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Energy Harvesting from RF Signals: A Comprehensive Review

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Abstract—*Radio Frequency energy harvesting is becoming increasingly important for remotely powered devices. This technology has the capability of converting the received Radio Frequency signal to electricity. For more than two decades there were extensive research activities on energy harvesting system to use it for human utility. In this work we have discussed an extensive literature review on the recent research progresses in radio frequency energy harvesting system.*

Indexwords*: Radio Frequency Signal, Energy Harvesting, Friss transmission formula.*

1. INTRODUCTION

Radio frequency (RF) energy harvesting (EH) system is an active research area which investigates a number of alternative ways to convert energy from electromagnetic (EM) radiation to electricity for energizing the low powered electronic circuits. The RF energy is freely available in the space to use for energizing the low power electronic devices. Therefore, research work has been carried out by many researchers in this field. RF-EH system has the great potential to impact on the cellular phones, portable electronic devices and wireless sensor network (WSN) etc. The RF-EH system needs an efficient antenna along with a circuit capable of converting RF signals to DC voltage. The rectenna is a rectifying antenna which converts the microwave power to DC power and it has received much attention in EH technology. Nowadays RF-EH system has emerged as a promising technology for reducing the slowdown of node energy and network lifetime of WSN.

Besides, RF-EH system is applied in cognitive radio networks, wireless body area network and other charging systems [1]. The energy carrier in RF-EH system is in the range of 3-300 KHz. RF energy sources are of two types:

a) Ambient RF sources: This kind of RF sources is freely available and includes most of the radiations from domestic appliances such as TV, Bluetooth, WiFi etc. The frequency range for such type of sources is 0.2-2.4 GHz.

b) Dedicated RF sources: This type of dedicated sources is required to recharge nodes that require predictable and high amounts of energy. It is fully controllable and it is supported for applications with quality of services (QoS). The frequency band used for dedicated energy transmission is from license free industrial, scientific and medical (ISM) band. Due to sharply decreasing RF-DC conversion efficiency at low receives powers; the RF-EH suffers from fading, energy dissipation, path loss etc. The amount of radiated power density at the receiver end in an ES system is given by the Friss transmission formula [2]:

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi R}\right)^2 \quad (2)$$

Where,
P_r: Received power

P_t: Transmitted power

G_t: Transmitted antenna gain

G_r: Received antenna gain

R: Distance between transmitter and receiver

λ: wavelength

The main objective of this work is to discuss various research technologies of RF-EH system. In the next sections of the work, we will discuss in details about the circuit design, techniques used and comparisons of some literatures.

2. OVERVIEW OF TECHNIQUES USED IN RF-EH

In this section, the background and techniques related to RF-EH system will be discussed. The purpose of this section is also to introduce the comprehensive survey of some research works related to the RF-EH circuit design which are discussed within the limit of this work. The system block and the system components of the RF-EH system are shown in **Fig.1 and Fig.2** respectively**.**

A. RF sources**:** The RF sources are divided into dedicated RF sources and ambient RF sources. The dedicated RF sources can use the license free ISM frequency bands for RF energy transfer. Ambient RF sources are divided into static ambient RF sources and dynamic ambient RF sources. The TV and radio sources are the examples of static ambient RF sources. On the other hand a WiFi access point and licensed user

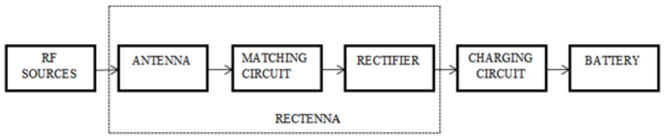

Fig. 1: System block used for RF-EH

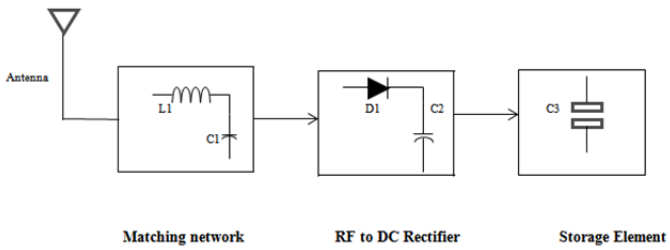

Fig. 2: RF-EH system componentsin a cognitive radio network are the examples of dynamic ambient RF sources. The authors in [3], [4], [5], [6], [7], and [8] used ambient sources and in [9], [10] dedicated sources are used.

B. Antenna: Antenna is an element of radios and transmitters that aid in the propagation or collection of radio waves. An antenna is simply a copper wire with flowing currents that help to transmit the radio signals further and more efficiently. Electric and magnetic fields are radiated from an antenna and it is responsible for transmission and reception of EM energy through free space. There are various types of antennas used by researchers for the purpose of RF-EH. The authors in [4] used a double-sided microstrip global system of mobile (GSM) embedded antenna which can detect several signals of different frequencies. The bigger antenna can increase power from very low power signals. As the directivity of the antenna increases with its size, and hence increases the gain of the antenna. The gain of the antenna is directly proportional to its directivity.

$$G_0 = e_t D_0 \quad (1)$$

Where D_0 is the directivity of the antenna and e_t is antenna efficiency.

Microstrip antennas have a bandwidth (BW) of 0% up to 5% of their center frequency. Hence the power gathered by his technique is small. An E- shaped single patch antenna was proposed by the authors in [5]. The topology of this antenna was designed on a FR4 substrate and is optimized to capture the energy from ambient at downlink RF range of GSM-900 band. In many research papers, the authors proposed the use of rectenna which is a combination of an antenna and rectifiers. In [11] the authors reported a 2.45 GHz, low power dual circularly polarized and dual access antenna. It contains two DC recombined rectifiers and a cross slot coupled square patch antenna fed by a microstrip line. A 2.13 GHz rectenna was developed by the authors in [12] for low power mobile devices. The rectenna element is a microstrip patch antenna with polymer thin film transistors (PTFT) board of 10 dielectric constant of 1.6 mm thick that has a gain of 5.8 dBi. A ferrite rod antenna is proposed in [13] which can power a wireless sensor node from ambient medium wave transmission. The coil diameter used for reference in this work was 30 mm and a length of 120 mm. By increasing the diameter of the coil the voltage and power level can be increased. Two compact patch antennas were designed for outdoor RF-EH in powering a soil sensor network as in [9]. The authors in [10] used two kinds of receiver antennas called Dipole and Patch antenna in terms of return loss and peak receiver power. Dipole antenna shows better impedance matching with the conversion circuit than that of the patch antenna. The spiral antenna was used by the authors in [6] to reduce the problem of impedance matching. The authors tried to design the antenna in such a way that the antenna impedance must match to the optimal diode impedance for all frequencies. In [14] it was showed that the dual polarized, dual frequency and dual access antenna show good measurement performances at 940 MHz and 2.45 GHz. It also exhibits harmonic rejection properties at 1.88 GHz and 4.9 GHz avoiding the use of RF filter when the antenna is connected to a nonlinear device. During the last decade ultra wide band (UWB) antenna has also been proposed as a power harvester. In [15] and [16], the use of UWB antenna has been discussed. The authors in [15] used UWB antenna for photovoltaic solar panel integration and EH. The UWB antenna was a transparent cone-top-tapped slot antenna covering the frequency range from 2.2 to 12. GHz. Again in [16] a compact UWB planar antenna fed with a microstrip line is proposed.

C. Matching circuit: Matching circuit is used to transfer maximum power from the antenna to the EH circuit. The authors in [5] used a π matching network to provide a good impedance match for a complex load impedance of 63-j117 and source impedance 377Ω to transfer maximum power from source to load. The output of the matching network is directly connected to the input of RF to DC converter. In [8], the authors used a simple L network in order to boast the efficiency of RF harvester at low power levels. Simulations of the circuit show the efficiencies of 75% for an input power of 10dBm but in printed circuit board (PCB) design, by actual components, the efficiency decreases below 50%. The impedance of a circuit depends on both frequency and input power. So in [17], the authors first measure the impedance of harvesting circuit without matching circuit and antenna. At a frequency of 866.6 MHz and an input power of -6 dB, the matching was done. The proposed T-match circuit (two series inductors and one parallel capacitor) in [18] measured an impedance of the circuit of 97+j96 ohm which was matched with the value of 50 ohm of the antenna. In [19], the authors proposed a method where they used a finite number of discrete capacitors with different capacitance values and the power transfer occurs in a finite number of input power stages. L and π type matching networks are also used in [20] to investigate the RF- EH circuit performances which are shown in **Fig.3** and **Fig.4**. The authors in [20] observed that output voltage of EH circuit using π matching network changes rapidly as compared to L-type matching network as π network has extra frequency dependent component than L network and hence more sensitive to frequency variations.

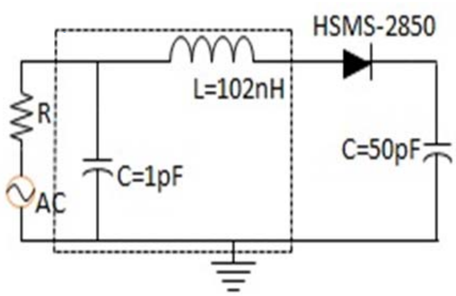

Fig.3: L-type matching network used in [20]

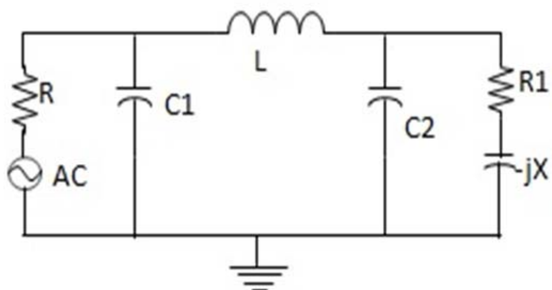

Fig.4: π matching network used in [20]

D. Rectifier: Rectifying circuits are used in EH circuits to convert the AC signals induced in the antenna to DC signals. Schottky diode is mostly preferred rectifying diode for most of the researchers due to its very low forward voltage drop (0.15V) and high switching property. HSMS-2850 is a widely used schottky diode for RF-EH circuits. Single stage rectifiers produce very low efficiency and due to increase in the efficiency and output voltage of the EH circuits, various multistage rectifiers are used by researchers. The authors in [4], [5], [8], [21] etc. have used Villard voltage doubler circuits which is also called Kockcroft - Walton voltage multiplier. In [22] the authors proposed a bridge voltage doubler circuit using active diodes. The authors in [23] proposed a novel highly efficient 5-stage RF rectifier in Semiconductor manufacturing international corporation (SMIC) 65 nm standard CMOS process. The authors applied the self-compensation approach in this proposed RF rectifier, which combines the gate-bias threshold compensation with the body-effect compensation to improve power conversion efficiency (PCE). The performance of the circuit can be increased by connecting a MOS transistor with the proposed diode [24]. For the compatibility with the CMOS processes a CMOS based Villard voltage multiplier circuit was proposed in [7]. The Greinacher voltage multiplier circuit which was also used by many researchers is also a Villard voltage multiplier with a rectifier circuit connected with it. In **Fig.5** and **Fig.6** Villard and Dickson voltage multipliers are shown.

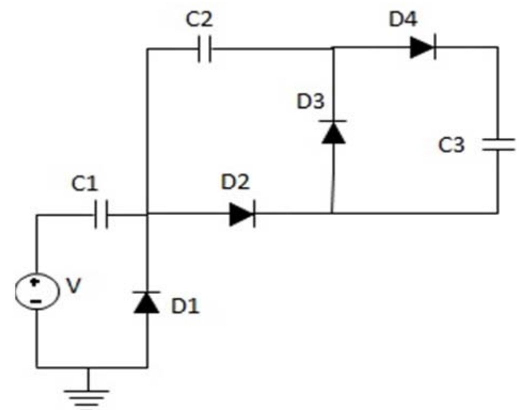

Fig. 5: Villard voltage multiplier in [43]

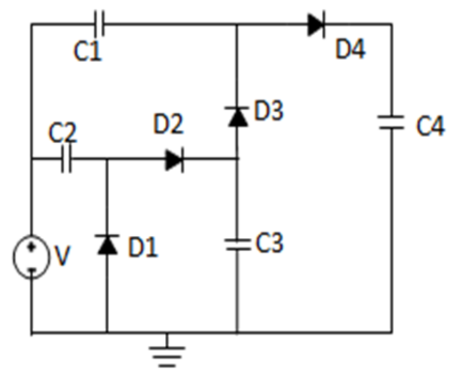

Fig. 6: Dickson voltage multiplier in [43]

3. PERFORMANCE COMPARISION

The comparison of the parameters of a few research workers used in RF-EH circuit are given in Table-I below:

Table-I

Scholar(s)/ Researchers	Techniques used	Output voltage	Efficiency	Receiving antenna
T. R. Ansari et. al (2015)	Schotttky diode(HSMS-2822,HSMS-2852) based Greinacher voltage doubler	1.8 V(0dB) 7.7V(10dBm) 17.88V(20dBm)	5.37% at 10 cm distance	Monopole antenna
N. M. Din et. al (2012)	A pi matching network and a 7-stage voltage doubler circuit	2.12 V and 5V (at 0dbm)	N. A	a single wideband 377 ohm E-shaped patch antenna
S. Agrawal et. al (2015)	LNA amplifier with HSMS-2852	-0.92V(-20dBm) -3.7V(-10dBm)	60% (input voltage 100mV)	N.A
M. S. B. Alam et. al (2014)	Greincher/single stage Cockroft-Walton voltage doubler rectifier	N.A	N.A	Microstrip antenna
S. B. Alam et. al (2013)	Single stage voltage multiplier, Greinacher voltage doubler (HSMS-2850)	(0.5-2.0)V	N.A	N.A
N. Akter et.al (2014)	10 stage voltage multiplier with HSMS-2850	5 V(0dBm) 36.06V(20dBm)	N.A	N.A
P. Kaddi et. al (2015)	CMOS technology	1.1V	42%(0.953 GHz) 47%(2.4GHz)	N.A
S. Agrawal et.al (2015)	Π and L type matching network	2 V	N.A	N.A
C. J. Ahn et. al (2014)	Step up converter(TPS61220)	0.7-5.5 V	80.9%	Microstrip patch antenna
L. M. Borges et. al (2014)	Five stage Dickson voltage multiplier	N.A	20%(-4dBm) 32%(-6dBm) 26%(-5dBm)	Wearable dual band antenna

4. DISCUSSIONS ON UNADDRESSED PROBLEMS

There are many practical challenges occurred in RF-EH circuits. Some of them are discussed below:

a) A high gain antenna is very essential to increase the efficiency of the RF-EH circuits as the harvesting rate is largely affected by the direction and gain of the receiving antenna. This is a major research issue now- a-days.

b) There is a need of proper impedance matching circuits which can minimize the loss of power from the antenna to the rectifier circuits. For the impedance mismatch the energy conversion efficiency decreases.

c) The RF-EH circuit components should be small enough so that these can be embedded in a low power device.

d) As the transmitted power is low in RF-EH circuits, multiple antennas can be adopted to increase the transmission efficiency. Hence power consumption increases with the increase of the number of antenna. But this type of implementation is going to provide problems in the dynamic environment.

5. CONCLUSION

In this work we have presented a comprehensive survey on RF-EH circuit design. First, we have discussed the background of the RF-EH circuit. Then, we have also discussed the techniques used in RF-EH circuits. There are many issues regarding the RF-EH circuit design and those can be modified in further research.

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REFERRENES

[1] Junior, J. M., Costa, J. P. C. L. D. and Freitas, E. P. D., “Improved Radiofrequency Energy Harvesting based on a Rectenna Array System and its Feasibility Evaluation in Urban Environments”, 3rd International Conference on Renewable Energy Research and Applications, Milwaukee, USA, pp. 561-565, October 2014.

[2] Lenin ,A. and Abarna, P., “Design and Simulation of Energy Harvesting System Using GSM Signal”, International Journal of Latest Trends in Engineering and Technology (IJLTET), vol. 3, pp. 19-25, march 2014.

[3] Hagerty, J. A., Zhao,T., Zane, R. and Popovic, Z., “Efficient broadband RF energy harvesting for wireless sensors”, Proceedings of The Government Microcircuit Applications and Critical Technology Conference, Lag Vegas, pp. 1-4, April 2005.

[4] Nasab, S.H., Asefi, M., Albasha ,L. and Quaddoumi ,N., “Investigation of RF signal energy harvesting”, Hindawi Publishing Corporation, Active and Passive electronic components, January 2010.

[5] Din ,N. M., Chakrabarty, C.K., Ismail ,A. B., Devi, K. K. A. and Chen, W. Y., “Design of RF energy harvesting system for energizing low power devices”, Progress in Electromagnetic Research, vol. 132, pp. 49-69, September 2012.

[6] Bouchouicha ,D., Dupont ,F., Latrach ,M. and Ventura ,L., “Ambient RF Energy Harvesting”, International Conference on

Renewable Energies and Power Quality (ICREPQ'10) Granada (Spain), March 2010.

[7] Jabbar ,H., Song ,Y. S. and Jeong ,T. T., " RF Energy Harvesting System and Circuits for Charging of Mobile Devices", IEEE Transactions on Consumer Electronics, vol. 56, no. 1, pp. 247-253, February 2010.

[8] Din ,N. M., Chakrabarty ,C. K., Ismail A. Bin, Devi ,K. K. A., and Chen ,W. Y., "Design of RF energy harvesting system for energizing low power electronic devices", Progress in Electromagnetic research, vol. 132, pp. 49-69, January 2012.

[9] Sim ,Z. W., Shuttleworth ,R., Alexander ,M. J. and Grieve, B. D., "Compact patch antenna design for outdoor RF energy harvesting in wireless sensor networks", Progress in Electromagnetic research, vol. 105, pp. 273-294, January 2010.

[10] Liu ,G., Mrad ,N., Xiao,G., Li,Z., and Ban, D., "RF-based power transmission for wireless sensor nodes", International Workshop on Smart Materials, Structures & NDT in Aerospace Conference, NDT in Canada, Montreal, Quebec, Canada, November 2011.

[11] Haboubi ,W., Takhedmit, H., Luk J. D. L. S., Adami ,S. E., Allard, B., Costa ,F., Vollaire ,C., Pinon, O. and Cirio ,L., "An efficient dual circularly polarized rectenna for RF energy harvesting in the 2.45 GHz ISM band", Progress in Electromagnetic Research, vol. 148, pp. 31-39, January 2014.

[12] Ahn, C. J., "Development of RF energy harvesting and charging circuits for low power mobile devices", ISBN: 9781-161804-035-0, pp. 131-134, September 2011.

[13] Ajmal ,T., Jazani ,D. and Allen ,B., "Design of a compact RF energy harvester for wireless sensor networks", IET Conference on Wireless Sensor Systems (WSS 2012), London, UK, pp. 1-5, June 2012.

[14] Haboubi ,W., Takhedmit, H., Picon, O. and Cirio, L.,"A GSM-900 MHz and WiFi-2.45 GHz dual polarized, dual-frequency antenna dedicated to RF energy harvesting applications", 7th European Conference on Antennas and Propagation (EuCAP), pp:3789-3791, April 2013.

[15] Peter ,T., Rahman ,T. A., Cheung ,S. W., Nilavalan, R. , Abutarboush ,H. F. and Vilches, A., "A Novel Transparent UWB Antenna for Photovoltaic Solar Panel Integration and RF Energy Harvesting", IEEE transactions on antennas and propagation, vol. 62, no. 4, pp. 1844-1853, April 2014.

[16] Sennouni, M. A., Zbitou, J., Abboud, B., Tribak ,A., Bennis,H. and Latrach ,M., "Compact Ultra-Wideband Printed Monopole Antenna with Inverted L-Shaped Slots for Data Communication and RF Energy Harvesting", International Journal of Electrical, Computer, Electronics and Communication Engineering vol.9, no.1, pp.109-113, May 2015.

[17] Echearte ,I. A., Lopez ,D. J., Gasulla ,M., Giuppi ,F. and Georgiadis,A., "A high efficiency matching technique for low power levels in RF harvesting", PIERS Proceedings, Stockholm, pp. 1806-1810, August 2013.

[18] Merz1, C., Kupris ,G. and Niedernhuber, M. , "Wireless and Battery-less Sensor Using RF Energy Harvesting", European Telemetry and Test Conference, pp. 8-13, 2014.

[19] Felini ,C., Merenda ,M. and Della Corte ,F. G., "Dynamic impedance matching network for RF energy harvesting systems", IEEE-RFID-TA Conferrence, September 2014.

[20] Agrawal ,S., Singh, J. and Parihar ,M. S., "Performance Analysis of RF Energy Harvesting Circuit with Varying Matching Network Elements and Diode Parameters", IET Microwaves, Antennas and Propagations, pp. 6-18, September 2015.

[21] Yan ,H., Montero ,J. G. M., Akhnoukh, A.,Vreede,L. C. N. d. and Burghartz, J.N., "An Integration Scheme for RF Power Harvesting",8th Annual Workshop Semiconductor Advances Future Electron. Sensors, pp. 64-66, September 2005.

[22] Cheng ,S., Jin ,Y., Rao ,Y. and Arnold, D. P., "A bridge voltage doubler AC/DC converter for low voltage energy harvesting applications", Technical Digest PowerMEMS, Washington DC, USA, pp. 25-28, December 2009.

[23] Liu, L., Mu , J., Ma , N. and Zhu, Z., "A hybrid threshold self-compensation rectifier for RF energy harvesting", IEICE Electronics Express, vol. 11, no. 23, pp. 1-7, January 2014.

[24] Shokrani , M. R., Khoddam M., Hamidon , M. N. B., Kamsani , N. A., Rokhani , F. Z., and Shafie , S. B., "An RF Energy Harvester System Using UHF Micropower CMOS Rectifier Based on a Diode Connected CMOS Transistor" Scientific World J., 2014.

[25] Adami , S. E., Marian , V., Degrenne ,N. and Costa , F., "Self powered ultra-low power DC-DC converter for RF energy harvesting", in IEEE Faible Tension Faible Consommation. IEEE, pp. 1-4, June 2012.

[26] Haboubi , W., Takhedmit , H., Luk, J. D. L. S., Adami ,S. E., Allard, B. Cirio ,Costa , F., Vollaire, C., Pinon ,O. and L., "An efficient dual circularly polarized rectenna for RF energy harvesting in the 2.45 GHz ISM band", Progress in Electromagnetic Research, vol. 148, pp. 31-39, January 2014.

[27] Scucchia ,L., Palomba ,M., Cleriti ,R., Ciccognani , W. and Limiti ,E., "Reconfigurable matching network for RF energy harvesting circuits", International Workshop on Integrated Nonlinear Microwave and Millimeter-wave Circuits (INMMiC), IEEE, April 2014.

[28] Mikeka, C., Arai ,H., Georgiadis ,A. and Collad ,A., "DTV band micropower RF energy-harvesting circuit architecture and performance analysis", IEEE International Conference on RFID-Technologies and Applications, pp. 561-567, January 2011.

[29] Barnett ,R. E., Liu, J. and Lazar ,S., "A RF to DC Voltage Conversion Model for Multi-Stage Rectifiers in UHF RFID Transponders", IEEE Journal of Solid –State Circuits, vol. 44, no. 2, pp. 356-370, February 2009.

[30] Saraiva, H. M., Borges, L. M., Barroca ,N., Tavares ,J., Gouveia ,P. T., Velez ,F. J., Loss, C., Salvado, R., Pinho ,P., Gonçalves , R.,Carvalho,N. B., Santiago, R. C. and Balasingham, I., "Experimental Characterization of Wearable Antennas and Circuits for RF Energy Harvesting in WBANs",79th IEEE Vehicular Technology Conference, pp.1-5, 2014.

[31] Hosain, M. K., Kouzani, A. Z., Samad ,M. F. and Tye, S. J.,"A miniature energy harvesting rectenna for operating a head mountable deep brain simulation device", IEEE Access, vol. 3, pp. 223-234, April 2015.

[32] Bouchouicha, D., Latrach, M.,Dupon, F. and Ventura ,L., "An experimental evaluation of surrounding RF energy harvesting devices", Proceedings of the 40th European Microwave Conference, pp. 1381-1384, September 2010.

[33] Wu ,Z. J., Biao ,W. L., Yak ,S. K., Ming ,T. C., Chye ,B. C., Cheng, W. K. and Anh ,D. M, "Wireless energy harvesting using serially connected voltage doublers", Proceedings of Asia-Pacific Microwave Conference, pp. 41-44, 2010.

[34] Devi ,K. K. A., Din ,N. M. and Chakrabarty ,C. K., "Optimization of the Voltage Doubler Stages in an RF-DC Convertor Module for Energy Harvesting", Journal Circuits and systems, pp. 216-222, 2012.

[35] Dyo ,V., Ajmal ,T., Allen, B., Jazani, D. and Ivanov ,I., "Design of a ferrite rod antenna for harvesting energy from medium wave broadcast signals", Published in The Journal of Engineering, pp. 1-8, November 2013.

[36] Rosli, M. A., Murad,S. A. Z. and Isa ,M. N. M., "Review of AC-DC Rectifier Circuit Based On Complementary Metal-Oxide Semiconductor for Radio Frequency Energy Harvesting System", ARPN Journal of Engineering and Applied Sciences, vol. 10, no. 18, pp. 1-4, ISSN: 1819-6608, October 2015.

[37] Ali ,M., Obaid ,N., Albasha ,L. and Quaddoumi ,N., "Enhanced Efficiency Threshold-Cancellation based rectifier for RF Energy Harvesting Application", IEEE 20th International conference on Electronics, Circuits and systems(ICECS), pp. 803-806, December 2013.

[38] Kundu ,D., Reza ,A. W., and Ramiah ,H., "Design of an U-slot Folded Shorted Patch Antenna for RF Energy Harvesting", 2nd International Conference on Innovations in Engineering and Technology (ICCET'2014), pp. 61-65, September 2014.

[39] Borges ,L. M., Barroca, N., Saraiva, H. M., Tavares ,J., Gouveia ,P. T., Velez ,F. J., Loss ,C., Salvado, R., Pinho ,P., Gonçalves ,R., Carvalho, N. B., Santiago ,R. C. and Balasingham, I., "Design and evaluation of multi-band RF energy harvesting circuits and antennas for WSNs", Proceedings of 21st International Conference of Telecommunications, Lisbon, Portugal, pp. 308–312, May 2014.

[40] Ungan ,T., Polozecv, X. L., Walker ,W. and Reindl, L., "RF energy harvesting design using high Q resonators", IEEE MlT-S International Microwave Workshop on Wireless Sensing, Local Positioning, and RFIO (IMWS 2009 - Croatia), October 2009.

[41] Wang ,D. and Negra, R.,"Novel TriBand RF Rectifier Design for Wireless Energy Harvesting", Microwave conference(GeMIC), Germany, VDE publisher, ISBN: 978-3-8007-3585-3, pp. 1-3, March 2014.

[42] Akter ,N., Hossain, B., Kabir ,H., Bhuiyan ,A. H., Yeasmin, M. and Sultana ,S.,"Design and Performance Analysis of 10-Stage Voltage Doublers RF Energy Harvesting Circuit for Wireless Sensor Network", Journal of Communications Engineering and Networks, vol. 2, pp. 84-91, April 2014.

[43] Nintanavongsa , P., Muncuk , U., Lewis , D . R. and Chowdhury, K.R.,"Design Optimization and Implementation for RF Energy Harvesting Circuits", IEEE Journal on Emerging and Selected Topics in Circuits and Systems, vol. 2, no. 1, pp. 24-33, March 2014.

[44] Barroca ,N., Saraiva ,H. M., Gouveia ,P. T., Taveres, J., Borges ,L. M., Velez ,F. J., Loss ,C., Salvado ,R., Pinho ,P., Goncalves, R., Carvalho ,N. B., Chantiago ,R. C., "Antennas and circuits for ambient RF energy harvesting in wireless body area networks", IEEE 24th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC), pp. 527-532.

[45] Alam, S. B., Ullah ,M. S. and Moury ,S., "Design of a low power 2.45 GHz RF energy harvesting circuit for rectenna", IEEE International Conference on Informatics, electronics and Vision(ICIEV), Dhaka, pp. 1-4, January 2013.

[46] Alam ,M. S. B. and Moury ,S., "Multiple-Band Antenna Coupled Rectifier Circuit for Ambient RF Energy Harvesting for WSN", IEEE International Conference on Informatics, electronics and Vision(ICIEV), Dhaka, pp. 1-4, May 2014.

[47] Roscia, M., Zaninelli, D., Lazaroiu ,G. C. and Shadmehr ,H., "Using design optimization in radio frequency energy harvesting systems", IEEE International Conference on Clean Electrical power", Alghero, pp. 740-744, January 2013.