



# A Survey of RF Energy Harvesting Techniques for Powering 5G Mobile Devices

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## Abstract

*Radio frequency (RF) energy harvesting has been established as a viable alternative for powering mobile devices without increasing greenhouse gas (GHG) emission, which is a threat to the environment. However, there are challenges facing effective harvesting of appreciable energy for these devices. Low RF power harvestable from various sources and low radio frequency-direct current (RF-DC) conversion efficiency has made it a very difficult task to harvest sufficient power to operate mobile devices such as smartphones. Lower frequency RF sources could yield appreciable harvestable energy but this comes with the challenge of portable antennas that could match these frequencies. This paper presents a review of various RF energy harvesting techniques in literature and exposes some of the challenges currently being faced by researchers in the design of RF energy harvesting circuits. The importance of using alternative renewable sources to power mobile devices in the face of the looming global energy crisis while avoiding global warming were highlighted. Suggestions for future work aimed at harvesting sufficient power for the operation of smartphones and other mobile devices were also made.*

**Keywords:** *Radio frequency energy, conversion efficiency, RF power, greenhouse gas, smartphones, mobile devices*

## 1. Introduction

Spectrum Crisis and high power consumption are some of the challenges that have emerged, which the fourth generation (4G) wireless communication networks have failed to address. It is expected that the fifth generation (5G) with its promise of huge facilities including capacity to connect 100 billion devices worldwide, massive multi-input-multi-output (MIMO) systems, 7.6 billion subscribers and up to 10 Gb/s individual user speed, will be able to handle these two challenges (spectrum scarcity and high power consumption). However, it requires enormous amount of operating power (Wang, Haider, Gao, You, Yang, Yuan, Aggoune, Haas, Fletcher and Hepsaydir, 2014). This envisaged increase in the demand for energy has led to a call, over a decade ago, for energy efficient based designs in mobile communication infrastructure and devices. Energy efficiency demand is



increasing globally as a result of high energy costs and environmental issues (Lakshmanan, Mohammed, Palanivelan, and Kumar, 2015). Globally, a rapid increase of mobile traffic by more than 60 % per year is expected due to the increase in smart phones and tablet terminals (Kimura, Seki, Kubo and Taniguchi, 2015). With the increase in the demand and use of smart phones giving rise to increased data services, there is consequent increase in demand for energy to power the devices. Increase in energy consumption in wireless networks directly leads to increase in greenhouse gas (GHG) emission. This has been recognized as a big threat to the environment. Hence the call on wireless network researchers and engineers to shift focus a little from wide-spread access and large capacity to energy efficient based designs (Lakshmanan, Mohammed, Palanivelan and Kumar, 2015). The major advantages of 5G over 4G according to Al-qasrawi (2016), include higher efficient spectrum allocation, longer battery life, higher bit rates in larger portions of the coverage area, higher total capacity for many users at the same time via both primary and secondary spectrum users, lower outage probability and lower infrastructure costs. Fig. 1 shows some of the differences between 4G and 5G.

It can be seen from Fig. 1, that there are many more devices connected via relay systems in the 5G network than in the conventional 4G network. Recently, interest has increased with respect to powering wireless network nodes using renewable energy sources such as thermal, vibration, solar, acoustic, wind and ambient radio frequency (RF) power, since these sources are used to facilitate the reduction of energy costs and harmful effects on the environment caused by carbon dioxide (CO<sub>2</sub>) emission (Liu, Zhang, Yu and Xie, 2015).

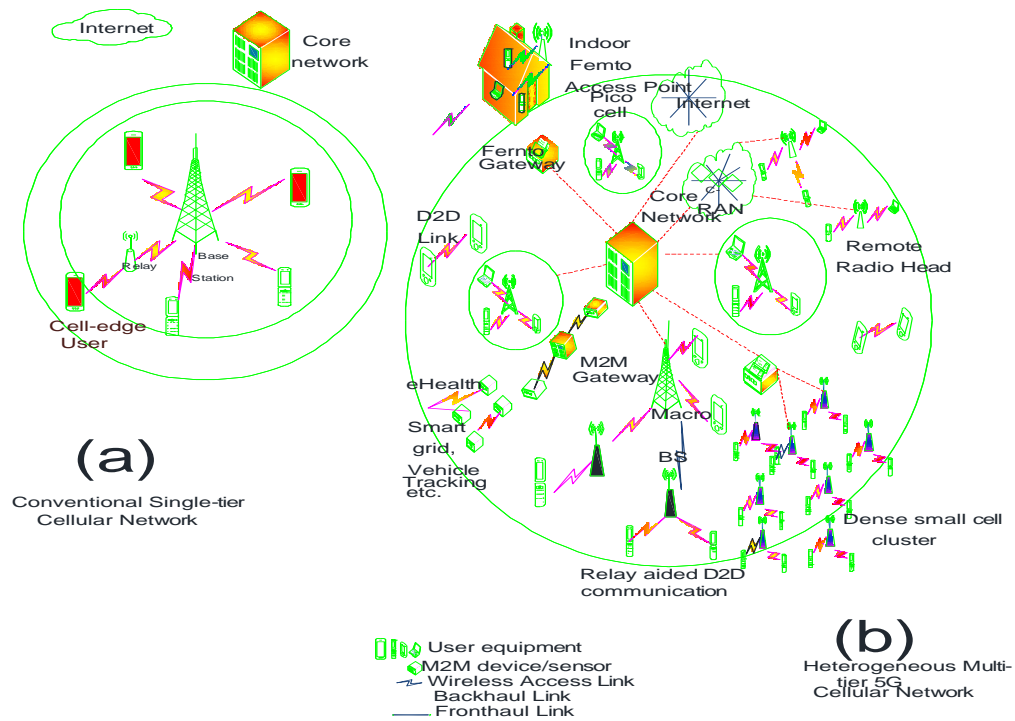


Fig. 1: Differences between 4G and 5G Networks.(a) Conventional single tier 4G cellular Network, (b) Heterogeneous Multi-tier 5G Cellular Network (Source: Al-qasrawi, 2016)

Reducing energy consumption is a major challenge in recent wireless systems that adopt 4G/5G technologies. According to Lakshmanan, Mohammed, Palanivelan and Kumar, (2015), 9 % of total carbon emission is due to mobile communications, specifically, radio access part consumes 70 % of its total power. Various organizations and groups are taking strategic positions to address this challenge. For example, European Union (EU) member states recently signed agreement to reduce greenhouse gas emission by 20 % by the year 2020. Also, Vodafone group agreed to reduce CO<sub>2</sub> emission by 50 % in the same year.

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It has been noted that the fifth generation (5G) wireless networks will support up to a 1000-fold increase in capacity in comparison with existing networks such as 4G (Wu, Li, Chen, Ng, and Schober, 2017). It is also projected that by 2021 over 28 billion devices will be connected to 5G wireless networks and over 15 billion of which will be machine-to-machine (M2M) connections.

This is to make provision for Internet of Things (IoT) communication which is one of the most important missions of 5G (Ercan, Sunay, and Akyildiz, 2018). These statistics are pointers to the enormous energy needed in the future. For more than a century, research and design of wireless networks have been concentrated on optimization of metrics such as data rate, throughput, latency etc. However, in the last decade, energy efficiency has become a new area of concern due to economic, operational, and environmental factors (Buzzi, Chih-Lin, Klein, Poor, Yang, and Zappone, 2016, Divakaran, Krishna, 2019). Research in energy efficient techniques is inevitable if digital economy must be sustained.

The energy challenges and accompanying environmental issues are worse for developing countries who, almost completely, depend on mobile wireless systems for their connectivity needs. For example, in Nigeria there is an acute energy insufficiency, and the little energy that is available is sourced mainly from fossil fuel. In order to achieve inclusive connectivity for developing nations and prepare for the global expectation of massive connection of smart phones and other mobile devices in the next generation of wireless networks (5G), there is urgent need to develop a system that will ensure that mobile devices are always powered with green energy sources. As a step in this direction, this paper reviews RF energy harvesting (RF-EH) techniques toward developing a system that will harvest sufficient power to operate smart phones and other mobile devices.

## 2. Review of RF Energy Harvesting Techniques

For more than a decade ago research has been going on in the area of RF energy harvesting. Various techniques have been proposed and implemented for a number of applications such as RF identification (RFID), wireless sensor nodes (WSN), wireless body area networks (WBAN) and wireless charging systems (WCS).

The general structure of an RF energy harvester is shown in Fig. 2:

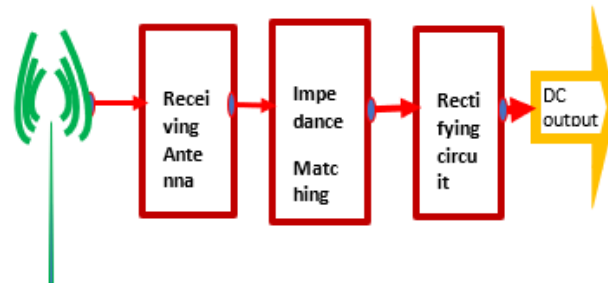


Fig. 2: General structure of RF Energy Harvester. (Source: Bakkali, Pelegrí-Sebastiá, Sogorb, Llarío and Bou-Escrive, 2016)

The general structure of a typical RF energy harvester consists of an RF energy source and a circuit capable of receiving and converting the RF energy into DC voltage and current. Key components of this circuit are reviewed here.

### 2.1 Antennas for RF Energy Harvesting

Mobile communication requires miniaturization of devices, hence the widespread research in patch antennas for RF-EH. For example, Song, Huang, Zhou, Zhang, Yuan and Carter, (2015), in their work- “A High-efficiency Broadband Rectenna for Ambient Wireless Energy Harvesting”, studied characteristics of ambient RF energy. The result of the study was then used to design and implement a broadband (1.8-2.5 GHz), dual-polarized, cross-dipole rectenna. It has an embedded harmonic rejection property that enables it reject 2<sup>nd</sup> and 3<sup>rd</sup> harmonics which further improves the efficiency of the rectenna. The results showed that the sensitivity goes down to -35 dBm while conversion efficiency is up to 55 % when the input power is -10 dBm. The rectenna powers low-power



devices and sensor nodes. As input power increases, efficiency of the RF-EH system increases. Therefore, it is necessary to target RF sources of high transmitting power, in order to harvest sufficient power for operating mobile phones and other similar devices ( Mrnka, Vasina, Kufa, Hebelka and Raida, 2016).

Mrnka, Vasina, Kufa, Hebelka and Raida, (2016), in their work “The RF Energy Harvesting Antenna Operating in Commercially Deployed Frequency Bands: A Comparative Study”, studied the performance of four basic antenna designs within the frequency range of 0.8 GHz to 2.6 GHz, which is covering the frequencies of operation in Global System for Mobile Communication (GSM), Universal Mobile Telecommunications System (UMTS) and Wi-Fi. They include the patch antenna, slot antenna, modified inverted F antenna and dielectric resonator antenna. Their performances were compared based on reflection co-efficient, efficiency, radiation patterns and dimensions. According to their results, the antennas have peak efficiency at different frequencies, for example, the patch antenna has its highest efficiency at 2.45 GHz, while the slot antenna has it at 1 GHz, the inverted F antenna at 1.7 GHz and the dielectric resonator antenna at 1.9 GHz respectively. In terms of reflection coefficient, the patch antenna was seen to be the best, followed by the slot antenna, then the inverted F antenna and the dielectric resonator antenna. All the four antennas proved to be effective for RF energy harvesting within the frequency range of interest, except that further miniaturization is required for them to be used in wireless sensor networks and mobile wearable devices.

In the same vein, Sharma and Saini (2016) in “Microstrip Antenna Array for RF Energy Harvesting System”- designed and fabricated first, a two-patch and then a four-patch antenna arrays. Antenna simulation, analysis, computation of return losses, 3D polar plots and gain were carried out using High Frequency Simulator software (HFSS). Simulation results showed that the four-patch array which is a modification of the previous two-patch array, achieved a gain of 9.2 dB at resonating frequency of 1.78 GHz that is, it could be used to capture RF signals in GSM 1800 MHz band. It was shown that increasing the number of patches will increase the gain and hence, the sensitivity. Also, Bakkali, Pelegrí-Sebastiá, Sogorb, Llario and Bou-Escriva ( 2016) worked on - “A Dual –Band Antenna for RF Energy Harvesting Systems in Wireless Sensor Networks”. They focused on the



design, simulation and fabrication of a dual-band receiving antenna, operating in the Wi-Fi bands of 2.45 GHz and 5 GHz. Measured and simulation results indicate that the designed and fabricated antenna has a multi-band characteristic with return losses up to 25 dB and 13.5 dB respectively, measured reflection co-efficient, which agrees with the result from simulated radiation patterns, are quasi-omnidirectional. However, the patch antenna is suitable only for narrowband.

Abdulhasan, Mumin, Jawhar, Ahmed, Alias, Ramli, Homan and Audah (2017) in their work- “Antenna Performance Improvement Techniques for Energy Harvesting: A Review Study” - several antenna designs for RF energy harvesting were reviewed, analyzed and compared. The designs considered include array antenna, slot patch antenna, gain enhanced, solar cells, coupled E-shaped patch antennas, dual-port pixel antenna, and substrate integrated waveguide (SIW) cavity reflector patch antenna. Different types of optimization schemes were compared. High frequency simulator software (HFSS) was used for simulation and analysis. The simulation results indicate that the highest efficiency will be achieved when transmitter has a zero phase shift at a distance of 15cm, array sets 2 and 4, with phase shift of  $-90^\circ$  control the main-lobe direction by  $15^\circ$  and achieved an efficiency of 3.72 %; Bandwidth improvement is directly related to total slot length and location. It improved from 5.4 MHz to 20.6 MHz. Generally, performance of RF-EH is better with arrays than with single patch or slot antennas.

Zeng, Andrenko, Liu, Li and Tan (2017) worked on “A Compact Fractal Loop Rectenna for RF Energy Harvesting”. This paper presented 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 %, an output DC voltage of 1.8 v across an output resistance of  $12\text{ k}\Omega$  for a power density of  $10\ \mu\text{W}/\text{cm}^2$  at 1.8 GHz. That is, the RF source is GSM 1800 MHz band. This output from the RF energy harvester was able to power a battery-less LCD watch at a distance of 10 meters from the GSM base station.



Asmeida, Mustam, Abidin and Ay (2017) presented a design and simulation of fast switching microwave rectifying circuit, with an ultra-wideband (UWB) patch antenna operating over the frequency range from 1.8 GHz for GSM to 2.4 GHz for ISM. The circuit was designed using Advanced Design System(ADS) software. Simulation results showed a maximum output voltage of 2.13 v, maximum conversion efficiency of 86 % for an input power of -5 dBm. The output voltage was only sufficient to power up a wireless sensor node (WSN). Zeng, Andrenko, Liu, Li, and Tan (2017) proposed “A simple wideband electromagnetically fed circular polarized antenna for energy harvesting” with high gain, that will be capable of fully harvesting RF energy in the environment. A survey on the feasibility of scavenging RF energy was carried out by power density measurements in an urban area. The result of the survey was used in designing a circularly polarized (CP) antenna to operate from 1.73 to 2.61 GHz in GSM 1800, UMTS, Wimax and ISM bands. Experimental results showed that the antenna achieved an axial bandwidth of 25 % with respect to 2.08 GHz centre frequency. The antenna also exhibited broad impedance bandwidth of 32.77 % with measured peak gain of 8.7 dBi at 2.05 GHz. The proposed antenna is simple and low cost with a size of  $0.462 \lambda \times 0.462 \lambda \times 0.01 \lambda$ .

In the work- “A Novel Wideband Circularly Polarized Antenna for RF Energy Harvesting in Wireless Sensor Nodes”, the authors, Nguyen, Bui, Le, Pham, Nguyen, Nguyen and Le (2018) presented a novel circularly polarized antenna array to operate at 5.05 to 7.45 GHz. In addition, a left-handed metamaterial was designed to operate at 2.4 GHz and increase the gain of the antenna. The highest gain obtained was 12 dBi at 6 GHz. The result of their work is a wideband circularly polarized left-handed metamaterial (CP LHM) antenna for Wi-Fi energy harvester, with 61 % conversion efficiency, 2.5v DC output voltage. A potential application of this antenna is in harvesting RF energy from Wi-Fi network for powering wireless sensor nodes. Hameed and Moez (2017), in their work –“Multiband Rectenna for microwave applications”, reported recent results obtained in the Ku and K bands, by using a multiband rectenna. They used cross dipole antenna arrays. Experimental results indicate that a DC power greater than 1 mW can be harvested in the Ku band (12 GHz) for electric field amplitude higher than 38 v/m. This power is sufficient to power a wireless sensor for satellite health monitoring application.





RF-to-DC conversion efficiency of 41 % was obtained. The rectenna exhibited multiband characteristics at frequencies of the cross-dipole antenna array.

A “Broadband Rectenna for Radio Frequency Energy Harvesting Application” was designed by Agrawal, Sachin and Singh (2018). It consists of a microstrip feed, double-sided printed monopole antenna and a wideband rectifier with enhanced bandwidth and gain. The proposed antenna, from measured results, showed an improved bandwidth of 4.3 dBi (from 2.03 dBi at 0.9 GHz). The entire rectenna offered a maximum efficiency of 62.5 % at 1.8 GHz and a load impedance of 5 k $\Omega$ . Issues and challenges with respect to powering wireless sensor networks (WSN) were also discussed. Desirable characteristics of a good RF-EH system include high power conversion efficiency (PCE), reduction in size without degrading efficiency, circular polarization in order to reduce mismatch losses, high gain and wide bandwidth. Selection of antennas for RF energy harvesting depends on desired application such as 5G, wireless sensor networks (WSN), RFID, etc. (Divakaran, Krishna 2019). Most of these antenna designs are targeted towards harvesting energy from high frequency RF sources, however, such sources generally yield low harvestable energies. Medium frequency RF sources would yield more appreciable energy but with the challenge of bigger sized antennas.

## **2.2 Review of Diversity Combiners for RF Energy Harvesting**

From the foregoing, it is obvious that harvested energy is generally low and almost insignificant at far distances from RF sources. In order to explore ways of increasing harvested energy, some researchers have investigated the effect of incorporating diversity combiners in the RF energy harvesting system. Two of such efforts are reviewed here.

Diversity combiners are implemented in wireless receivers in order to mitigate the effects of multipath fading, which gives rise to weak signals at receiver inputs. There are three basic diversity combining techniques, these are: the selection combining (SC), the maximal ration combining (MRC) and the equal gain combining (EGC). In selection combining, the RF signal with the greatest signal-to-noise ratio (SNR) is selected at the receiver input

for the next level of processing, leaving other incoming signals. On the other hand, all the incoming signals are captured in maximal ratio combining (MRC). They are first weighted according to their amplitudes, then co-phased to avoid or reduce destructive interference and finally summed to obtain the optimal SNR. The equal gain combining (EGC) is similar to MRC except that the signals are equally weighted (Sharma and Sachdeva, 2012).

Kumar, Gupta, Singh and Chauhan, (2013), in the work- “Performance Comparison of Various Diversity Techniques Using MATLAB Simulation”- investigated the performance evaluation of the three diversity combining techniques - MRC, EGC and SC. MATLAB simulation was used as a tool, with four receiving antennas. The result showed that MRC gives the best performance in improving signal-to-noise ratio (SNR) followed closely by EGC while SC is the worst in performance (Kurt and Kurt 2017). The difference between MRC and EGC is 0.5 dB while EGC is better than SC by 2.5 dB (Pham. and Pham, 2013).

Kurt and Kurt (2017) worked on “Diversity Combining for RF Energy Harvesting”. In this work, the authors proposed the incorporation of diversity combining in RF energy harvesting systems for the purpose of increasing the amount of harvested energy. Fig. 3 illustrates the proposed model which comprises a RF source, a diversity combining unit, energy conversion and energy storage units.

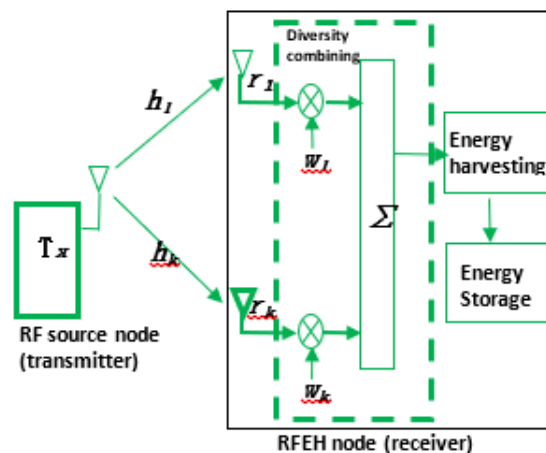


Fig. 3: RF Energy Harvesting System with Diversity combining ( Source: Kurt and Kurt, 2017)

The multipath signals received are combined in the diversity combiner, using maximal ratio combining (MRC).

The harvested energy is stored in a super capacitor or rechargeable battery. Considering one transmitter-harvesting point pair and assuming  $K$  receive antennas, the received signal at the  $k$ th antenna is given by the following expression:

$$r_k = \sqrt{P_T} h_k x + z_k, \quad k = 1, 2, 3, \dots \quad (1)$$

where  $P_T$  is the average transmit power,

$h_k$  is the channel coefficient,

$x$  is the transmitted signal,

$z_k$  is the additive white Gaussian noise (AWGN).

Assuming the transmitted signal is normalized with respect to power, so that  $E[|x|^2]=1$ , the received power from  $k^{\text{th}}$  antenna without diversity combiner ( $P_{r,k}$ ) is:

$$P_{r,k} = P_t |h_k|^2 \quad (2)$$

The harvested power from  $k^{\text{th}}$  antenna ( $P_{h,k}$ ) is given as:

$$P_{h,k} = \eta P_t |h_k|^2 \quad (3)$$

where  $\eta$ ,  $0 < \eta < 1$ , is the conversion efficiency. Similarly, the total harvested power with diversity combiner is modeled as the expression:

$$P_h = \eta P_t \left| \sum_{k=1}^K w_k h_k \right|^2 \quad (4)$$

They investigated the performances of RF energy harvesting systems for three main diversity combining techniques namely MRC, EGC and SC. The power consumption of the diversity combiners was also taken into account. Results obtained showed that the net obtained power depends on the power consumption of the circuit

during the combining process. MRC gave the best performance in the RF energy harvester; followed by EGC and the worst is the one with SC. In terms of circuitry, the simplest is SC while the most complex is the MRC. Thus there is a tradeoff between complexity and performance. There is need, therefore, to carefully select the components in the combining circuit in order to reduce power consumption and size of the combiners and increase the net obtained power.

### **2.3 Review of Impedance Matching circuits for RF Energy Harvesting**

Impedance matching is of necessity in RF-EH systems in order to ensure maximum power transfer between the antenna and the rectifier/multiplier circuit. Frequency and amplitude variations of the RF input at the rectifier/multiplier circuit cause impedance mismatch, leading to losses and efficiency degradation. The major role of the impedance matching network is to force the load impedance, in this case, the rectifier/multiplier impedance, look like a complex conjugate of the source (antenna) impedance, thus resulting in maximum power transfer to the load ( Rengalakshmi .and Brinda, 2016).

An optimized RF energy harvesting system operating in GSM 900 band for the purpose of powering wireless sensor network is presented in “Rectifier for RF Energy Harvesting” (Rengalakshmi P.and Brinda, 2016). The RF energy harvesting is improved by optimizing the impedance matching network and rectifier. Agilent Advanced Design System (ADS) software was used for simulation and analysis. The RF energy harvester is to receive power from a dedicated microwave source to operate a health monitoring system. DC output voltage from the RF energy harvesting is 4.03 V for a load resistance of 5 K $\Omega$ . Power conversion efficiency of the proposed system is 72 %. In order to increase DC output voltage there is need for a broadband antenna. This will also ensure continuous reception of RF signals.

Shahabuddin, Shalu and Akter (2018), in” Optimizing Process Design of RF Energy Harvesting Circuit for Low Power Devices” a design and simulation of five-stage voltage multiplier with  $\pi$  type matching circuit for RF energy harvesting system was presented. RF energy source used in this work was GSM-900 band. Specifically



input power range of -30 dBm at 915 MHz was used. Simulation was carried out with ADS simulator and the output voltage of 9.6 v at 0 dBm and maximum voltage of 33.9 v at -20 dBm were obtained across a load resistance of 180 k $\Omega$ . A comparison of the work with previous ones showed that increase in the number of stages of voltage multiplier increases the output voltage and the  $\pi$  type matching circuit performed better than other matching circuits such as T- and L- types. However, when the number of stages exceed three, the efficiency drops due to parasitic effects. Also circuit complexity increases.

## 2.4 Review of Voltage Rectifier/Multiplier for RF Energy Harvesting

Voltage rectifier circuit is a vital unit in RFEH systems since it is responsible for the conversion of RF signal to DC voltage. Incorporation of voltage multiplying circuit is mainly to increase the harvested power. Selecting the right topology for optimum performance is key to obtaining maximum harvestable power. Available topologies of rectifiers include halfwave, full-wave 2-diode and full-wave 4-diode (bridge). Fundamental multipliers include Cocroft-Walton and Dickson rectifier/multipliers. Advancement in technology has provided alternatives to diode rectifiers and multipliers, thus overcoming the limitations of diodes in terms of output power available. Alternatives to diode rectifier/multipliers are Dickson charge pump (CMOS technology) and Differential drive voltage multiplier (C-MOS technology) ( Tran, Cha, and Park, 2017). Using a diode rectifier/multiplier has the advantage of simplicity and low cost while the C-MOS rectifier/multiplier offers higher output power at a higher cost, more complexity and lower efficiency due to large leakage currents. Research efforts are also being made to obtain suitable rectifier/multiplier systems for harvesting RF energy. A few works in literature are reviewed in the subsection.

Song, Huang, Zhou, Zhang, Yuan and Carter (2015) in their work- “A High-efficiency Broadband Rectenna for Ambient Wireless Energy Harvesting”, studied characteristics of ambient RF energy. The result of the study was then used to design and implement a broadband (1.8-2.5) GHz, dual-polarized, cross-dipole rectenna. It has an embedded harmonic rejection property that enables it reject 2<sup>nd</sup> and 3<sup>rd</sup> harmonics which further improves the

efficiency of the rectenna. The results showed that the sensitivity goes down to -35 dBm while conversion efficiency is up to 55 % when the input power is -10 dBm. The rectenna powers low-power devices and sensors.

The design, simulation, analysis and comparison of multiple stage voltage multiplier for a RF energy harvesting in the ISM band (2.4 GHz) was reported by Hameed and Moez (2017) in the work “Novel Technique for wireless Power Transmission Using ISM Band- RF Energy Harvesting for Charging Applications”. It is proposed for powering mobile devices, Mp3 player, digital camera, laptop etc. Target distance is 3-5 m between the RF sources and receive antenna. Advanced design system (ADS) simulator was used for simulation and analysis. The results were compared with existing systems and showed an improvement in terms of harvested voltage, current and with respect to distance. DC output voltage obtained was 7 v at a distance of 5 meters.

An optimization of rectifier circuit when a time-varying envelope is applied, was presented by Bolos, Blanco, and Collado (2016) in the work “RF Energy Harvesting From Multi-Tone and Digitally Modulated Signals”. It was shown that for a series diode rectifier the optimum load is

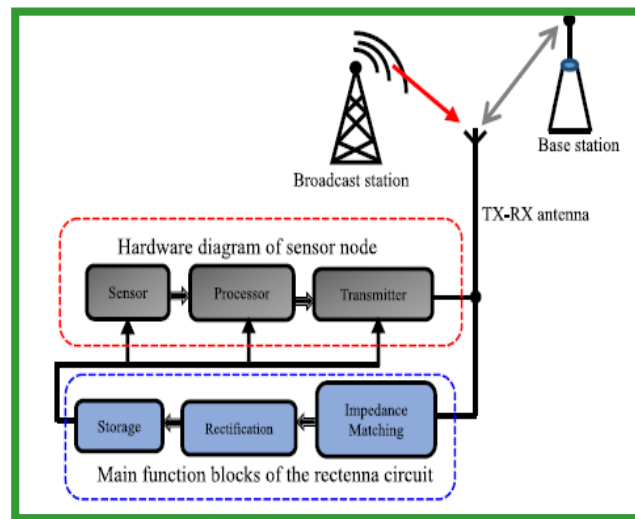


Fig. 4: RF Energy Harvesting system with enslaved sensor node ( Source: Mouapi, Hakem, and Delisle, 2017) .

reduced slightly, but it is increased as the signal peak-to-average- power ratio (PAPR) is increased. A UHF prototype that was designed, fabricated and tested, showed a good agreement with simulation. Mouapi, Hakem, and Delisle (2017) presented- “A new approach to design of RF energy harvesting system to enslave wireless sensor networks”. The authors set up an autonomous wireless sensor network powered by RF energy through a RF energy harvesting system, which they designed with the goal to minimize return loss between 2.3 GHz and 2.6 GHz as well as maximize the DC output voltage of the RF energy harvesting system. The WSN was deployed 800 meters from the base station. Fig. 4 shows an arrangement for sharing one antenna as receive antenna for the RF energy harvester and as a transmit antenna for the wireless sensor node.

In the work, “Design of Impedance Matching Circuits for RF energy harvesting systems”, Hameed and Moez (2017) proposed a systematic design methodology for impedance matching circuits of an RF energy harvester in order to maximize the harvested energy for a range of input power levels. In an experimental example, a RF energy harvester was designed to maximize the harvested energy in the 902-928 MHz band, using an off-chip impedance matching circuit. The measured results showed that maximum conversion efficiency was 32 % at -15 dBm (32  $\mu$ W) and an output DC voltage of 3.2 v into a load of one mega-ohms. Again, Assimonis, and Daskalakis (2016) presented the design and implementation of an efficient and sensitive RF energy harvesting system, consisting of a single-series circuit with a double diode, fabricated on a low-cost lossy FR-4 substrate. Experimental results showed that rectifier microstrips trace dimensions improved efficiency while rectennas connected in series and placed in appropriate topologies, increased the sensitivity of the RF harvester.

In the work, “Enhanced Passive RF-DC Converter Circuit, RF energy harvesting at low input power level from -40 dBm for a resistive load of 50 k $\Omega$  was demonstrated. The Dickson topology was employed for better conversion efficiency than the Dickson and Villard topologies (as shown in Fig. 5). The results showed that increased number of stages increased output power, but increased parasitic effects caused the maximal efficiency to remain almost constant.

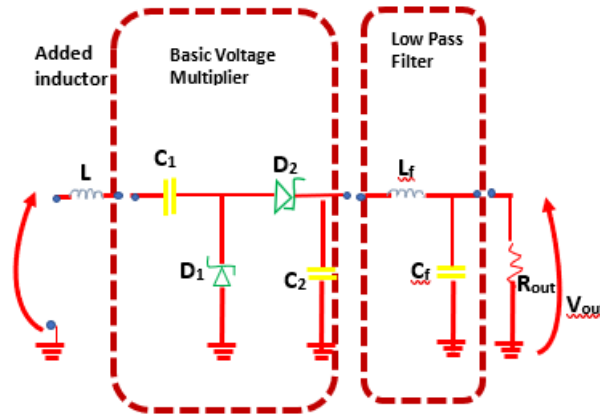


Fig. 5: Proposed single stage voltage multiplier RF-DC converter ( Source: Chaour, Fakhfakh, and Kanoun, 2017).

Leon-Gil, Cortes-Loredo, Fabian-Mijangos, Martinez-Flores, Tovar-Padilla, Cardona-Castro, Morales-Sanchez and Alvarez-Quintana (2018) in “Medium and Short Wave RF Energy Harvester for Powering Wireless Sensor Networks” developed a RF energy harvester based on a four-stage full wave Cockcroft-Walton voltage multiplier (shown in Fig. 6) with conversion efficiency of up to 90 %. RF input source from AM broadcast (Medium and Short Wave) was used. An output power of 62  $\mu\text{W}$  over 1.5  $\text{M}\Omega$  output impedance, and at a distance of 2.5 km, was obtained and thus was able to power a low-power electronic calculator. It was observed that output impedance of the harvester depends strongly on the stage capacitors.

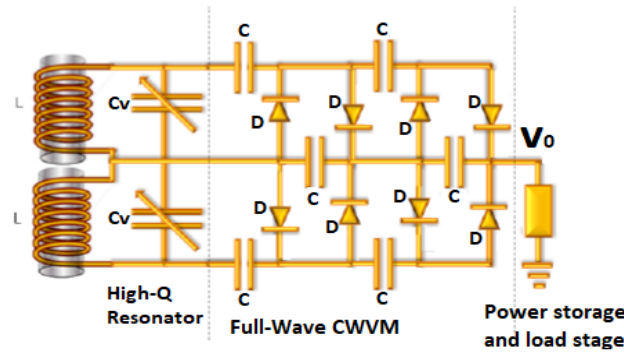


Fig. 6: The AM RF Energy Harvesting system ( Source: Leon-Gil J. A. *et al.*, 2018)

Aminov .and Agrawal, (2014) presented the result of their work, “RF Energy Harvesting”. They carried out experiments on RF energy scavenging which led to the observation that medium wave frequency band, 531-1,611





kHz offered the most efficient source for RF energy harvesting. Using an antenna, LC tuning circuit, 5-stage of Villard voltage multiplier circuit and a super-capacitor as energy storage device, the authors developed a RF energy harvester. The harvester provided an output voltage of 2.8 v, with a field-strength of 103.724 dBu at a distance of 1.609 km from the transmitter. The challenge of using this frequency band is the large size of the antenna which limits the portability of the harvester.

Kim, Vyas, Bito, Niotaki, Collado, Georgiadis and Tentzeris (2014) in their work- “Ambient RF Energy-Harvesting Technologies for Self-Sustainable Standalone Wireless Sensor Platforms”- reviewed in detail various ambient technologies and the possibility of applying them in the development of self-sustaining wireless platforms. The prototype of a RF energy harvester that uses a digital TV signal at UHF band (512-566 MHz) as RF source, 6.3 km away from the proposed RF energy harvester, a high-efficiency dual-band ambient energy harvester at 915 MHz and 2.45 GHz as well as an energy harvester for on-body application at 460 MHz were also presented to confirm the capabilities of ambient UHF/RF energy harvesting as a suitable technology for Internet of Things and Smart skin applications.

Valenta and Durgin (2014), in “Harvesting Wireless Power”- identified and discussed research progress made so far in two outstanding wireless energy harvesting technologies. They include space-based solar power (SSP) or solar power satellite (SPS) and RF identification (RFID). Merits and demerits of these technologies were also identified and discussed. Suggestions on the way forward to increase conversion efficiency and harvested energy were made. In SPS systems Schottky diodes are employed due to their low voltage threshold and lower junction capacitance than PN diodes. However, low voltage threshold allows high efficiency only at low powers. In order to produce sufficient power for SPS systems, large arrays of RF rectifiers must be used. This limitation is as a result of the fact that CMOS processes do not support fabrication of Schottky diodes. On the other hand CMOS technology is used in RFID applications. With diode-connected transistors, high efficiency at lower powers is achieved due to lower parasitic values. RFID requires low power levels and it is possible to have the entire system on a single integrated circuit (IC). Therefore, CMOS is the preferred technology in RFID systems.



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In order to reduce size of antenna and weight of the entire energy harvester in both SPS and RFID systems, research into the use of higher frequencies such as 5.8 GHz as against the traditional use of UHF frequencies, has been intensified recently. This will also reduce the amount of land required for ground-based power collecting stations for SPS and minimize the profiles of tags and sensors for RFID systems “Wireless Networks with RF Energy Harvesting: A contemporary Survey” is a survey paper presented by Lu, Wang, Niyato, Kim and Han (2014). This is an extensive review on the research advances in wireless communication networks with RF energy harvesting (RF -EH) which focused on system architectures, techniques and existing applications. The paper also gave a background in circuit design, state of the art circuit implementations and a review of communication protocols particularly designed for RF-EH. Various design issues as they relate to resource allocation in different network types and up-to-date solutions are discussed as well as practical challenges in RF energy harvesting techniques. In the same trend, Naderi, Chowdhury and Basagni (2015) in “Wireless Sensor Networks with RF Energy Harvesting: Energy Models and Analysis”- discussed formulation of expressions for power harvesting rates in planes of 2D dimension and 3D dimension and - placement of multiple RF Energy Transmitters (ETs). These are used in recharging the nodes of wireless sensor networks (WSNs). The authors studied distribution of total available and harvested power within the entire WSN. They provided closed matrix forms for obtaining harvestable power at any given point in space. Energy transfer in the WSN was analyzed based on power outage probability and harvested voltage, considering the effects of constructive and destructive interference of the transmitted energy. The results indicate that receive power within the entire network and interference power from concurrent energy transfers are characterized with Log-Normal distributions while the harvested voltage has a Rayleigh distribution.

Kuhn, Lahuec, Seguin and Person (2015) designed a 4-band rectenna to operate over the range of frequencies: GSM900, GSM1800, Universal Mobile Telecommunications System and WiFi bands. Maximum RF-to-DC conversion efficiency of 84 % with an input power of 5.8 dBm was achieved. The conversion efficiency exceeded double the amount measured with only one RF source. [25], in their work “RF power harvesting: a review on



designing methodologies and applications”, presented a summary of RF power harvesting technologies, analysis and trade-offs, including recent applications of RF power harvesting. The review serves as a general guide for designing RF energy harvesting circuits.

Muncuk, Alemdar, Sarode, and Chowdhury (2018) worked on- “Multi-band Ambient RF Energy Harvesting Circuit Design for Enabling Battery-less Sensors and IoTs”. In this work, the authors first studied the characteristics of ambient RF signals in particular locations. Then they designed and fabricated a RF energy harvester that receives ambient RF energy from LTE 700 MHz, GSM 850 MHz and ISM 900 MHz bands. That is a multi-band RF source (GSM700, 850, 900 MHz) with a single receive antenna. The output power obtained could power sensors with current consumption of 45  $\mu$ A.

Khan, Oh, Shezad, Basim, Verma, Pu, Lee, Hwang, Yang, and Lee (2019) presented a configurable RF-DC converter operating at 902 MHz, with dual paths for harvesting both low and high power RF signals. The work included among other units an adaptive control circuit in order to maximize the harvested power. The system was designed to accept a wide range of input power between -18 dBm and -5 dBm. It provided a power conversion efficiency (PCE) of above 20 % and a maximum PCE of 33 % at -requires low power levels and it is possible to have the entire system on a single integrated circuit (IC). Therefore, CMOS is the preferred technology in RFID systems.

In the work reported by Muhammad, Trang, Wong, Iqbal, Alibakhshikenari and Limiti (2020), the authors focused on reduced size of the RF-DC converter circuit. It operated at 900 MHz. The obtained include a power conversion efficiency of 44.3 % at 0 dBm, 3.1 V DC across 2 kilohm load for 14 dBm input power and a sensitivity of -20 dBm. Compared to other related works, the size of the rectifier in this work is quite reduced with good power conversion efficiency, although the frequency of operation is lower than that of other related works.



### **3. Summary of the Review and Direction for future work**

Most of the previous works reviewed could only develop RF energy harvesters placed few meters away from the transmitters, which is not good enough for practical purposes. An isolated case of a distance of 6.3 km was recorded, however, the maximum output power achieved was 62  $\mu$ W. None of these researchers considered combining RF sources from TV, Radio broadcasting and GSM for the same RF energy harvester, which is anticipated to yield higher output power. It is believed that the consideration of antenna size could be one of the limiting factors faced by these researchers in considering lower frequency RF sources, which could yield higher outputs. Also, it is observed that most of the previous RF energy harvesters are limited to powering wireless sensors which are low-power devices, and these sensors are not mobile, which means that the sensor nodes must be stationed in the vicinity of a given RF source. RF to DC conversion efficiency has been observed to be generally low. However, with higher harvestable power, it is anticipated that harvested power will improve appreciably. All of these means that further research is needed to increase harvested RF energy at practical distances, and to use harvested energy to power devices other than sensor nodes.

The amount of harvested power depends primarily on the received power by the antenna at the front end of the harvester, which in turn depends on the transmitted power from the RF sources and the losses in between. Low frequency RF sources such as medium wave (MW) (540-1,600 kHz), short wave (SW) (2-22 MHz), frequency modulation (FM) (88-108 MHz) and television (VHF and UHF) (175-860 MHz) transmit higher powers at longer distances than high frequency sources such as GSM (900-2100 MHz) and ISM (2.4 - 5 GHz). The low frequency RF sources are suggested for harvesting sufficient power. However, to receive sufficient RF power from the high power sources requires bulky antennas, due to their long wavelengths. This is a major challenge that has limited harvestable power to a very low level, resulting into powering only wireless sensor nodes and wearable electronic devices. Further research is needed in the design of portable antennas for medium frequency signals such as HF and UHF bands.



Also, very few works have been done in the area of incorporating diversity combiners into RF energy harvesters, which could mitigate the effect of multipath losses. This is important because it will certainly increase the amount of harvestable power. Again, most of the reviewed works dwelt on wireless sensor nodes which are usually stationary once they are deployed. This is, probably, another reason that RF energy harvesting has not been considered for mobile devices. For these devices such as mobile phones, mobility, with its associated parameters such as arrival angles, Doppler shifts, and multipath fading must be factored into the models. Therefore, to receive appreciable power at the energy harvester input, research into efficient diversity combining systems deserves a serious attention.

It is important, therefore, for future research work to focus on designing high gain, portable antennas such as patch antennas that are circularly polarized and are broadband for capturing energy from broad range of high power RF sources such as medium and short-wave radio transmitters, frequency modulated radio transmitters and TV transmitters, in order to harvest sufficient power to operate mobile devices. An energy harvester for a mobile device requires a multi RF sources such that as the mobile leaves the vicinity of one source it enters the vicinity of another. In this way, it will remain always powered, offering a lot of convenience to the user. Fig. 7 shows a proposed high-level structure for such multisource arrangement. This is achievable with arrays of small antennas and diversity combiners. Using RF energy harvesting to power mobile devices will go a long way in alleviating the global energy crisis especially for the future generations of wireless networks, while safeguarding the environment from GHG emissions.

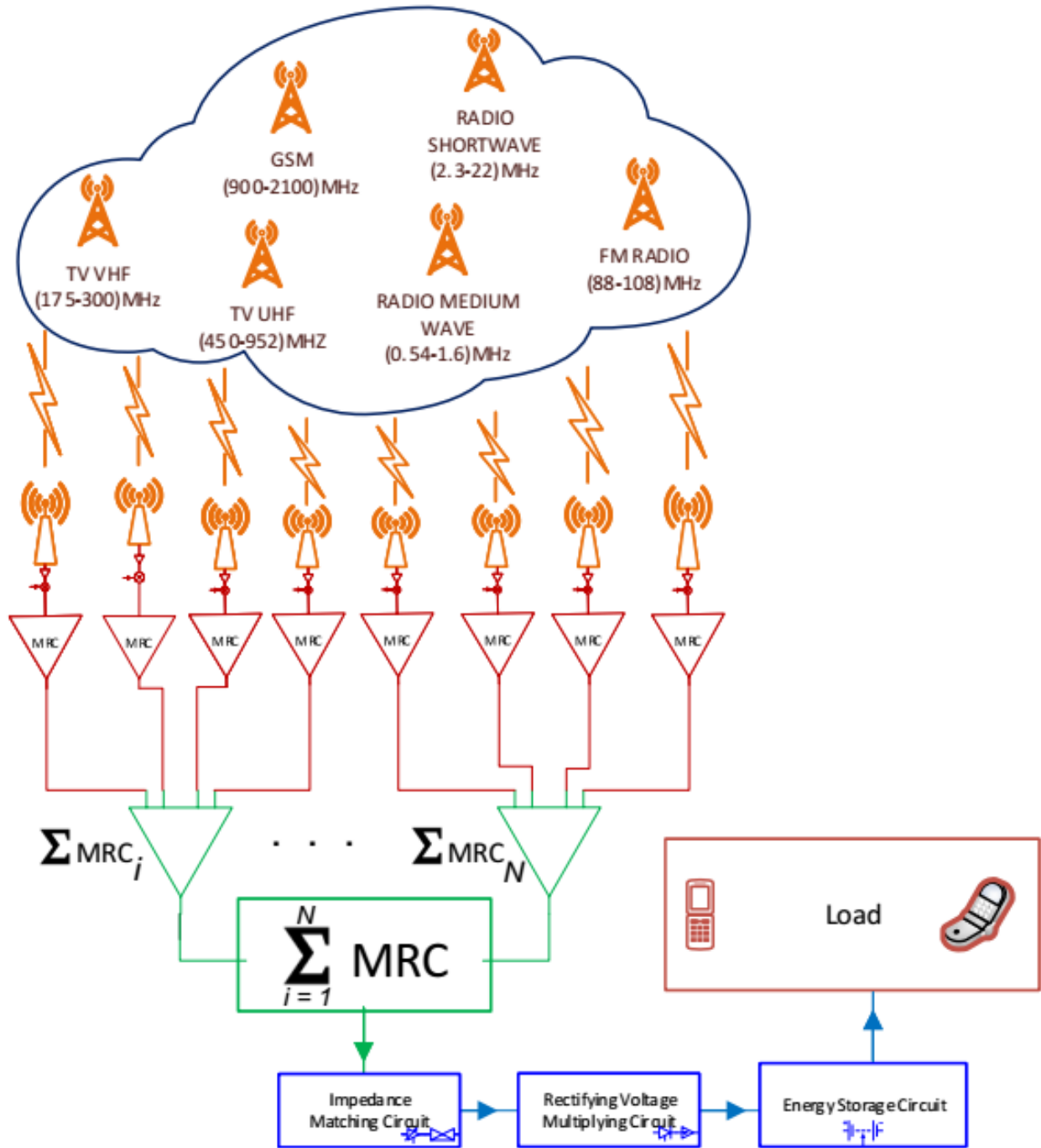


Fig. 7: A proposed multi RF system energy harvester for mobile devices



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