RADIO FREQUENCY ENERGY HARVESTING SOURCES

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ABSTRACT

This radio frequency (RF) energy harvesting is an emerging technology and research area that promises to produce energy to run low-power wireless devices. The great interest that has recently been paid to RF harvesting is predominantly driven by the great progress in both wireless communication systems and broadcasting technologies that have availed a lot of freely propagating ambient RF energy. The principle aim of an RF energy harvesting system is to convert the received ambient RF energy into usable DC power. This paper presents a state of the art concise review of RF energy harvesting sources for low power applications, and also discusses open research questions and future research directions on ambient RF energy harvesting.

Keywords: *ambient, radio frequency (RF), energy harvesting, rectenna, low power, wireless sensor*

1. INTRODUCTION

The quest to power mobile electronics and wireless sensor devices has greatly spurred energy harvesting research. Energy harvesting technologies aim to convert ambient environmental energy into usable electricity to power a wide range of wireless devices. Energy can be harvested from external sources such as solar radiation [1-3], thermal energy [3-5], mechanical vibrations [5-10] and radio frequency (RF) sources [5-9]. Among these ambient energy sources, there has been a dramatic growth of RF energy harvesting mainly because of the abundant availability of electromagnetic signals such as television/ digital television (TV/DTV) [11-13], FM/AM radio [14,15], mobile base stations and mobile phones [16-19], and Wi-Fi signals [20-24]. The recent interest in RF harvesting has also been driven by the great progress in both wireless communication systems and broadcasting technologies that have availed a lot of freely propagating ambient RF energy [25-29]. While ambient RF sources have a comparably low power density of 0.2 nW/cm^2 to 1 μW/cm^2 [26,30-31] relative to other ambient energy sources such as solar, RF signals have the advantage of being fairly ubiquitous and the associated energy is radiated continuously. Unlike solar/light energy harvesting which can be intermittent, RF energy harvesting is viable continuously during day and night hours for both indoor and outdoor environments. As we get into the future, and the society gets even more wirelessly interconnected, the number of RF energy sources will continue to increase, especially as the number of mobile subscribers to wireless networks increases. The increase in the number of operating mobile phones, together with Wi-Fi routers, laptops and smartphones will greatly avail electromagnetic signals from which useful electrical energy can be extracted [25-34]. The ubiquitous ambient RF energy can be extracted and used to charge batteries [27] or energize a multiple range of low-power electronic devices, including wearable smart devices [21], RFID tracking tags [35], and wireless sensor devices [13-15,36]. RF energy harvesting technology is particularly useful in enabling the powering-up of wireless sensor networks (WSNs). Energy harvesting WSNs are the core technology which is currently revolutionizing application spaces such as structural health monitoring, industrial automation, environmental monitoring, health and medical smart systems. In these applications, it has been demonstrated that ambient RF energy-harvesting technologies can be readily integrated with other energy harvesting systems such as solar cells [37], piezoelectric energy harvesters [38] and thermoelectric energy harvesters [39].

This paper gives a concise review or RF energy harvesting sources aimed at powering low energy wireless sensor devices. The paper is organised as follows: section 2 presents an overview of RF energy harvesting while section 3 gives a state of the art review of RF energy sources. Section 4 presents the discussion highlighting future outlook and research directions, finally section 5 concludes the paper.

2. OVERVIEW OF RF ENERGY HARVESTING

2.1. RF energy harvesting system

RF energy harvesting sources can be classified as either dedicated RF energy sources or ambient RF sources [25]. Ambient RF energy typically covers transmission frequency in the range 0.2 - 2.4 GHz, and is freely available from public communication services such as television (TV), GSM, wireless local area networks (WLAN), and Wi-Fi. On the other hand, dedicated RF sources are on-demand supply and generally have high power density due to directional transmission, and it is used to power wireless nodes that require predictable and high amount of energy [17,40].

In conventional RF energy harvesting systems, the extraction of RF power is realised by receiving an RF signal using an antenna, then rectifying this RF signal to produce the desired direct current (DC) which is then conditioned to power an external circuit or device (see Fig. 1). To effectively manage the RF energy received by the antenna, an impedance matching circuit is needed. The impedance matching network prevents the reflection of

RF energy into free space and helps to boost the RF signal voltage power as well as the peak input voltage to the rectifier circuit.

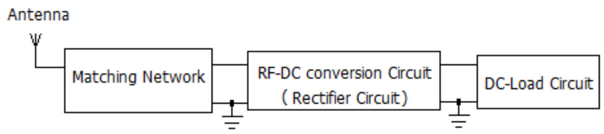

Fig. 1 Schematic of an RF energy harvesting system

2.2. RF harvesting environment

One of the main challenges to RF energy harvesting from commercial telecommunications networks is the low power density which is in the order of 0.2 nW/cm^2 - 1 μW/cm^2 [26, 30-31], compared to that of fairly mature energy harvesting techniques like solar photovoltaic with higher densities in the range of 20 µW/cm^2 − 10 mW/cm^2 [41]. Nevertheless, the pervasive distribution of commercial information and communications networks in urban, metropolitan and peri-urban environments make RF a comparatively strong and reliable ambient source, despite the traffic fluctuations and some unpredictable nature in radio wave propagation [42]. It is critical to note that ambient RF energy in both indoor and outdoor environments is accessible at different frequencies and frequency bands, levels and polarizations.

For proper design and deployment of RF energy harvesting systems in indoor or outdoor environments, it is critical that the RF energy resource available in the localities of interest be quantified. This can be effectively achieved by ascertaining the power density levels of the available RF frequency bands by means of spectrum density measurements. As may be expected, the different spectra in different localities possess different characteristics which are dependent on such environmental factors as humidity, and the distance from the RF signal transmitters [43]. Barroca [44] presented extensive spectrum measurement surveys within the frequencies of 300–3000 MHz in urban and suburban areas of Covilhã in Portugal. Piñuela [17] reported a comprehensive city-wide RF spectral measurement survey which was conducted from outside all of the 270 London Underground stations at street level with the aim of optimizing RF energy harvesting. Kawahara [45] also investigated and measured RF signal energy density for TV, mobile and FM radio bands in 16 locations of Tokyo city centre in Japan. Andrenko [46], reported outdoor RF spectrum survey results conducted in the shopping square and residential area in Shunde, China. Mimis [47] presented results of indoor RF spectrum survey that was carried out in a variety of residential locations around the city of Bristol, UK between frequencies of 500 MHz and 6 GHz. In all these reported studies, there is a general conclusion that the maximum RF power density can be obtained from GSM 900/18000 bands [17, 42-47].

The power harvested from an RF source (a transmitting antenna) by an RF energy harvesting system (receiving rectenna), is dependent on the signal frequency, the incident power level, and the conversion efficiency of the rectenna circuit. For simple cases where the receiving the antennas are polarised and properly aligned, the power received (hence obtained) is as given by the simple form of Friis equation as shown in Eq. 1:

$$P_r = P_t G_r G_t [\lambda/(4\pi R)]^2 \tag{1}$$

where P_r is the power at the receiving antenna (hence obtained power), P_t is the output power of the transmitting antenna G_t and G_r are gain of the transmitting and receiving antenna, respectively; λ is the wavelength of the transmitted signal, and R is the distance between the source and receiver. The transmitted power level is very important for these systems. As is evident from Eq. 1, the RF signal level decreases rapidly with distance, and hence the energy harvesting rectenna circuit should be designed very carefully and efficiently. In addition, highly efficient high-gain receiving antennas are ideal.

3. RF ENERGY SOURCES

In this section Wi-Fi, GSM/Cellular and TV/DTV radio frequency sources are presented as the main sources from which RF energy can be harvested. Fig. 2 shows RF power densities of these main RF energy sources as measured outside the Northfields London Underground station [17]. As can be seen from Fig. 2, GSM 900/1800 bands have high RF power densities. While other RF sources like AM radio stations [12,14] and UHF RFID [48,49] are promising sources they are still very limited.

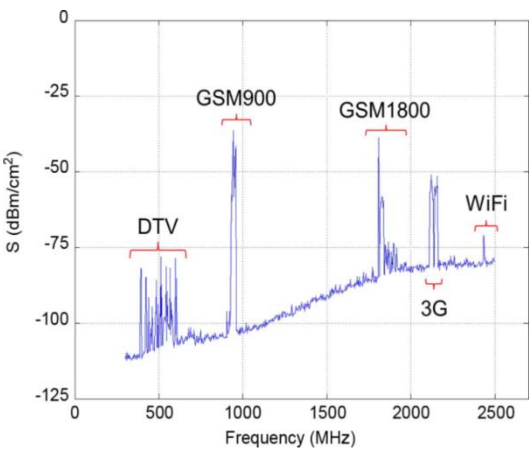

Fig. 2 Typical RF power densities [17]

3.1. Wi-Fi RF sources

The Wireless Fidelity (Wi-Fi) is a short-range wireless transmission technology used to interconnect personal computers, laptops, smart phones, small mobile- personal digital assistant (PDA) and other such terminals. Wi-Fi is based on IEEE802.11 standards for wireless local area networking (WLAN) and was designed for interoperability between wireless network products based on the standards. Wi-Fi uses the unlicensed ISM band of 2.4 Hz to 5 GHz. Wi-Fi technology was mainly designed for indoor applications optimized for a coverage distance of 100 metres. An exciting development which is recently taking over this area is the massive deployment of Wi-Fi in populated and public areas known as hotspots were Wi-Fi internet access is publicly availed.

Hotspots are often found in coffee shops, restaurants, hotels, college campuses, airports and other public areas where there is high demand for wireless internet access.

Table 1 gives a summary recent RF energy harvesting research from Wi-Fi sources.

Table 1 State of the art energy harvesting Wi-Fi sources

Author, Year & Ref.	*Wi-Fi sources*	*Description of energy harvesting system*	*Applications*
Talla, 2015 [20]	Wi-Fi router	Called *PoWiFi* harvester- efficiently harvested energy across multiple 2.4 GHz Wi-Fi channels. Sensitivities of -17.8 dBm @ 2.4 V at bandwidth of 100MHz & -19.3 dBm @ 2.4/3.0 V.	Used to power camera and an LMT84 temperature sensor, an microcontroller and the. The fabricated battery charger managed to charge two AAA 750mAh low discharge current Li-Ion and NiMH batteries at 2.4V
Talla, 2015 [21]	Wireless transmitter on Smartphone	Designed a wearable temperature sensor which harvested energy from Wi-Fi transmissions and transmitted data back to an access point, also designed a 2.45 GHz front end to power an ANT radio SoC using a smartphone as a Wi-Fi source. The harvesting system achieved a sensitivity of -16.5 dBm with 100% duty cycle Wi-Fi transmissions. The system had an operating range of 11.5 cm from a 2 dBm Wi-Fi transmitter on a smartphone and a 92 cm range from a 20 dBm Wi-Fi access point with a 3 dBi antenna on the wearable device. Consisted of an RF harvesting front end and an ANT radio SoC.	Used to power wearable temperature sensor and an ANT SoC radio. The study also avails an analytical report on the bursty nature of the 802.11 Wi-Fi signals
Kellog, 2014 [24]	Off-the-shelf Wi-Fi devices	The novel system, called *Wi-Fi Backscatter* enables internet connectivity for RF-Powered Devices. The prototype demonstrated the first communication between an RF powered device and a Wi-Fi device. It achieved communication rates of up to 1 kbps up to 2.1 m from a Linksys router.	Establishment of communication link between an RF-powered device and commodity Wi-Fi devices
Kadir, 2014 [48]	Indoor Wi-Fi transmitters	The multiple antenna system -each antenna able to harvest energy from 3 Wi-Fi channels. The system was built on FR4 substrates and delivered maximum voltage of 2 V; system efficiency of 18.6 %.	Low-power wireless applications (e.g charging of supercapacitors)
Alneyadi, 2014 [49]	2.42 GHz Wi-Fi-WLAN band	Consisted of multiple microstrip patch antennas, power combiner and voltage quadruple Greinacher rectifier; measured peak efficiency was up to 57.8% at 6 to 8dBm input power. In the presence of realistic -10dBm continuous signal, the system can charge a 33 mF super capacitor to 1.6 V in 20 minutes.	Charging capacitors and powering wireless sensors
Hong, 2013 [35]	Low power Wi-Fi signals	The prototype harvester, based on the multiple stage Cockroft-Walton rectifier, was built on RT/Duroid 5880 PCB substrate; 2 V output voltage harvested from an operating frequency of 2.48 GHz with −9 dBm (0.13 mW) sensitivity.	Low Power RFID applications
Olgun, 2012 [22]	Wi-Fi- routers	The system consisted of 3 x 3 miniaturised antenna arrays, rectifier circuit and a power management circuitry with a sensitivity of -40 dBm.	Was used to successfully power an off-shelf temperature-humidity sensor
Hong, 2012 [50]	Wireless routers	The system could deliver final DC power of 76.35 μW at a distance of 40 cm away from the wireless router. The total RF- DC power conversion efficiency is measured to be from 9.76% at 2.4 m to 33.7% at 40 cm away from the router. The output DC voltage are in the range of 1.5 to 7.36 V.	Demonstrated potential applications in powering portable calculators, LED arrays and charging of super-capacitors and batteries

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3.2. Discussion on harvesting from Wi-Fi sources

In the period 2012 to 2016, several researches on energy harvesting from Wi-Fi were conducted by as shown in Table 1. In 2012, Hong [50] designed an energy harvesting system that delivered a DC power of 76,35 µW and the system to run low power devices like calculators ,LED lights as well as charging capacitors. The system achieved a maximum RF-DC conversion efficiency of 33,7% at a distance of 40 cm from a Wi-Fi router. Olgun [22], also in 2012 successfully powered a temperature-humidity sensor with a 3x3 miniaturised antenna array from a Wi-Fi router. In 2013, Hong [35] designed a Crockfort–Walton based rectifier that delivered 2 V from low power Wi-Fi signals at 2.48 GHz. In addition, the device produced enough power for RFID applications. Alneyadi [49], in 2014 constructed a voltage quadruple Greinacher rectifier with a peak efficiency of 57,8% at 8 dBm input power from a 2.42 GHz WLAN –band for trickle charging of capacitors and powering of wireless sensors. In the same year Kadir [48] and Kellog [24] came up with systems for low power wireless applications. Kellog demonstrated the first ever communication between RF powered devices and off-shelf Wi-Fi devices. In 2015, Talla [20,21] designed a novel Power Over Wi-Fi (POWIFI) harvester that successfully harvested energy from a 2.4 GHz Wi-Fi router. The harvesters successfully powered a camera, a temperature sensor, Li-Ion and NiMH battery chargers.

3.3. Mobile bases station/GSM/cellular sources

The past two decades have witnessed spectacular growth of mobile phone (cellular) communications, and there are currently in excess of 7.3 billion mobile phone subscribers in the world [51]. The expansion of cellular phone networks entails an increase in base stations. Basically, with this growth comes the inevitable increase in the number of base station sites. Cellular phones and their base stations are essentially two-way radio systems and they produce RF radiation to communicate. The base stations and mobile phones communicate with each other, and share a range of operating frequencies. In the Global System for Mobile (GSM) communication system, the main operating frequencies are 900 MHz (called GSM 900) and 1800 MHz (called GSM 1800). The GSM 900 band of is widely used for RF energy scavenging since RF power at this frequency is transmitted more efficiently for longer distance with lower propagation loss compared with higher frequency bands for 3G and Wi-Fi (i.e., 2.4 GHz).

Table 2 Summary of the RF energy harvesting research from Mobile Base Station/GSM/Cellular Sources

Author, Year & Ref.	*Sources*	*Description of energy harvesting system*	*Applications*
Uzun, 2016 [52]	GSM 900	Consisted of a 2-stage Dickson voltage multiplier and L-type impedance matching circuit; an efficiency of 45 % at 0 dBm input power.	Low-power sensors
Nimo, 2015 [53]	GSM900	Based on a dual-band antenna and a passive dual-band rectifier. The system delivered RF power of −27 dBm to −50 dBm from the various GSM frequency bands at a distance of about 110 m from the GSM base station.	Powered commercial thermo-hygrometer
Zhang, 2014 [54]	GSM/3G/4G	Wide band rectenna system based on cross planar dipoles with low-pass filter and voltage doubler planar cross dipoles. The system efficiency of about 32% in the frequency range 1.9–2.3 GHz.	Potential applications in wireless sensing
Beng, 2014 [55]	GSM900/1800	Prototype system designed around high Q coil antenna; harvested a voltage in the range of 2V from the air without a prominent source nearby.	Trickle charging of a super-capacitor
Hoang, 2014 [56]	GSM900/1800	Energy harvesting rectenna system based on the printed-IFA for GSM bands with 1.3 dBi at 900 MHz band and 3.2 dBi at 1800 MHz band.	Potential applications in wireless mobile devices
Parks, 2013 [36]	738MHz cellular BTS (cell tower)	Based on 6dBi receiver antenna that could power a sensor node at a distance of 200m from the BTS.	Wireless sensor nodes for measurements of light and temperature
Din, 2012 [19]	GSM900	The system consisted of a single wideband E-shaped patch antenna, a pi matching network and a 7-stage voltage doubler; harvested 2.9 V DC voltage at an approximate distance of 50 m from GSM cell tower.	Powering STLM20 a temperature sensor
Arrawatia, 2011 [16]	GSM900	A system based on square microstrip antenna and a Schottky diode-based single stage & six-stage voltage doubler circuits; delivered 2.78 V output voltage at a distance of 10m from the cell tower and a voltage of 0.87 V at a distance of 50 m.	Potential applications in wireless sensor devices

3.4. Discussion on harvesting from Mobile Base Stations

Tremendous research has been conducted on RF energy harvesting from Base Transceiver stations/GSM sources. Many researchers came up with novel systems in the period 201 to 2016. Table 2 gives a summary of some of these researches. In 2011, Arrawatiwa [16] designed a microstrip patch antenna and a voltage doubler circuit to potentially power wireless sensor devices from GSM 900. An output voltage of 2.78 V was successfully delivered at a distance of 10 m from tower. However as the distance from the tower increased, the voltage dropped as expected from theory. In 2012, Din [19] constructed a wideband E shaped patch antenna, a pi-matching network and a seven stage voltage doubler circuit that successfully realised an output voltage of 2.9 V at a distance of 50 m from a GSM 900 cell tower. The realised power successfully powered an STML20 temperature sensor. Parks [36], in 2013 designed a 6dBi receiver antenna that successfully powered light and temperature measuring sensor nodes at a distance of 200 m for the base transceiver station at a frequency of 738 MHz. The year 2014 registered a remarkable research output, Hoang [56] designed a printed-IFA based rectenna for potential applications in wireless mobile devices. The system harvested from both GSM 900 and GSM 1800 platforms and had a gain of 1.3dbi @ 900 MHz and 3.2dBi @ 1800 MHz. Beng [55] constructed a high Q coil antenna for trickle charging of super capacitors. The system realised an output voltage of 2 V from the air without any prominent sources in vicinity. In the same year Zhang [54] designed a wideband rectenna system that consisted of a low pass filter and a voltage doubler cross dipole for potential powering of wireless sensing platforms. A system efficiency of 32% was realised in the frequency range 1.9 – 2.3 GHz. In 2015, Nimo [53] designed a dual band antenna with a passive dual band rectifier that produced RF power in the order of -27dBm to -50 dBm which managed to power a thermos-hygrometer at a distance of 110m from a GSM 900 base transceiver. In 2016, Uzun [52] made a rectenna that consisted of a two –stage voltage multiplier and an L – type impedance matching circuit for powering of low power sensors from a GSM 900 cell tower. the system had an efficiency of 45% at 0 dBm.

3.5. TV and DTV sources

Intel Research demonstrated perhaps the first major demonstration of RF ambient power harvesting from Digital Television (DTV) in 2009, when 60 µW of energy was harvested at a distance of about 4 km from a 960-kW TV broadcasting tower [57]. Mikeka et al [11] presented an RF energy harvesting rectenna with conversion efficiency of 18.2% for -20 dBm input and 0.4% for -40 dBm input, respectively. They reported power of -44 dBm and +3 dBm as measured from Tokyo TV broadcasting towers at 400 m and 4 km respectively. In 2013, Parks et al [36] successfully powered a wireless sensor platform with energy harvested from a 500-MHz digital TV (DTV) broadcasting radio wave. The wireless sensor node was operated while 10.4 km from the 1 MW TV broadcasting tower. TV and DTV signals are artificially produced and are fairly independent of weather (as is the case with solar energy). These signals are broadcast 24 hours and hence have potential to be a sustainable source of ambient energy. Table 3 summarises some status of the important reported researches on energy harvesting from television sources.

Table 3 Summary of the RF energy harvesting research from TV/DTV sources

Author, Year & Ref.	*Sources*	*Description of energy harvesting system*	*Applications*
Gabrillo, 2015 [58]	TV broadcast tower (165 MHz)	Produced 1.80mW output power at a distance of 77.84 m from a TV signal tower operating at 165 MHz.	Low power wireless device
Moura, 2015 [59]	Portuguese DTV Signal	Rectenna systems were demonstrated, and measurements indicate 63 % efficiency at -10.5 dBm input power with the Portuguese D-TV signal.	Powering-up self-sustainable devices
Xie, 2014 [60]	TV broadcast tower (515 MHz)	TV broadcast RF energy harvesting employing square antenna array consisting of four square electrically small Egyptian-axe dipole (EAD) antennas; demonstrated ability to harvest 1 V from TV broadcast tower.	Low power applications
Vyas, 2013 [13]	Ambient Digital-TV Signals	The system consisted of an optimized log periodic antenna and an RF-to-DC charge pump circuit with sensitivity of -14.6 dB; successfully powered a PIC microcontroller at 6.3 km from source.	Embedded microcontroller for sensing and machine to machine comms
Vyas, 2012 [61]	Japanese ISDB-T	A unique prototype capable of scavenging wireless power from TV broadcast; an output of 3 V at 6.5 km from source.	Capacitor charging
Nishimoto, 2010 [62]	TV broadcast airwaves	The system consisted of a rectenna, a microcontroller and an RF transmitter rectenna	Wireless sensor nodes

Sample, 2009 [57]	VHF/UHF energy from TV	Consisted of broadband log periodic antenna (5 d’//’Bi); Output of 5.0 V open circuit when tower 4.1 km away from TV tower.	Wireless identification and sensing platform (WISP)

3.6 Discussion on energy harvesting from TV sources

RF energy harvesting from terrestrial TV broadcasting has become an attractive area for researchers. Quite a number of researches were recorded in the period spanning from 2009 to 2015. In 2009, Sample [57] constructed a log periodic antenna with an antenna gain of 5 dBi for Wireless identification and sensing platform (WISP). The rectenna system had an open circuit voltage of 5.0 V some 4.1km from a TV tower. Nishimoto [62] in 2010 successfully made a rectenna system that harvested TV broadcast airwaves for powering wireless sensor nodes. In 2012, Vyas [61] scavenged wireless power from a Japanese ISDB-T TV broadcast at a distance of 6.5 km from the tower. The prototype had an output voltage of 3 V which was sufficient to trickle charge a capacitor. In 2013, Vyas [13] designed an optimised log periodic antenna and an RF to DC charge pump circuit that succesfully powered a PIC microcontroller at 6.3km from a TV tower. Xie [60], in 2014 harvested RF energy from TV broadcast towers at a frequency of 515 MHz using four electrically small Egyptian –axe dipole antennas and managed to realise an output voltage of 1 V for potential low power applications. In 2015, Moura [59] and Gabrillo [58] came up with RF harvesters for powering low power wireless devices. Moura had a rectenna system that harvested energy from a Portuguese DTV signal. Gabrillo produced 1.8 mW of power at a distance of 77.84 m from a TV signal operating at 165 MHz.

4. DISCUSSION

Apart from path losses, fading, shadowing and energy dissipations, RF energy harvesting is challenged by low power sensitivity and legal restrictions of maximum RF radiation power due to human health concerns. This may mean that some devices reported in recent literature may have limited practical applications especially in the context that RF-to-DC conversion efficiency sharply decreases at low RF powers [40]. The most natural ways to enhance conversion efficiency of RF rectennas is to maximise the incident power collected by a receiving antenna, and also to introduce multiband and broadband rectennas. The RF energy density incident on the receiving antenna influences the RF-to-DC conversion efficiency of an RF energy harvesting system. Research efforts towards efficient RF-DC and DC-DC converter circuits will potentially yield highly efficient RF energy harvesting rectennas. RF energy harvesting rectennas deployed in real operating environments will often need to be functional under conditions which do not match the designed input power levels and loads. In such cases, there is need to make the sensitivity of the rectifier circuits independent of the incident input power and variable output loads [35]. The use of resistance compression networks (RCN) have been proposed to address this scenario [63]. In a related sense, improved RF-DC conversion efficiency of rectifier circuits is witnessed when appropriate time varying signals with high peak-to-average power ratio (PAPR) are employed [64]. Further research on the use of RCNs and PAPR signals to optimize the performance of multiband RF energy harvesting systems is needed, and is potentially promising to significantly improve the performance of RF rectennas in real world applications.

5. CONCLUSION

This paper presented a concise review of RF energy harvesting sources, highlighting the key achievements and challenges. The conversion efficiency of RF energy harvesting systems at low input RF power is currently very low and hence particular research efforts at improving this performance metric is a key milestone in realising practically viable rectenna systems for real world deployment. While the power delivered by RF energy harvesting devices has significantly increased over the past decade, it is still critical to note that the targeted applications are essentially ultralow power wireless sensor devices which do not support computationally intensive algorithms.

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