A Survey of Radio Frequency Energy Harvesting Techniques Toward Effective Powering of Mobile Devices Using Cockcroft Walton Voltage Multiplier

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ABSTRACT

The fundamental goal of energy harvesting systems is to reduce the need for a wired power supply or battery replacements. 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 smart devices. 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 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, Cockroft-walton voltage multiplier, 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 for 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 require enormous amount of operating power (Wang, Haider, Gao, You, Yang, Yuan, Aggoune, Haas, Fletcher & Hepsaydir, 2014). Energy efficiency demand is increasing globally as a result of high energy costs and environmental issues (Lakshmanan, Mohammed, Palanivelan, & Kumar, 2016). 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, & Taniguchi, 2015). With the increase in the demand and use of smart phones, giving rise to increased data services, there is increased 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. Therefore, there has been a 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 *et al.*, 2016). The major advantages of 5G over 4G according to Qasrawi and Al-qasrawi(2016), include better 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 licensed and unlicensed spectrum, lower outage probability and lower infrastructure costs. Low latency and highly reliable communication is accommodated by 4G in terms of throughput and user density but challenges such as delay reduction and reliability improvement cannot be realized in 4G. Figure 1 shows some of the differences between 4G and 5G:

2 REVIEW OF RF ENERGY HARVESTING TECHNIQUES

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

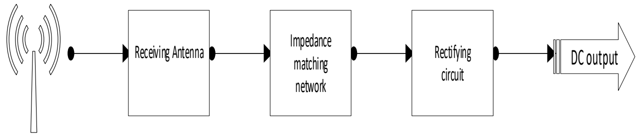

Figure 2: General structure of RF Energy Harvester. Source: (Bakkali, Pelegrí-Sebastiá, Sogorb, Llario, & Bou-Escriva, 2016)

The general structure of a typical RF energy harvester consists of a 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 Review of Antennas for RF Energy Harvesting

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 has 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 *et al*., (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° control the main-lobe direction by 15° 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 20.6MHz. Generally, performance of RF-EH is better with array 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 incorperated 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 kΩ for a power density of 10μW/cm^2 at 1.8GHz. 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. Again, Song et al., (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 wasthen 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 2nd and 3rd harmonics which further improves the efficiency of the rectenna. The results showed that the sensitivity goes down to -35dBm while conversion efficiency is up to 55 % when the input power is -10 dBm. The rectenna powers low-power devices and sensors.

In the work- "A Novel Wideband Circularly Polarized Antenna for RF Energy Harvesting in Wireless Sensor Nodes", the authors, Nguyen et al.,(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 6GHz. 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, 2.5 v DC output voltage. A potential application of this antenna is in harvesting RF energy from Wi-Fi network for powering wireless sensor nodes. Okba, Charlot, Calmon, Takacs and Aubert (2016), 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 1mW can be harvested in the Ku band (12 GHz) for electric field amplitude higher than 38v/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.

Asmeida, Mustam, Abidin and Ashyap (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 2.13v, maximum conversion efficiency of 86% for an input power of – 5dBm. The output voltage was only sufficient to power up a wireless sensor node (WSN).Adam, Yasin, Soh, Kamardin, Jamlos, Lago and Razalli, (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 8.7dBi at 2.05 GHz. The proposed antenna is simple and low cost with a size of 0.462 λ x 0.462 λ x 0.01 λ. A "Broadband Rectenna for Radio Frequency Energy Harvesting Application" was designed by Agrawal , Parihar, and Kondekar (2018). It consists of a micro strip 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 4.3dBi (from 2.03dBi at 0.9 GHz). The entire rectenna offered a maximum efficiency of 62.5 % at 1.8 GHz at a load impedance of 5kΩ. Issues and challenges with respect to powering wireless sensor networks (WSN) were also discussed.

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 investigate the effect of incorporating diversity combiners in the RF harvesting system. Two of such efforts are reviewed here.

Altinel 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. Figure 3 illustrates the proposed model which comprises a RF source, a diversity combining unit, energy conversion and energy storage units.

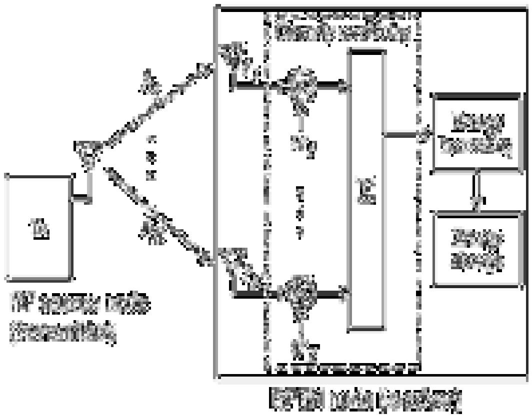

Figure 3: RF Energy Harvesting System with Diversity combining (Altinel and Kurt, 2017)

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 Kth antenna is given by:

$$rk = \sqrt{P_T} h_k x, + z_k \quad , \quad k = 1, 2, 3, \ldots. K (1)$$

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)

(Altinel and Kurt, 2017)

They investigated the performances of RF energy harvesting systems for three main diversity combining techniques namely maximal ratio combining (MRC), equal gain combining (EGC) and selection combining (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-EH; followed by EGC and the worst is the one with SC. There is need therefore, to carefully select the components in the combining circuit in order to reduce power consumption in the combiners and increase the net obtained power.

Kumar, Gupta, Singh, and Chauhan, (2013), in the work- "Performance Comparison of Various Diversity Techniques Using MATLAB Simulation"- the authors investigated the performance evaluation of three diversity combining techniques- Maximum Ratio Combining (MRC), Equal Gain Combining (EGC) and Selection Combining (SC). MATLAB simulation was used as a tool, with four (4) receiving antennas. The result showed that MRC gives the best performance in improving signal-to-noise ratio (SNR) followed closely by EGC (difference between MRC and EGC is 0.5 dB) and SC is the worst in performance (2.5 dB difference between MRC and SC).

2.3 Review of Impedance Matching circuits for RF Energy Harvesting

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 & Brinda, 2016). The RF energy harvesting is improved by optimizing the impedance matching network and rectifier. Agilent Advanced Design System (ADS) software is 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 KΩ. 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)." Optimizing Process Design of RF Energy Harvesting Circuit for Low Power Devices". In this paper, a design and simulation of five-stage voltage multiplier with π 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 -30dBm at 915MHz was used. Simulation was carried out with ADS simulator and the output voltage of 9.6v at 0dBm and maximum voltage of 33.9v at -20dBm were obtained across a load resistance 180kΩ. 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 π type matching circuit performed better than other matching circuits.

2.4 Review of Voltage Rectifier/Multiplier for RF Energy Harvesting

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 Panda and Deshmukh (2016) 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 7v at a distance of 5 meters.

Leon-Gil *et al.*, (2018). "Medium and Short Wave RF Energy Harvester for Powering Wireless Sensor Networks". The authors developed a RF energy harvester based on a four-stage full wave Cockcroft-Walton voltage multiplier (shown in Figure 4)with conversion efficiency of up to 90 %. RF input source from AM broadcast (Medium and Short Wave) was used. An output power of 62 µW over 1.5 MΩ output impedance, and at a distance of 2.5 km, was obtained and thus was able to power low-power electronic calculator. It was observed that output impedance of the harvester depends strongly on the stage capacitors.

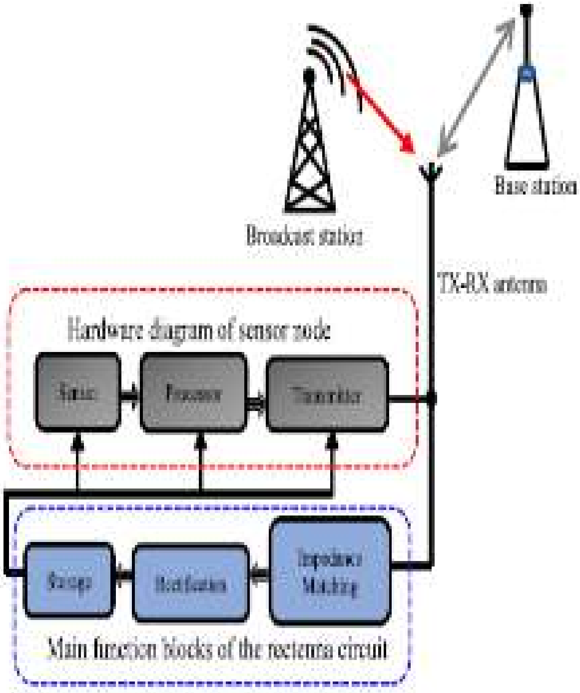

Figure 5: RF Energy Harvesting system with enslaved sensor node (Mouapi, Hakem, and Delisle, 2017)

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 µW) and an output DC voltage of 3.2 v into a load of 1 MΩ.Assimonis, Daskalakis and Bletsas (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.

An optimization of rectifier circuits when a time-varying envelope is applied, was presented by Bolos, Blanco, Collado and Georgiandis (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 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.
In the work, "Enhanced Passive RF-DC Converter Circuit, RF energy harvesting at low input power level from -40dBm for a resistive load of 50kΩ was demonstrated. The Dickson topology was employed for better conversion efficiency than the Dickson and Villard topologies (as shown in Figure 6).

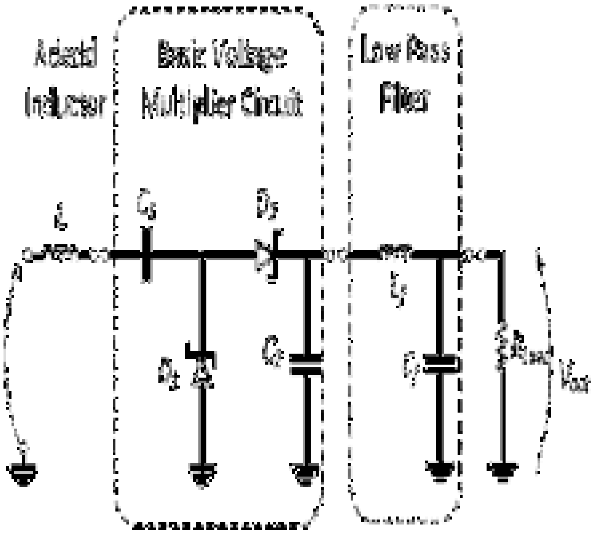

Figure 6: Proposed single stage voltage multiplier RF-DC converter (Chaour, Fakhfakh and Kanoun, 2017)

The results showed that increased number of stages increased output power, but increased parasitic effects caused the maximal efficiency to remain almost constant.

Song et al., (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 2nd and 3rd 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.

Muncuk et al., (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 singlereceive antenna. The output power obtained could power sensors with current consumption of 45 µA.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.

Kim *et al.*, (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 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.

”Wireless Networks with RF Energy Harvesting: A contemporary Survey” is a survey paper presented by Lu, Wang, Niyato, Kim, and Han, (2015). This is an extensive review on the research advances in wireless communication networks with RF energy harvesting (RF -HNs) which focused on system architecture, 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-EHNs. 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 plane 2D dimension and 3D dimension and -placement of multiple RF Energy Transmitters (ETs). These are used in recharging the nodes of wireless sensor network (WSN). 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.

1 SUMMARY OF THE LITERATURE 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. An isolated case of a distance of 6.3km was recorded; however, the maximum output power achieved was 62 µW. 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, but with higher harvestable power, it is anticipated that harvested power will improve appreciably.

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 than high frequency sources such as GSM (900-2100 MHz) and ISM (2.4 - 5 GHz). 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.

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 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 and Doppler shift, must be factored into the models.

It is important, therefore, to focus on designing high gain, portable antennas for capturing energy from low frequency, high power RF sources, in order to harvest sufficient power to operate mobile devices such as mobile phones. Design of miniaturized, self-sustainable diversity combiners is also key to harvesting sufficient power for mobile phones and similar devices. Using RF energy harvesting to power mobile devices will go a long way to alleviating the global energy crisis especially for the future generations of wireless networks, while safeguarding the environment from GHG.

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