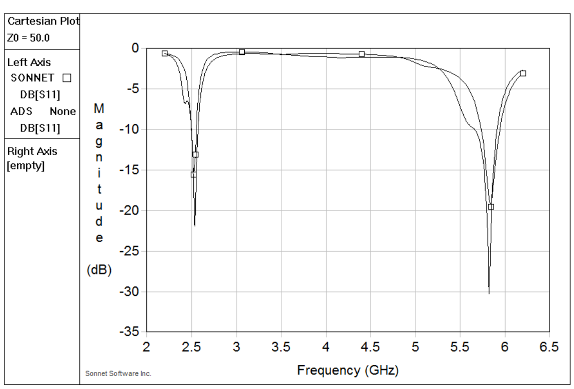


Fig. 5: Input Reflection Coefficients (S11) of Proposed Antenna

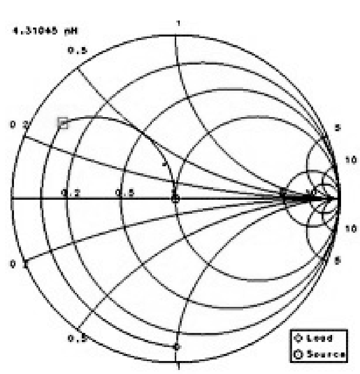


Fig. 6: Impedance Matching using Smith Chart on ADS Agilent

C. Impedance Matching Circuit

Impedance matching is important in the design of energy harvesting system. It reduces the transmission loss between antenna and rectifier and thus increases the voltage for rectifier circuit [7]. In the presented work, ADS smith chart utility as shown in Fig. 6; is used to obtain a LC-matching network with optimal values of inductor and capacitor such as high RF-DC conversion efficiency is achieved.

D. RF-DC Rectifier

RF signals are converted into DC voltage at the given frequency band to energize the low power devices/circuits. HSMS-2850 Schottky diode having threshold voltage of 250 mV and diode capacitance of 0.18 pF is used [6]. It provides low forward voltage, low substrate leakage and have unidirectional flow of current [15]. Fig. 3 shows integrated matching networks and voltage doubler for the receiving side of RF energy harvesting system. Coupler is used to combine antenna model with voltage rectifier after impedance matching. Selection of number of rectifier stages is very crucial so that overall efficiency of a system can be maximized. Optimal number of stages should be added to the system because parasitic losses of non-linear devices increase by increasing number of stages [9] [12]. In our case 4-stages are used that can provide maximum power of 1.4mW across 10kΩ load for an input power of 5dBm.

E. Storing Circuit

The storing circuit is of importance because when RF signals are unavailable, energy storage ensures smooth power delivery to the load and is used as a backup source [12]. Our proposed circuit design includes a capacitor across the load to store and provide DC output voltage. The output is not a good DC signal without a capacitor across the load [15] so it is optimized to store maximum charge i.e. its charging time should be increased. In addition to the above, an optimized load resistor is connected in parallel to capacitor. Without the load resistor, the voltage would look like a DC signal and held indefinitely on the capacitor.

IV. Simulation Results

In simulation setup, indoor office environment is considered to analyze the effect of distance on the P_r at certain transmitting power as mentioned in Table I. The designed receiving antenna captures RF signal at dual operating band of

WLAN, but in this scenario we only consider one RF incident frequency of 2.4GHz.

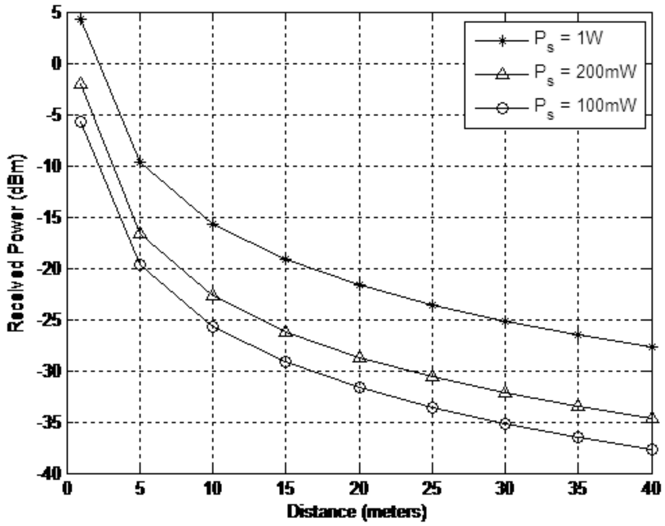
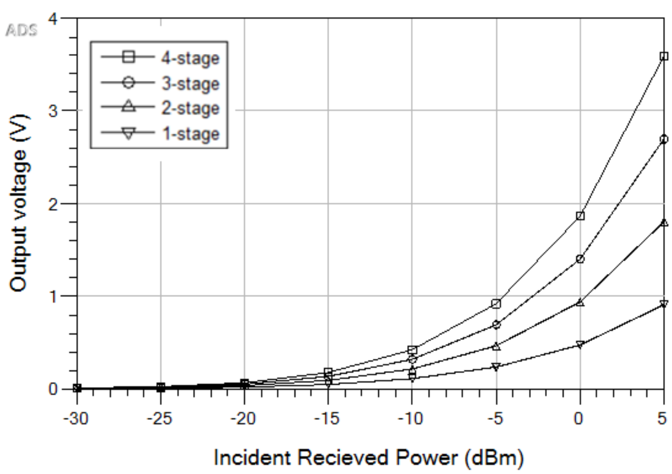
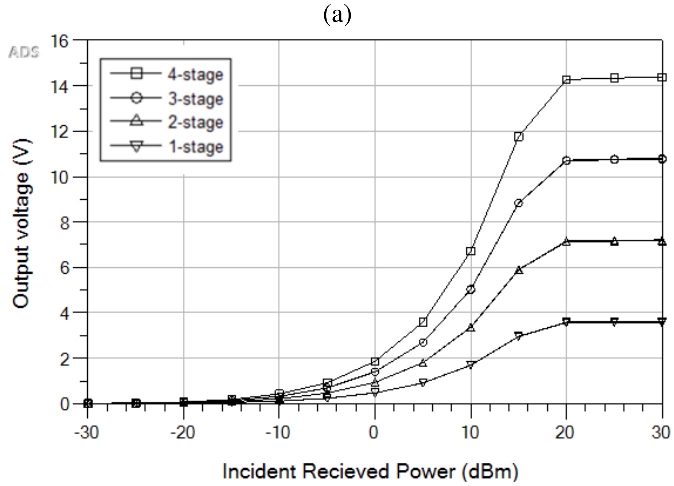


Fig. 7: Received Power (P_r) vs. Distance at different Source Power (P_s)



(a)



(b)

Fig. 8: (a) Output Voltage versus P_r (-30dBm to 5dBm) (b) Output Voltage versus P_r (-30 dBm to 30 dBm) at load=10 kΩ

For different values of P_s, i.e. 100mW, 200mW and 1W, simulations are repeated to analyze the impact of source power on the received power versus distance as shown in Fig. 7. It can be inferred from this figure that by increasing transmitting power, P_r increases linearly at a fixed distance, whereas with increase in distance it decreases as an inverse square function of distance. For example, when P_s=1W, P_r ranges from 4.3 dBm to -28 dBm. For the rest of comparison and analysis, P_r ranges from 5dBm to -30dBm has been considered. The number of rectifier stages has a major impact on the output voltage of the energy harvesting circuit. The output voltage is directly proportional to the number of stages as shown in Fig. 8a and Fig. 8b. The maximum voltage we can obtain is 3.2V at the output of 4-stage rectifier circuits such that input received power is 5dBm and 15V against 20dBm respectively. Fig. 8a shows the relation between output voltage and input power; when transmitter is at distance range of 1meter to 40meters from receiver. When $P_r > 20$dBm, the output voltage reaches its steady state as shown in Fig. 8b.

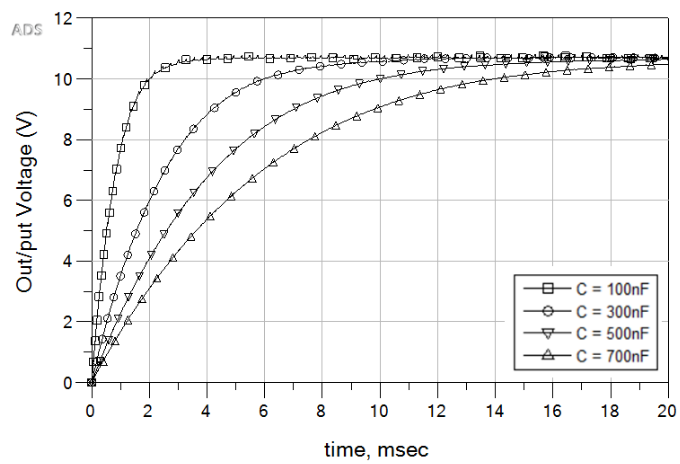


Fig. 9: Output Voltage versus Time at load=10k on Different Storing Capacitors (nF)

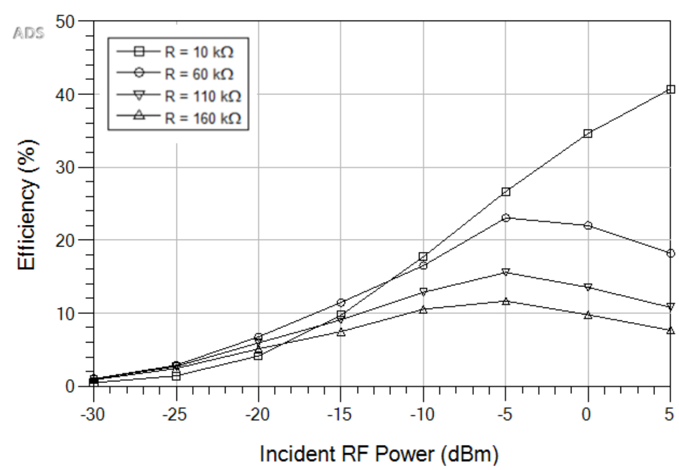


Fig. 10: Efficiency (%) versus Input RF Power (dBm) at Different Loads (kΩ)

The selection of storing capacitor is done carefully such that it can store maximum charge and takes reasonable charging time instead of filling up in short time. It is seen in Fig. 9 that at 700nF capacitor, the transient time is more i.e. it achieves steady state after 10ms; thus it fills up late and can store more charge then 100nF capacitor. Wide range of capacitors is checked in the designed circuit but 700nF is the optimum one as it has both reasonable charging time and stores maximum possible charge. The load impedance for specific energy harvesting circuit is of significant importance and in our design its effect is demonstrated in Fig. 10. Efficiency of the energy harvesting circuit is plotted against P_r at different values of load i.e. for ranges from 10 to 160 kΩ. The effect of load impedance on the efficiency of system shows that maximum efficiency that can be achieved is 40% at P_r=5dBm when load is set to be 10 kΩ. Thus, we can say that designed circuit is optimized to provide maximum efficiency at 10 kΩ load under defined conditions.

V. Conclusions and Future Work

In this paper, analysis and optimization of RF energy harvesting system from WLAN source with dual band antenna are performed. The designed system architecture consists of WLAN source, wireless channel, dual band microstrip patch antenna which operates at 2.4GHz and 5.8GHz, an impedance matching network, 4-stage voltage rectifier and a storing circuit. Our work elaborates the effect of distance on received power at different source power values i.e. P_s=1W, 200mW and 100mW. The simulated results show that the system can provide output power of 1.3mW across 10kΩ load, which can be used to energize low power devices. Moreover, it also explains the optimization of storing capacitor to store maximum charge and smooth voltage supply to the load. Similarly, load resistor value is chosen to maximize overall efficiency of system. In our results, overall efficiency of 40% is achievable at 10kΩ load when P_r=5dBm. Moreover, the efficiency can further be increased by increasing rectifier stages and available RF power to the input of receiver side. Therefore, it indicates that design schematic is correct and can lay a good foundation for future research. The future work includes the real implementation of proposed circuit which provides a promising solution to energize low power wireless communicating devices such a wireless sensor networks.

References

[1] X. Lu, P. Wang, D. Niyato, D. Kim and Z. Han Wireless Networks With RF Energy Harvesting: A Contemporary Survey, *IEEE Communication Survey & Tutorials*, vol. 17, no. 2, May 2015.

[2] T. Soyata, L. Copeland, and W. Heinzelman RF Energy Harvesting for Embedded Systems: A Survey of Tradeoffs and Methodology, *IEEE Circuits and Systems Magazine*, Feb. 2016.

[3] Z. Zakaria, N. A. Zainuddin, M. N. Husain, M. Abidin, A. Aziz, M. Mutalib and A. Othman, Current Developments of RF Energy Harvesting System for Wireless Sensor Networks, *International Journal on Advances in information Sciences and Service Sciences(AISS)* , vol. 5, no. 11, June 2013.

[4] M. Arrawaita, M. S. Baghini, G. kumar, RF Energy Harvesting Systems From Cell Towers in 900 MHz Band, *IEEE-Conference In Communications*, pp. 1-5, Jan. 2011.

[5] N. M. Din, C. K. Chakrabarty, A. Bin Ismail, K. K. A. Devi and W. Y. Chen, Design of RF Energy Harvesting System for Energizing Low Power Devices, *Progress in Electromagnetics Research*, vol. 132, Sep. 2012.

[6] L. T. Beng, L. N. Meng, P. B. Kiat and T. kyaw, Pervasive RF Energy Harvesting System (GSM 900 and GSM 1800), *IEEE-Conference on Technologies for Sustainability (SusTech)*, July. 2014.

[7] M. S. Alam and S. Moury, Multiple-Band Antenna Coupled Rectifier Circuit for Ambient RF Energy Harvesting for WSN, *International Conference on Informatics, Electronics and Vision*, 2014.

[8] F. Alneyadi, M. Alkaabi, S. Alketbi, S. Hajraf, and R. Ramzan, 2.4GHz WLAN RF Energy Harvester for Passive Indoor Sensor Nodes, *IEEE-International Conference on Semiconductors Electronics*, Aug. 2014.

[9] J. H. Kim, J. Bito and M. Tentzeris, Design Optimization of an Energy Harvesting RF-DC Conversion Circuit Operating at 2.45GHz, *IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting*, 2015.

[10] S. Shrestha, S. Noh and D.Choi, Comparative Study of Antenna Designs for RF Energy Harvesting, *International Journal of Antennas and Propagation*, Jan. 2013.

[11] H. J. Visser and R. J. Vullers, RF energy harvesting and transport for wireless sensor network applications: Principles and requirements, *Proceedings of the IEEE*, vol. 101, no. 6, pp. 14101423, April 2013.

[12] P. Nintanavongsa, U. Muncuk, D. R. Lewis and K. R. Chowdhury, Design Optimization and Implementation for RF Energy Harvesting Circuits, *IEEE Journal on Emerging and Selected Topics in Circuits And Systems*, March 2012.

[13] T. R. Ansari, A. Khan and I. Ansari Wireless Charging of Mobile Battery via Optimization of RF Energy Harvesting System, *International Journal of Scientific & Engineering Research*, Volume 6, Issue 7, July-2015.

[14] M. Hoang, H. Phan, T. Q. V. Hoang, T. P. Vuong, Efficient Compact Dual-Band Antennas for GSM and Wi-Fi Energy Harvesting, *IEEE International Conference on Advanced Technologies for Communications*, Oct. 2014.

[15] K. K. A. Devi, N. Md. Din and C. K. Chakrabarty, Optimization of the Voltage Doubler Stages in an RF-DC Converter Module for Energy Harvesting, *Circuits and Systems*, vol. 3, no. 3, 2012.