RADIO FREQUENCY ENERGY HARVESTER FOR WIRELESS SENSOR NODES AND MOBILE PHONE BATTERIES: A REVIEW

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Abstract

There is an increase in the deployment of wireless sensor nodes, most especially with the advent of 5G and application of internet of things (IoTs). These nodes and user equipments (UEs) requires an uninterrupted power supply, which cannot be guaranteed using an alternating current (AC) power source or battery direct current (DC); due to inadequate supply of AC power in most developing countries, need for recharging and replacing damage batteries, and harsh deployment terrain of sensor node. The use of radio frequency (RF) energy harvester have been postulated in literature as a promising technology that can be used to power UEs, sensor nodes and other low power electronic devices wirelessly. The basic component of RF energy harvester is an antenna and rectifier, coined together as Rectenna. Researchers have been working towards deploying an RF energy harvester with lower threshold voltage, and better power conversion efficiency (PCE). This paper gives an overview of related designs of existing RF energy harvesters.

Keywords: User Equipments (UEs), Radio Frequency, Rectenna and Power Conversion Efficiency (PCE).

Introduction

The exponential increase in the deployment of wireless sensor nodes for IoT, wireless sensor networks and user equipment (UE) requires the use of an autonomous power source to power such low power electronic devices. New

electronic devices consumes low power. Wireless sensors are said to consumed power within the range of 10 – 100 µW depending on the manufacturer, sensing application and radio protocol (Zohaib and Kambiz, 2015). Because of the low power consumption rate of new electronic devices, battery are used as their source of power.

The limitation of battery lifespan, difficulty in replacing sensor node batteries in harsh environment, recharging of batteries from an Alternating Current (AC) source which is inadequate in most developing countries such as Nigeria, and the harsh deployment areas of sensor node are limitations to using rechargeable batteries as primary source of power to sensor nodes, IoT devices and UEs. This limitations are major setback for a continuous power supply (Sampe *et al.*, 2019; Sun *et al.*, 2018; Yunus *et al.*,2020). This necessitate the used of energy harvester as source of power to recharge batteries of electronic devices wirelessly and to power the devices directly. According to Danial *et al*. (2019), RF harvester is a promising technology for powering low-power sensor nodes used for Internet of Things (IoT) and Wireless Sensor Network (WSN).

Researchers and developers have suggested the collection of non-electrical energy, among which are: Radio Frequency (RF), thermal, light and wind energy; and converting them into electrical energy. This process of collecting energy from other sources and converting it into electrical energy is called energy harvesting (Yang *et al.*, 2020). RF energy harvester is an electronic device that collects RF energy using antennas, converts the RF energy into AC, then into DC using rectifiers and directly powers a low power electronic device (Wireless sensor nodes, and UE), and stores the excess direct current (DC) power in a battery or a super-capacitor for higher power low duty-cycle operations (Clerckx *et al.*, 2018).A UE can be on call or connected to the internet and still be charging its battery wirelessly using RF energy harvester (Rosli *et al*. 2018). The major electronic component of an RF energy harvester is a rectifier and an antenna; which is commonly referred to as Rectenna or RF-DC.

The signal power of RF is limited and it includes several spectral bands in the environment. In order to harvest an increasing amount of power, it is expected than an RF–DC harvester operates at multi-bands over a wide input power range Danial *et al*. (2019).

Working Principle of RF Harvester

An RF harvester collects RF energy using an antenna, and then feeds in the collected RF energy to the matching network that ensure the maximum delivery of power to the rectifier (main component of an energy harvester) which converts the RF power to DC power. The working principle of an RF harvester is summarized using a block diagram presented in Figure 1.
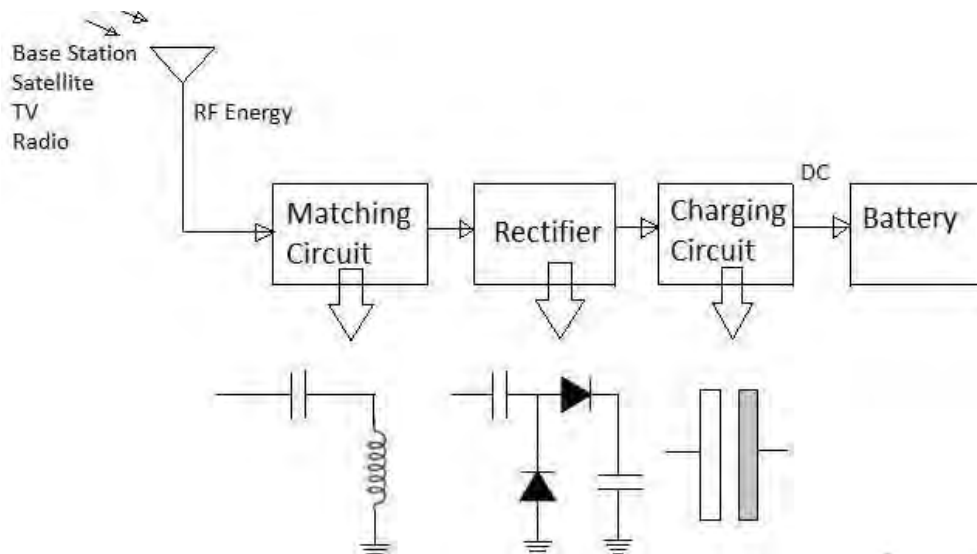

Figure 1: Hard ware block diagram of RF energy harvesting system
(Reji and SaiChakresh 2019)

RF Signal

An RF signal is an electrical oscillation, with frequency ranging from 3 kHz to 300 GHz that contains both information and RF energy (Rosli *et al*. 2018; Clerckx *et al.,* 2018). Table 1 presents summary of electromagnetic spectrum RF signal that can be sourced from radio transmission (Amplitude and Frequency modulation) Television (TV) transmission and cellular communication nodes. An RF signal is transmitted or received using an antenna into the space. The transmission lines of RF includes wired medium (coaxial cables, parallel wire lines) and wireless medium (space)

Table 1: Classification of electromagnetic wave spectrum

Band Designation	Frequency	Wavelength	Example Uses
Extremely Low Frequency (ELF)	3 – 30 Hz	100 – 10 Mm	
Super Low Frequency (SLF)	30 – 300 Hz	10 – 1 Mm	Power lines
Ultra Low Frequency (ULF)	300 – 3 KHz	1 Mm – 100 Km	
Very Low Frequency (VLF)	3 – 30 KHz	100 – 10 Km	Submarine Communication
Low Frequency (LF)	30 – 300 KHz	10 – 1Km	RFID
Medium Frequency (MF)	300 – 3 MHz	1 Km - 100 m	Amplitude Modulation (AM) broadcast
High Frequency (HF)	3 – 30 MHz	100 – 10m	Shortwave
Very High Frequency (VHF)	30 – 300 MHz	10 – 1 m	Frequency Modulation (FM) and Television (TV) broadcast
Ultra High Frequency (UHF)	300 MHz – 3 GHz	1 m - 10 cm	TV, WLAN, GPS, Microwave Ovens
Super High Frequency (SHF)	3 – 30 GHz	10 – 1 cm	Radar, WLAN, Satellite Communication
Extremely High Frequency (EHF)	30 – 300 GHz	10 – 1 mm	Radar, Radio astronomy, point-to-Point high rate data

			links, satellite Communication
Microwaves	1 – 300 GHz	30 cm – 1 mm	
Millimeter wave	30 – 300 GHz	10 – 1 mm	
Sub millimeter Waves	>300 GHz	< 1mm	

(Source: Stutzman and Thiele 2012)

The mathematical expression for converting from wavelength to frequency is presented in equation (1)

RF Antennas

RF antenna plays a vital role in maximizing the reception of RF energy from the surrounding. It is defined by IEEE as part of a transmitting or receiving system that is designed to radiate or receive electromagnetic waves (Stutzman and Thiele 2012). The type of antenna used affects: the RF energy that will be matched to the RF-DC converter, the output power of an RF harvester and cascade rectifiers. The performance parameters of antenna is presented in Table 2.

Table 2: Performance parameters of antennas

S/N	Parameter	Description
1	Radiation Pattern, F(θ, Ø):	Angular variation of radiation around the antenna, including: directive single or multiple narrow beams, Omnidirectional and shaped of main beam
2	Directivity, (D):	Ratio of power density in the direction of the pattern peak to the average power density at the same distance from the antenna
3	Gain, (G):	Directivity reduced by the losses on the antenna
4	Polarization	The instantaneous electric field vector associated with the radiation from an antenna

		when transmitting. Antenna Polarization include: Linear, Circular and Elliptical
5	Impedance, Z_A:	The input impedance at the antenna terminals
6	Bandwidth:	Range of frequencies
7	System Considerations:	Mechanical considerations (size, weight, aerodynamics, vibration, positioning accuracy), environmental aspects (effects of wind, rain, temperature, altitude)
8	Special consideration for transmitting antennas:	Power handling, inter modulation, radiation hazards
9	Special Considerations for receiving antennas:	Noise

(Source: Stutzmanand Thiele 2012)

Matching Network

A matching circuit is placed between the antenna and rectifier sub-blocks of an RF energy harvester to maximize the power transfer from the antenna to the rectifying circuit. There are various matching circuits in used; but the common design is an L-section matching circuit presented in Figure 3, made up of capacitor, resistor and inductor.
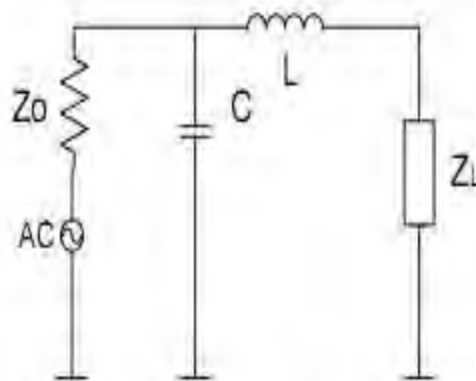

Figure 3: A matching network of an RF energy harvester

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Rectifier

Sampe *et al.* (2019) opines that voltage doubler is the best selection of RF-DC rectifier due to its simplicity in terms of circuit design and it ability to produce twice of the amplitude of the corresponding input signal, and to attain high efficiency. A circuit diagram of a single stage voltage doubler is presented in Figure 4.
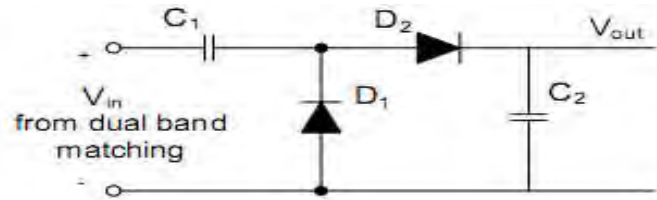

Figure 4: A circuit diagram of voltage doubler (Source: Sampe *et al.,* 2019)

The output voltage of a voltage doubler is mathematically expressed in equation (1)

$$V_{out} = 2V_{in} - 2V_{th}$$

(1)

where Vin and Vth are the input voltage and the threshold voltage of the diodes, respectively.

Key Performance Indicators
Power Conversion Efficiency

The Power Conversion Efficiency (PCE) of an energy harvester is a ratio of output dc power to input RF power. According to Danial *et al.* (2019); Sampe *et al.* (2019), equation (2) is use for computing PCE

$$eff\ (\%) = \frac{P_{out}}{P_{in}} = \left(\frac{V_{R_L}^2}{R_L}\right)\left(\frac{1}{P_{in}}\right) \times 100\ \% = \frac{V_{R_L}^2}{R_L P_{in}} \times 100\ \%$$

(2)

Where $eff\ (\%)$, is the Power Conversion Efficiency in percentage, P_{out} stand for dc output power, P_{in} stand for input RF power, R_L stand for load resistance and $V_{R_L}^2$ stand for voltage across load resistance.

The input power to an antenna can be computed using equation (3)

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$$P_{in} = P_{tx}G_{tx}G_{rx}\left(\frac{\lambda}{4\pi d}\right)^2 \qquad (3)$$

where P_{in} stand for antenna input power, P_{tx} stand for transmitter power, G_{tx} and G_{rx} antenna gain of transmitter and receiver respectively, λ represents wavelength of RF, d stand for distance between transmitter and receiver. The bulk energy loss in an RF energy harvester has to do with the RF-DC converter. Researchers have proposed different circuit design and topology to reduce the losses in the system.

Power Up Threshold

Power up threshold of an RF harvester also referred to as threshold rectifying voltage is the minimum required power or voltage that will turn on an RF – DC converter. The value of power up threshold and leakage current in the circuit affects the output voltage (Zohaib and Kambiz, 2015). For the same input power, RF harvesters with lower power up threshold will yield higher output voltage when compared to those with higher threshold power. And Harvesters with low up power can operate with low input RF power.

Literature Review

In the work of Bertacchini *et al.* (2015) they proposed the use of customized Biconial dipole antenna with inductive coupling on a printed circuit board (PCB) for harvesting RF energy at different frequencies. The RF harvester was accomplished using CMOs technology. The result obtained from their design yielded an output voltage of 2V over an RF input power of 14 dBm and maximum efficiency of 18 % at 915 MHz. Their harvester had low Power Conversion Efficiency (PCE) at 14 dBm which needed to be looked into for better output and less losses.

Likewise, in a related development Gabrillo, (2015) considered RF to DC converter with LC resonant circuit operated at 165 MHz for TV broadcasting tower. It Produced 1.80mW output power at a distance of 77.84 m from a TV signal tower operating at 165 MHz. This can be used to run low power devices. However, 1.80mW was obtained at a distance less than a kilometer, which will not make it practically significant.

Also, the work of Yogesh *et al,* (2015) a complete harvesting circuit was developed by coupling multiple basic harvesting circuits. The basic circuits were connected in such a way that it harvest quite large amount of voltage. Here five stages of basic circuits with copper wired antenna were connected in series and Capacitor C is also connected to store voltage harvested by all stages. Several experiments with various diodes and current carrying conductor combinations were conducted. The results revealed that with easily available components, up to 1-2 mw of power can be harvester. However the RF harvesting system has very low conversion efficiency.

Similarly, a related work of Zohaib *et al.* (2015) proposed the used of auxiliary transistor to reduce the threshold voltage of transistors in their RF – DC converter. The RF energy harvester had peak Power Conversion Efficiency (PCE) of32%at input power of 15 dBm (32μW) and corresponding output voltage of 3.2 V. When input power was low as -20.5 dBm (8.9 μW), the output voltage gotten was 1 V. The harvester was able to convert low RF power, even though the PCE was less than 40%. The harvester collected low RF power and it should be improved to collect more RF power and transfer same to the rectifier.

According to Nechibvute *et al.*, (2017) considered a concise review of RF energy harvesting sources, highlighting the key achievements and challenges. The conversion efficiency of RF energy harvesting systems at low input RF power is currently very low and hence particular research efforts at improving this performance metric is a key challenge in realizing practically viable rectenna systems for real world deployment. While the power delivered by RF energy harvesting devices have significantly increased over the past decade, it is noted that the targeted applications are essentially ultralow power wireless sensor devices which do not support high computationally algorithms.

Also, Sachin *et al.* (2017) proposed an RF harvester that made use of a novel broadband hybrid dielectric resonator antenna (DRA). Their antenna had a peak gain of 9.9 dBi and impedance bandwidth, which ranges from 1.67 – 6.7 GHz. For a load impedance of 4.7 KΩ, the peak PCE at 1.8 GHz, 2.1 GHz, 2.4 GHz and 3.6 GHz gave 1.4%, 60.4%, 54%, and 44% respectively. Basically the RF environment is characterized with RF from broadcasting radio stations (AM stations operates at 2.3-22 MHz, and FM station at 88-108 MHz), television

broadcasting stations (175-300 MHz) 3G (operates at 900 MHz) and 4G (operates at 1.8 GHz) communication networks. The RF harvester had PCE above 40% at 2.4 GHz, 3.6 GHz and 3.6 GHz only, which are uncommon RF sources in the environment. Their RF harvester should work with the commonly available RF sources in the environment and give high output power, to make it more practical.

Also Zeng *et al,* (2017) repotted "A Compact Fractal Loop Rectenna for RF Energy Harvesting". This paper presents the design and the fabrication of a compact fractal loop rectenna for RF energy harvesting. A high-efficiency rectifier is incorporated in the loop antenna to form a compact rectenna. Measured results indicate an efficiency of 61 percent, an output DC voltage of 1.8V across an output resistance of 12kΩ for a power density of 10μW/cm2 at 1.8GHz. That is,the RF source is GSM 1800MHz band. This output from the RF energy harvester was able to power a battery-less LCD watch at a distance of 10meters from the GSM base station. However this RF harvester operated at short distance. A distance of 10m from base base station to harvester, however is too short for any practical purpose.

Likewise, Daniel *et al.* (2018) reported proposed a reconfigurable RF- DC converter that used IVC and maximum power point tracking (MPPT) algorithm. The rectifier threshold voltage is controlled dynamically in the forward and reverse biased transistors. The positive half-cycle of proposed RF–DC converter reduces the voltage drop across the forward-biased transistors and minimizes the reverse leakage current during the negative half-cycle to increase the system power efficiency and to prevent the loss of energy stored in the prior stages. The RF harvester yielded a maximum efficiency of 39.3% at input power of -21 dBm at 900 MHz. Their RF harvester was able to convert RF power to DC power but had losses that account for less than 40% PCE needed to be addressed.

In the work of Lakshmi *et al.,* (2018) multiple dedicated RF sources was proposed for an efficient RF energy harvesting system to prevent energy losses. The greatest energy transmission challenge was solved as an optimization problem with minimum energy charge by each node as the constraints. Some of the shortcomings of the proposed techniques are that the sensor nodes are

constantly on while receiving the RF energy and the received RF energy needs to be greater than the energy required by sensor nodes to operate.

Similarly, Rosli *et al* (2018) proposed RF energy harvester comprising of rectifier (RF - AC), DC – DC converter, and voltage regulator, that was implemented in 0.13 μm CMOS technology. The DC-DC converter (made up of charge pump and ring oscillator) was to boost input voltage. Their result indicated a regulated output voltage 1.25 V at RF frequency range of 900 MHz and 2400 MHz, input RF power of -16.48 dBm, and load resistance of 50Ω. The DC – DC converter boosted inputted 370 mV from rectifier into high output voltage of 1.75 V, that was regulated into 1.25 V. The RF harvester DC-DC converter was able to boost low input power to a significant output voltage. But more need to be done to reduce losses in the rectifying input for higher DC-DC converter output that can conveniently power android phones that work at 5V and microcontrollers.

Similarly Caselli, *et al*. (2019) considered the analysis and design of an integrated RF energy harvester for ultra low-power environments. They did an RF power survey in urban (Reggio Emilia, Italy), semi-urban (University Campus, Parma, Italy) and rural (a village called Valestra, Italy) settlement. The average input power of urban settlement for GSM – 900 MHz, GSM – 1800 MHz and LTE bands gave -21.3, -32.3 and -36 dBm respectively. That of semi-urban gave -28.9, -48.8, and – 40.2 dBm respectively, rural settlement for GSM-900 Hz and GSM – 1800 Hz gave -55 and -70 dBm respectively. Their RF harvester design comprised of an RF-AC converter (antenna), AC – DC converter and DC – DC converter, which gave a good sensitive and end-to-end efficiency over full process, voltage and temperature (PVT) space. Their RF harvester was designed using 65nmComplementaryMetal-OxideSemiconductor (CMOS) technology to operate over the range of −40 to 85°C temperature and output voltage ranging from 1.1 to 2.5V.

The input control strategy adopted for the converter allows the adaptation of the harvester to the available RF power and enable maximum power point tracking (MPPT). However the maximum output voltage of 2.5V cannot power microcontrollers and android phones.

The work of Danial *et al*. (2019) titled CMOS RF Energy Harvester with 47% peak efficiency using internal threshold Voltage Compensation considered a

single stage complementary metal oxide semiconductor (CMOS) RF energy harvester based on internal threshold voltage cancellation (IVC) technique, to harvester energy from of 0.902and 2.45GHz frequency bands. They used two matching networks for the dual frequency band. Their results at 0.902 GHz within the input power ranges of -9 to 10 dBm gave more than 20% power conversion efficiency (PCE). At 2.45 GHz RF band, it had the maximum PCE of 27.1% at 20 dBm, and more than 11% PCE within input power range of -2 to 15 dBm. Their RF harvester had an efficiency that is below 40%. However the losses in the RF harvester needed to be minimized to give high output power. In a related development, Sampe *et al*. (2019) proposed an RF harvester that operated at 1.8 GHz and 2.5 GHz frequency band using an antenna they referred to as rectifying antenna. They simulated their design RF harvester using Computer Simulation Technology Microwave Studio (CST-MWS) software. The output voltage of the simulation gave 1.35 V and 1.8 V at input power of -25 dBm and -20 dBm respectively. And the PCE of the RF-DC converter at 1.8 GHz and 2.5 GHz was 59.51% and 45.75% respectively. Sampe *et al* (2019) RF harvester had a better PCE when compared to Danial *et al*. (2019) and Danial *et al*. (2018) RF harvesters. But they did not produce the prototype of their designed RF harvester, and the harvester was limited only to two RF bands.

In a new development Timothy *et al*. (2020) considered a dedicated Radio Frequency (RF) energy harvesting for complete off-grid application. Their work proposed a battery-less wireless sensor node to be powered by 4W, 920MHz. A power based station has been developed that derived energy through PV panels to radiate RF energy to power the sensor node. A step down DC-DC converter coupled with a microcontroller for implementation of CC-CV battery charging algorithm which controls it (DC-DC converter) that charges lithium-ion batteries that power the RF transmitter and amplifier, respectively. A 12 element Yagi antenna was designed and optimized using the FEKO Electromagnetic software. To end this, a power base station was designed which derives its power from solar PV panels to radiate the RF energy used to power the sensor node. The results obtained from the experiments performed showed that enough RF energy was harvested over a distance of 15 m to allow the sensor node complete one sense-transmit operation for duration of 156 min. The Yagi antenna achieved a gain of 12.62 dBi and a return loss of -14.11 dB at 920 MHz,

while the battery was correctly charged according to the CC-CV algorithm through the control of the DC-DC converter. However, the harvested power was over a short distance of 15m

Likewise, (Joy deep & Subhasish, 2021) considered different RF energy harvesting circuits and transmission line-based RF power combiner systems for future applications. Low series resistance Schottky diodes was used for RF energy harvesting circuit due to its almost zero threshold voltage. However, as parallel a MOS-based Dickson's charge pump circuit was also proposed as it can be achieved by well-developed CMOS manufacturing technology to get higher performance. It is observed from the results that output voltage at final stage was increased by 4.7 times for 1 V input voltage after 500 μ sec and increased by 2.73 times for 300 mV input voltage after 1 msec. Results conclude that output capacitor is charged quickly for comparatively higher input voltage. Wilkinson power combiner followed by voltage multiplier circuits has been found very effective to harvest energy from multiple RF energy sources. The results are encouraging to implement these energy harvesting circuits as emerging techniques for low power electronics applications. However the circuit implementations required the used of several antennal which may is capital intensive

Conclusion

The low power usage of modern electronic devices makes it possible to be powered using low power DC battery which requires charging. To overcome the limitation of charging and replacing batteries in harsh environment. Most sensor nodes, microprocessors, UEs and wireless sensor network devices are said to adopt the use of alternative sources of power, such as an RF energy harvester. Since new electronic devices consume less power and RF energy harvester produced less output power. This paper review an RF signal, RF energy harvester and gave review of existing RF energy harvesters

REFERENCES

Action, N., Albert C., Nicholas, T. & Pearson, L. (2017) Radio Frequency Energy Harvestin g Sources. *A journal of Acta Electrotechnica et Informatica*, 17(4), 19–27

Bertacchini, A., Larcher, L., Maini, M., Vincetti, L., & Scorcioni, S. (2015). Reconfigurable RF Energy Harvester with Differential PCB Antenna. *Journal of Low Power Electronis Application*, 5, 257-273

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March, 2022.

Caselli, M., Tonelli, M. & Boni, A. (2019) Analysis and Design of an Integrated RF Energy Harvester for Ultra LowPower Environments. *International Journal on Circuit Theory Applications,* 47, 1086–1104

Clerckx B., Zhang, R., Schober, R., Ng, D. W. K., Kim, D. I., & Poor, H. V. (2018). Fundamentals of Wireless Information and Power Transfer: From RF Energy Harvester Models to Signal and System Designs. *IEEE Journal on Selected Areas in Communications,* 37(1), 4 - 33

Danial, K., Seong, J. O., Khuram, S., Deeksha, V., Zaffar, H. N. K., Young, G. P., Minjae, L., Keum, C. H., Youngoo, Y., & Kang-Yoon, L.,(2019). A CMOS RF Energy Harvester with 47% Peak Efficiency Using Internal Threshold Voltage Compensation. *IEEE Microwave and Wireless Components Letters.* 29(6), 415 - 417

Danial, K., Hamed, A., Sang-Yun, K., Zaffar, H.N.K., Syed, A.A.S., Young, G.P., Keum, C.H.I., Youngoo, Y., Minjae, L., & Kang-Yoon, L. (2018). A design of an ambient RF Energy Harvester with Sensitivity of 21 dBm and Power Efficiency of a 39.3% Using Internal Threshold Voltage Compensation. Journal of energies. *Energies* 11(5), 1258

Lakshmi, P.S.; Jibukumar, M.; Neenu, V. Network lifetime enhancement of multi-hop Wireless Sensor Network by RF energy harvesting. In Proceedings of the 2018 International Conference on Information Networking(ICOIN), Chiang Mai, Thailand, pp. 738–743.

Rosli, M. A., Murad, S. A. Z., Norizan, M. N., & Ramli, M. M.(2018). Design of RF to DC Conversion Circuit for Energy Harvesting in CMOS 0.13-μm Technology. *Electronic and Green Materials International Conference* 4(1), 265 - 271

Sachin, A., Ravi, D. G., Manoj, S. P., Praveen, N. K. (2017). A Wideband High Gain Dielectric Resonator Antenna for RF Energy Harvesting Application. *International Journal of Electronics and Communications.* 125 – 148

Sampe, J., Yunus, N.H.M., Junas, J., & Pawi, A. (2019). Architecture of an efficient dual band 1.8/2.5 GHz rectenna for RF energy harvesting. *Telkomnika*, 17(6), 3137 - 3144

Stutzman, W.L., & Thiele, G.A. (2012). *Antenna theory and design*. John Wiley & Sons.

Timothy, M., Stephen, S. O., Adnan, M. A., & Gabriel P. H (2020) Enabling a Battery-Less Sensor Node Using Dedicated Radio Frequency Energy Harvesting for Complete O_-Grid Applications. *Journal of Multidisplinary Digital Publishing Institute.* Retrieved from (http://creativecommons.org/licenses/by/4.0/).

Yunas, J., Yunus, N. H. M., Sampe, J., & Nandiyanto, A. B. (2020). Design and Fabrication of Glass based MEMS Patch Antenna for Energy Harvester. *IEEE International Conference on Power and Energy (PECon),* 362 – 365.

Yunus, N.H.M., Sampe, J., Yunas, J., Pawi, A. & Rhazali, Z.A. (2020). MEMS based antenna of energy harvester for wireless sensor node. *Microsystem technologies,* 26(9), 2785-2792

Zeng, M., Andrenko, A. S., Liu, X., Li, Z., & Tan, H. Z. (2017). A Compact Fractal Loop Rectenna for RF Energy Harvesting. *IEEE Antennas and Wireless Propagation Letters*, *16*, 2424–2427

Zohaib, H., & Kambiz, M. (2015). A 3.2V–15 dBm Adaptive Threshold-Voltage Compensated RF Energy Harvester in 130nm CMOS. *IEEE Transactions on Circuits and Systems,* 62 (4), 948 – 956.

Gabrillo, L. J., Galesand, M. G., Hora, J. A. (2015): Enhanced RF to DC converter with LC resonant circuit, IOP *Conference Series: Materials Science and Engineering, IOP Publishing*, 79(1),