A Multi-source Broadband Radio Frequency Energy Harvester with Cascaded Diversity Combiner for 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, low RF power harvestable from various sources and low radio frequency-to-direct current (RF-DC) conversion efficiency has made it a very difficult task to harvest sufficient power to operate mobile devices such as smartphones. Considering the anticipated deluge of mobile devices and high data rates in the forth-coming fifth generation (5G) mobile networks, which will place a strict demand on the already dwindling global energy needs, this paper presents a RF energy harvester model aimed at harvesting sufficient power for the operation of smartphones and other mobile devices.

Keywords: *Radio frequency, 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 in mobile communications, which the fourth generation (4G) wireless communication networks have failed to address. Moreover, it is expected that the fifth generation(5G) with its huge promising facilities, which include 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). It is therefore not surprising that energy efficiency demand is increasing globally due to high energy costs and environmental issues (Lakshmanan, Mohammed, Palanivelan, & Kumar, 2016).

Globally, a rapid increase of mobile traffic, estimated at over 60 % per year, is anticipated due to the increase in the number of smartphones and tablet terminals (Kimura, Seki, Kubo, & Taniguchi, 2015). As the increase in the demand and usage of smartphones will directly translate to increased data services, there will certainly be 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).

Reducing energy consumption is a major challenge in recent wireless systems that adopt 4G/5G technologies. 5G is expected to address all of these challenges (Kimura *et al.*, 2015). 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, which are used to reduce energy costs and harmful effects on the environment caused by carbon dioxide (CO_2) emission (Liu, Zhang, Yu, & Xie, 2015). According to Lakshmanan et al (2016) 9 % of total carbon emission is attributed to mobile communications. Specifically, radio access part consumes 70 % of its total power. European member states recently signed agreement to reduce greenhouse gas emission by 20 % by 2020. Also, Vodafone group agreed to reduce CO_2 emission by 50 %. (Wu, Li, Chen, Ng, & Schober, 2017).

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 portion 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. All of these cannot be achieved without a sustainable source of energy. 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:

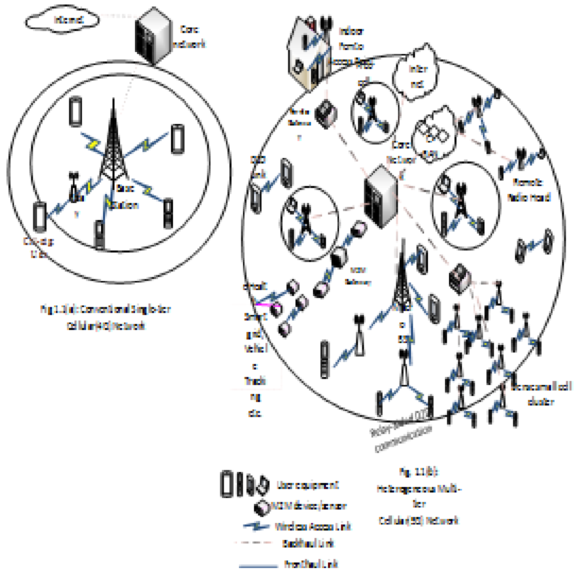

Figure 1: Differences between 4G and 5G Networks. (Qasrawi & Al-qasrawi, 2016)

It is projected that by 2021 over 28 billion devices will be connected to 5G wireless networks and over 15 billion of these will be machine-to-machine (M2M) connections. This is to make provision for Internet of Things (IoT) communications, which is one of the most important missions of 5G (Ercan, Sunay, & Akyildiz, 2018). For more than a century research and design of wireless networks has been concentrated on optimization metrics such as data rate, throughput, latency et cetera. However, in the last decade, energy efficiency has become a new area of concern due to economic, operational and environmental factors (Buzzi, I, Klein, Poor, Yang, & Zappone, 2016).

The energy challenge in Nigeria and other developing countries is peculiar as there is, generally, insufficient energy and what is available is mainly fossil fuel, and these developing countries are notably dependent on wireless networks for communications. In order to ameliorate this pitiable situation and to prepare for the global expectation of massive connection of smartphones and other mobile devices in the next generation of wireless networks (5G), there is urgent need to develop a green system that will ensure that mobile devices are always powered and therefore improve energy efficiency and reduce greenhouse gas (GHG) emission.

2 THE LOOMING GLOBAL ENERGY CRISIS

Energy supply grossly inadequate to meet energy demand is termed energy crisis according to Machado (2018) (History com, 2018, Kinney 2015).

Since the middle of 1960s, nations of the world have suffered the effects of energy crises, the toughest being the one between 1973 and 1974 during the oil embargo by members of organization of Arab Petroleum Exporting countries (OAPEC). It greatly affected countries such as United States, Great Britain, Germany, Switzerland, Norway and Denmark (History .com, 2018). It has been predicted that the next energy crisis will be between 2018 and 2030. This will be as a result of dwindling capital spending in the global oil business from 2014 till date (Martenson, 2017, Constable, 2019 and Tambari, 2019). Other reports warning of looming global energy crisis include Weyer (2019), Mrza (2018).

Energy crisis is of two kinds: Naturally occurring scarcity of fuel in the form of dwindling supply from coal mines, oil wells and man-made crisis due to embargo, insensitivity and lack of political will of the ruling class to take necessary actions to boost energy supply (Kinney, 2015). Energy crisis will continue to loom over humanity until strategic steps are taken to solve it. There is ever-increasing demand for energy, which is being satisfied mainly with conventional energy from coal, oil and gas, despite calls and agreements at various international conferences such as Villach conference, 1985; Vienna convention, 1987; Toronto conference, 1988; conference in Rio de Janeiro, 1992; Kyoto conference, 1997 (History. aip.org, 2019) to reduce the use of these conventional sources that deplete the protective Ozone layer and has caused continuous climate change (including global warming).

Global warming due to emissions of greenhouse gasses (GHG) from fossil fuel was first reported in 1896 by Arrhenius (History .aip.org, 2019). Since the first report of global warming, the major international body on climate change, the intergovernmental Panel on Climate Change (IPCC) has been issuing warnings on the consequences of not reducing greenhouse gas (GHG) emissions. Notably in 2007, IPCC issued a warning that serious effects of warming had become evident and that cost of reducing GHG emissions would be far less than the damage they will cause (History. aip.org, 2019). The solutions to global energy crises, global warming and its devastating effects have been identified by scientists and engineers as follows:

i. Energy efficiency,
ii. Electrifying transportation,
iii. Pulling carbon dioxide (CO2) out of the atmosphere by reforesting and using carbon capture technology, and
iv. rapid deployment of renewable energy.(Worland, 2018)

Energy efficiency is defined as the harnessing of technology to avoid or reduce energy waste, and thereby make efficient use of available energy (Shinn, 2018). The solution proposed in this paper, which is a multi-source broadband, radio frequency (RF) energy harvester to capture some of the RF energy radiated from broadcast radio, television (TV) and global system for mobile communication (GSM) transmitting stations, is in line with the above four identified solution lines. It is efficient because it is converting the waste from radiated RF power to useful energy, it is renewable and therefore sustainable, it clean because it reduces the unwanted radiations in the environment. The captured energy will be used to charge batteries in mobile phones and similar devices.

3 RELATED WORKS

Some interesting works have been done in the area of RF energy harvesting. A few of the related works are examined in this section. Key challenges facing the technology of RF energy harvesting include: low amount of harvested energy; short transmitter- harvester (T – H) distances, which are usually too short for practical purposes; inefficient RF- to- DC energy converter; use of dedicated RF sources et cetera..

In an effort to increase the amount of harvested RF energy, Altinel and Kurt (2017) proposed the idea of using diversity combiner for RF energy harvesting. This idea is captured in their model shown in Figure 2.

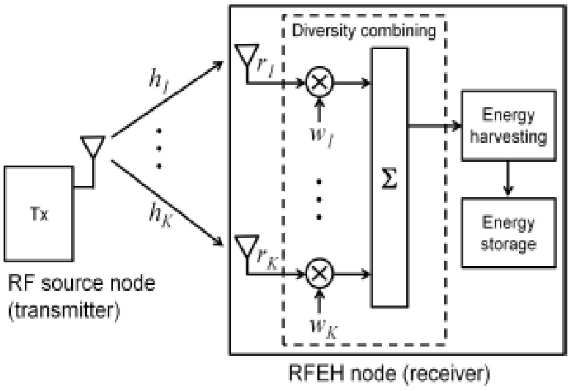

Figure 2: RF Energy Harvesting System with Diversity combining (Altinel and Kurt, 2017)

The 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-harvester pair and assuming K receive antennas, the received signal at the kth antenna is given by:

$$r_k = \sqrt{P_T}\ h_k x, + z_k \ , \ k = 1, 2, 3, \dots . K \tag{1}$$

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)

This work focuses on RF energy harvesting, so the noise component of equation (1) also contributes to power to be harvested. Therefore, the received power from kth antenna, $P_{R,k}$ is

$$P_{R,k} = P_T|h_k|^2\ |x|^2 + |z_k|^2 \tag{2}$$

The received power having gone through conversion (RF – to DC), the harvested power from kth antenna of the Transmitter- Harvesting node pair, say TV VHF, is

$$P_H\ Tv\ VHF = \eta \left[P_{T|h_k|^2|x|^2 + |z_k|^2}\right] \tag{3}$$

where η; which is 0 < η < 1, is the conversion efficiency (ie RF power to DC power). This depends on the performance of the RF energy harvesting system harvested energy from kth antenna in VHF.Channel is

$$E_{H,K= \eta T[P_T|h_k|^2\ |x|^2 + |z_k|^2]} \tag{4}$$

where T is the period of harvesting.

Considering contribution of diversity combining, the received signal is

$$y_k = \sqrt{P_t}\, w_k\, h_k x + w_k z_k \qquad \text{k = 1, 2, 3.... K} \tag{5}$$

where w_k is aggregate value of combiner weight coefficient with respect to kth antenna (Altinel and Kurt, 2017).

Therefore, total harvested power with diversity combiner in place is

$$P_{h=}\,\eta\, P_T \left|\sum_{k=1}^{K} w_k h_{kX}\right|^2 + \eta \left|\sum_{k=1}^{K} w_k z_k\right|^2 \tag{6}$$

and the maximum harvestable power ($P_{h,\ max}$) is

$$P_{h,\max} = \sum_{k=1}^{k} \{\eta\, P_T\ \left|w_k\right|^2\ \left|h_k\right|^2 + \eta \left|w_k\right|^2\ \left|z_k\ \right|^2\} \tag{7}$$

Their major concern in this work is to investigate the performance of three different diversity combiner techniques on RF energy harvesting with respect to amount of energy harvested. The three combiner techniques are maximal ratio combining (MRC), equal gain combining (EGC) and selection combining (SC). The power consumption of the diversity combiners was also taken into account. Their results showed that the net harvested 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 result came from the harvester with SC. There is need therefore, not only to employ the adequate diversity combiner technique but also to carefully select the components in the combiner circuitry in order to reduce power consumption in the combiners and increase the net harvestable power.

Considering both destructive and constructive interferences at any given location by factoring path lengths and path differences between target sources, the total received power from any number of RF sources is given by

$$P_T^r = G_r \left(\frac{\lambda}{4\pi}\right)^2 \left[\sum_{i=1}^{k} \frac{P_i G_i}{R_i^2} + \sum_{\substack{i=1 \\ i\neq j}}^{k} \sum_{j=1}^{k} \frac{\sqrt{G_i G_j P_i P_j}}{R_i R_j} \cos\left(k(\Delta r_{ij})\right)\right] \tag{8}$$

where P_i and G_i are transmission power and the gain of the transmitting antenna of RF sources and $\Delta r = \left|R_i - R_j\right|$, differences of distances between the RF sources and the harvesting node and G_r is the gain of the receiving antenna (Naderi, Chowdhury and Basagni, 2015)

Radio frequency (RF) wireless charging model is given by

$$P_H = \eta\, P_T^r \tag{9}$$

where P_H is the harvested power, P_T^r is the received power at the harvesting node, and η is the RF - to - DC conversion efficiency.

Therefore, harvested power from K RF sources is

$$P_H = \eta \left[G_r \left(\frac{\lambda}{4\pi}\right)^2 \left[\sum_{i=1}^{K} \frac{P_i G_i}{R_i^2} + \sum_{\substack{i=1 \\ j\neq 1}}^{k} \sum_{j=1}^{k} \frac{\sqrt{G_i G_j P_i P_j}}{R_i R_j}\ cos\ \left(k(\Delta r_{ij})\right)\right]\right] \tag{10}$$

where k = 6

Considering the contribution of the cascaded diversity combiner, the harvested power from k RF sources

$$P_H\ diversity = \eta\ [|\mathrm{w}|^2] \left[\mathrm{G_r} \left(\frac{\lambda}{4\pi}\right)^2 \left[\sum_{\mathrm{i=1}}^{\mathrm{k}} \frac{\mathrm{P_i G_i}}{\mathrm{R_i^2}} + \sum_{\substack{\mathrm{i=1} \\ \mathrm{j\neq 1}}}^{\mathrm{k}} \sum_{\mathrm{j=1}}^{\mathrm{k}} \frac{\sqrt{\mathrm{G_i G_j P_i P_j}}}{\mathrm{R_i R_j}} \cos\ (\mathrm{k}(\Delta \mathrm{r_{i,}j}))\right]\right] \tag{11}$$

Kim, Vyas, Bito, Niotaki, Collado, Georgiadis, and Tentzeris (2014) reviewed in detail various ambient technologies and the possibility of applying them in the development of self-sustaining wireless platforms. A prototype RF energy harvester that harvests from a digital TV transmission at UHF band (512-566 MHz) 6.3 km away from the proposed harvester was presented. Also 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 presented to confirm the capabilities of ambient UHF/RF energy harvesting as a suitable technology for Internet of Things and Smart skin applications. The harvested energy here, though at a reasonable distance, can only operate very low power devices. To power devices such as smartphones and tablets, there is need to make the harvester broadband to enable it harvest sufficient power from varied RF sources such as AM, FM, and TV transmitters.

Naderi, Chowdhury, and Basagni (2015) discussed formulation of expressions for power harvesting rates in plane 2D and 3D dimensions and the placement of multiple RF Energy Transmitters (ETs). These harvesters were used in recharging the nodes of wireless sensor network (WSN). The authors studied distribution of total available and harvested power within the entire WSN system. They provided a closed matrix forms for estimating harvestable power at any given point in space. Energy transfer in the WSN is analyzed using power outage probability and harvested voltage considering the effects of constructive and destructive interference of the transmitted energy. The results indicate that received 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.

An optimized RF energy harvesting system operating in GSM 900 band for the purpose of powering wireless sensor network is presented by Rengalakshmi and Brinda (2016). The RF energy harvester was improved by optimizing the impedance matching network and rectifier. Agilent Advanced Design System (ADS) software was used for simulation and analysis. The harvester is to receive power from a dedicated microwave source to operate a health monitoring system. DC output voltage from the RF energy harvester 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 and current there is need for a broadband antenna and randomly placed multiple RF sources. This will ensure continuous reception of RF power.

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 players, digital cameras, laptops et cetera. 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 is 7 v at a distance of 5 meters. This is too short a distance to be practical.

A design and simulation of five-stage voltage multiplier with π type matching circuit for RF energy harvesting system was presented by Shahabuddin, Shalu, and Akter (2018). 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 and maximum voltage of 33.9 v at -20 dBm were obtained across a load resistance of 180 kΩ. 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. Leon-Gil, Cortes-Loredo, Fabian-Mijangos, Martinez-Flores, Tovar-Padilla, Cardona-Castro, and Alvarez-Quintana (2018) developed a RF energy harvester based on a four-stage full wave Cockcroft-Walton voltage multiplier 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 was obtained at a distance of 2.5 km from the harvester and thus was able to power low-power electronic calculator. This is impressive, but the harvested power could be enhanced by harvesting from both AM and FM transmitters. This will enable the powering of higher power devices such as mobile phones.

4 THE PROPOSED MODEL

Most of the previous works reviewed could only develop RF energy harvesters placed few meters away from the transmitters. The farthest is 6.3 km, but the harvested power could only operate a wireless sensor node. None of the previous researchers considered combining RF sources from TV, Radio broadcasting and GSM for the same RF energy harvester. Most of the previous RF energy harvesters are limited to powering wireless sensors which are low-power devices in comparison to smartphones. Such amount of harvested power cannot power mobile hand-held devices such as mobile phones, tablets and the like. To support mobile wireless communications in the 5G era, which promises billions of mobile hand-held and wearable devices without, at the same time, endangering the environment via GHG effect from fossil fuels, it is imperative to power mobile devices of the future with green energy sources such as RF. Therefore, a multi-source, broadband RF energy harvester with a cascaded diversity combiner is proposed with the anticipation that enough power will be harvested to ensure always powered mobile devices both in the urban and rural areas. It is believed that for a desired level of RF power to be harvested such as could keep a mobile device always powered, anywhere and anytime, a few factors have to be considered: (i) the effective isotropic radiated power (EIRP) of transmitters should be reasonably high to enable RF energy harvester receive sufficient power at practical distances, (ii) to make the harvester applicable for mobile devices, multiple RF sources that are easily available in the mobile environment should be considered, as this will enable a mobile device to always have RF sources to harvest from wherever it may be, (iii) considering the challenges of multipath fading, an efficient space diversity combiner is needed to enhance the power receivable at harvester antenna. A good combiner output can go a long way to counter the additional challenge of the currently low efficient energy converters, (iv) to reduce power losses due to impedance mismatch, it is important to have well designed impedance matching circuits that will ensure maximum power transfer of the enhanced RF power from the diversity combiner to the RF-DC converter. To achieve all these, the harvester model of figure 3 is proposed. This will reduce the burning of fossil fuel in generators used at phone charging centres commonly found in developing countries.

The proposed model is shown in Figure 3. Each of the antennas will be connected to the same energy harvesting circuit via a cascaded combiner (MRC/MRC). It is intended to harvest from each of the six RF sources using an array of 4 directional antennas arranged circularly to cover 360 degrees. This arrangement will provide higher gain than using omnidirectional antennas, which are usually of lower gain. Each array of 4 antennas is connected to one diversity combiner (MRC). The output of the first stage of the cascaded diversity combiner will feed the second stage which is a 6-input-1-output MRC. This second stage feeds an enhanced RF power to the impedance matching circuit. The harvested energy will be used to charge a mobile phone battery.

5 CONCLUSION

This paper presented an RF energy harvester model that is anticipated will help alleviate the energy challenges in the forth-coming 5G networks. It briefly discussed the energy challenges currently facing the world in general and specifically pointed out how it will affect the 5G mobile network standards. It noted that the global energy crisis will impact negatively on the future of mobile communications if technology did not move fast to address the challenges. The paper also noted that whatever energy solutions that is proposed must be environmentally friendly. Literature generally agrees that renewable energy is a viable direction to go in search of sustainable energy solutions. The paper, therefore, focused on RF energy harvesting for powering mobile communication devices and pointed out some gaps in literature. It concluded with a proposed RF energy harvester model, which is believed will close major gaps in literature.

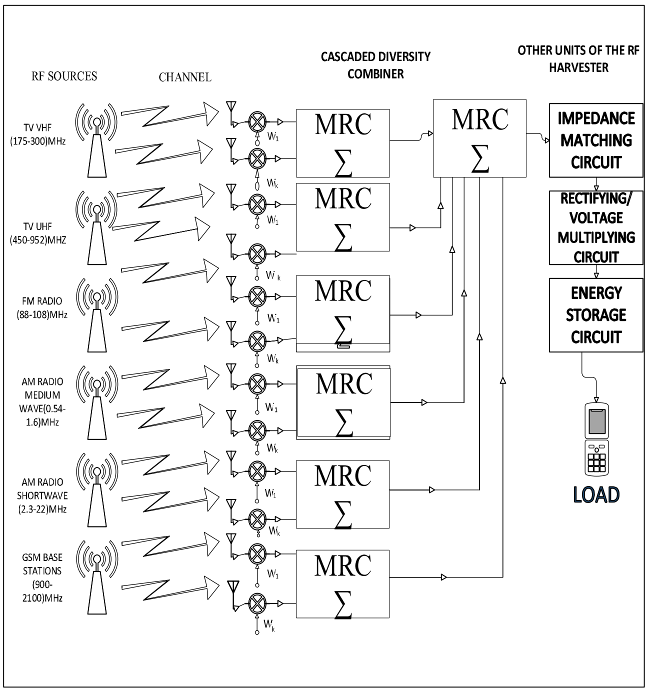

Figure 3: Proposed model for the research.

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