A Survey on RF Energy Harvesting System with High Efficiency RF-DC Converters

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ABSTRACT

Radio frequency (RF) energy harvesting technology have become a reliable and promising alternative to extend the lifetime of power-constrained wireless networks by eliminating the need for batteries. This emerging technology enables the low-power wireless devices to be self-sustaining and eco-friendly by scavenging RF energy from ambient environment or dedicated energy sources. These attributes make RF energy harvesting technology feasible and attractive to an extended range of applications. However, despite being the most reliable energy harvesting technology, there are several challenges (especially power conversion efficiency, output DC voltage and sensitivity) poised for the implementation of RF energy harvesting systems. In this article, a detailed literature on RF energy harvesting technology has been surveyed to provide guidance for RF energy harvesters design. Since signal strength of the received RF power is limited and weak, high efficiency state-of-the-art RF energy harvesters are required to design for providing sufficient DC supply voltage to wireless networks. Therefore, various designs and their trade-offs with comprehensive analysis for RF energy harvesters have been discussed. This paper can serve as a good reference for the researchers to catch new research topics in the field of RF energy harvesting.

1. INTRODUCTION

Recently, research interests in energy harvesting (EH) technology have been increasingly growing courtesy rapid increase in the numbers of low-power wireless sensor devices in the Internet-of-Things (IoT), and wireless senor networks (WSN) [1], [2]. The EH technology can be considered as an ultimate solution to replace the batteries and provide a long-term (over 10 – 20 years) power supply for wireless sensor nodes in IoT and WSN applications. These wireless sensors are usually powered-up by the batteries which impose several limitations including routine charging and maintenance of the batteries, their replacement in remote environments [3], [4], safety issues (explosion risk at high temperature or under severe shock), and reliability (failure risk after long operation time) [5]. These limitations of the batteries for billions of wireless sensors in the IoT and WSN can be very costly and time consuming [6]. To overcome need for batteries, energy harvesting solutions, which scavenge
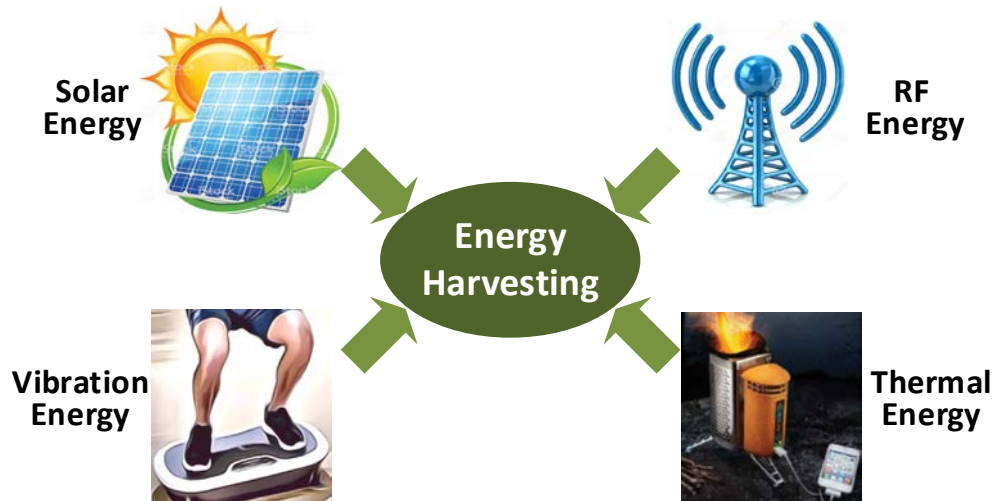
Figure 1. Different types of energy sources for energy harvesting.

energy from ambient environment sources, have been emerged as alternate methods to power-up wireless sensor devices.

Figure 1 shows different sources of energy available in the ambient environment such as vibration energy [7], thermal energy [8], solar energy [9], and RF energy [10]–[14]. Vibration energy harvesters convert human movement or machinery vibration (kinetic energy) into electrical energy by piezoelectric effect [15], [16]. However, the person has to rest or machine cannot operate constantly. Thermoelectric energy harvesting converts the thermal energy into electrical energy due to thermal temperature difference between the two objects [17], [18]. This is only possible in the presence of temperature gradient in the environment which is not usually the case in many applications. Another drawback of thermoelectric energy harvesting is high cost and low efficiency [19]. Solar energy harvesting converts sunlight into electrical energy using photovoltaic effect. Though solar energy is the most abundant energy source, it is not a promising energy source for wireless sensors that are typically installed indoors and operate continuously day and night. A typical solar cell has a power conversion efficiency (PCE) of around 20% [20], [21]. RF energy harvesting converts RF energy into usable electrical energy. The RF energy is almost everywhere in the environment radiated by wireless radio networks, television (TV) towers, and cellular towers [22]–[25]. Table 1 summarizes the alternate energy sources available in the environment for power harvesting [26], [27].

RF energy harvesting technique has many useful features that differentiates it from other sources. Reliability and cost are the main features that differentiate RF energy harvesting from other energy sources. Reliability is actually harvesting enough energy for continuous operation of sensor nodes in any sensor network for any time at any location. Since RF energy sources such as cellular networks, TV networks, radio networks, Bluetooth signal and Wi-Fi are available indoor and outdoor environments, enough and continuous energy can be harvested from them for RF-powered wireless sensors. The wireless sensors that are powered from other energy sources are more costly than those using RF energy source. The main reason is that the other energy harvesting techniques require power conversion modules to harvest their respective energies that are not fully integrated and compatible with standard CMOS process. This drawback increases the total cost of the energy harvesting system. On contrary, RF energy

Table. 1 Alternative energy sources to replace batteries

| Source	Power density	Harvesting tech	Advantages	Disadvantages
Vibration	Human: 4 µW/cm² Industrial: 100 µW/cm²	Piezoelectric Electrostatic Electromagnetic	Implantable High efficiency	Not always available Material physical limitation
Thermal	Human: 30 µW/cm² Industrial: 1-10 mW/cm²	Thermoelectric Pyroelectric	High power density Implantable	Not always available Excess heat
Solar	Indoor: 10 µW/cm² Outdoor: 10 mW/cm²	Photovoltaic	High power density Mature	Not always available Required exposure to light Expensive
RF	GSM: 0.1 µW/cm² Wi-Fi: 1 mW/cm²	Antenna	Always available Implantable	Low density Efficiency inversely proportional to distance

(a)

(b)
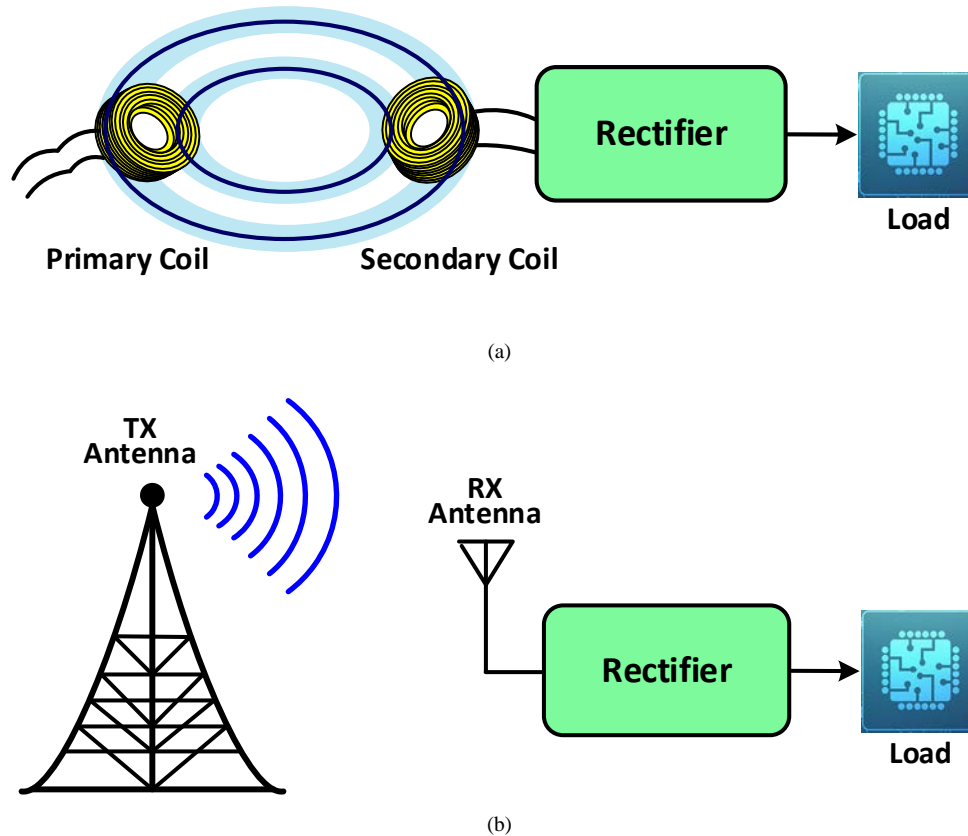
Figure 2. Types of wireless power transfer (WPT). (a) Near-field WPT technique, and (b) Far-field WPT technique.

harvesting system is fully compatible and integrated with other wireless sensor systems on a single chip.

In RF energy harvesting, radio signals carry energy in form of electromagnetic radiations with frequency range from 3 kHz to 300 GHz. Generally, there are two wireless power transfer (WPT) techniques that are used to transfer the power; (i) near-field (non-radiative) technique [28], and (ii) far-field (radiative) technique [29]. Figure 2(a) shows the generalized form of the near-filed WPT technique that is further divided into two main categories; (a) inductive coupling, and (b) magnetic resonance coupling. In the inductive coupling, energy is transferred between the transmitter and the receiver coils by magnetic field [30]. In magnetic resonance coupling, the energy is transferred between the two resonators which are formed by adding a capacitor on an induction coil [31]. In the near-field WPT technique, power strength is dependent on the distance between the coils and the power transfer degrades drastically with the distance (signal is attenuated by 60 dB per decade of the distance in free-space) [32]. Similarly, the transmitter and the receiver coils must be aligned to transfer the maximum power between the coils. Therefore, near-field techniques cannot scale well in the IoT architecture, where wireless sensor nodes receive power across wide outdoor and indoor environments.

On the contrary, the far-field WPT technique transfers the power over a longer distance by electro-magnetic radiation beams such as laser beams and

Table 2. Comparison between Near-field and Far-field WPT techniques

| Field region	WPT technique	Propagation	Effective distance	Efficiency
Near-field	Resonant inductive coupling	Non-radiative	From a few millimeters to a few centimeters	From 5.81% to 57.2% when frequency varies from 16.2 kHz to 508 kHz [33]
	Magnetic resonance coupling	Non-radiative	From a few centimeters to a few meters	From above 90% to above 30% when distance varies from 0.75m to 2.25m [31]
Far-field	RF energy transfer	Radiative	Depend on distance and frequency and the sensitivity of RF energy harvester (typically from several meters to several kilometers) [33]	0.4%, above 18.2% and over 50% at -40 dBm, -20 dBm and -5 dBm input power, respectively [34]

*WPT = Wireless power transfer
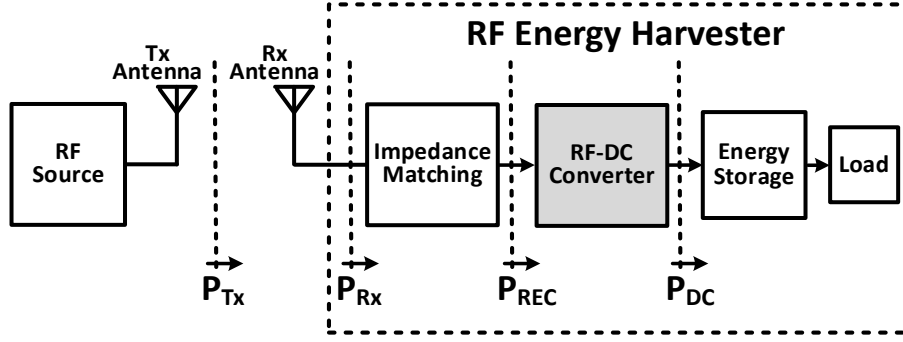
Figure 3. Block diagram of a far-field wireless power transfer system.

microwaves (Figure 2(b)). In the far-field, power strength of the signal is attenuated by 20 dB per decade of the distance in the free-space. Table 2 shows comparison between near-field and the far-field wireless WPT techniques [32]. It is clear that far-field WPT technique has advantages over near-field WPT in terms of effective energy transfer distance. However, it has low PCE for RF-DC converter at low harvested RF power.

2. RVIEW OF RF ENERGY HARVESTING SYSTEM

Figure 3 shows the block diagram of a far-field WPT system. The system is composed of a RF power source that is connected to a transmitted antenna T_X. The power P_{TX} is transmitted from T_X to a receiving antenna R_X through a transmission medium which has the free space path loss. The R_X can be designed to operate on either signal frequency or multiple frequency bands depending upon energy harvesting capability of the RF energy harvester. The R_X is connected to an RF energy harvester that consists of
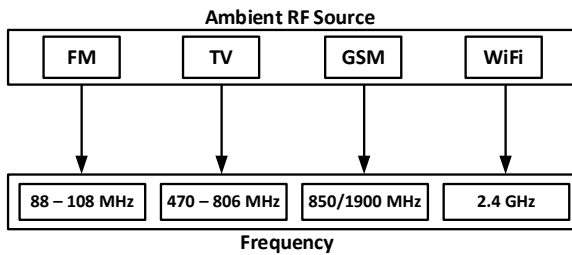

Figure 4. Prominent available ambient RF sources in frequency spectrum.

Table 3. ISM frequency bands in UHF spectrum

Frequency	Center Frequency
433.05 - 434.79 MHz	433.92 MHz
902 - 928 MHz	915 MHz
2.4 - 2.5 GHz	2.45 GHz

an impedance matching network, a rectifier circuit, and an energy storage element. The R_X receives the incoming RF power P_{RX} and sends to the impedance matching network. The impedance matching network is usually a resonator circuit that operates at a desired frequency to ensure the maximum power transfer P_{REC} from the R_X to the rectifier. The rectifier converts the incoming power into DC power P_{DC}. The energy storage element is usually a capacitor that delivers smooth P_{DC} to the load.

The far-field RF energy harvesting scavenges the electromagnetic energy from ambient RF sources such as cellular transmission, TV signals, AM/FM radio transmission or dedicated RF sources. Figure 4 shows available RF sources that can be used for RF energy harvesting. The RF power transmitted by a dedicated RF transmitter is limited due to the standards defined by Federal Communication Commission (FCC) [35]. FM band, TV band, and GSM band, all require a license for the transmission of their signals. But there are some frequency spectrums which are reserved internationally for industrial, scientific, medical purposes. These bands are called ISM bands which do not need a license for the transmission of RF signals. However, ISM band needs to follow strict regulations based on the operating frequencies, signal strength, output power and other things as defined by the International Telecommunication Union Radio-communication Sector (IT-R) [36]. Table 3 shows three ISM bands working in the ultra-high frequency (UHF) spectrum.

In the far-field, path loss is the loss of transmitted signal power in the free space during the propagation. In the far-field, the power received at the antenna can be expressed as [37]:

$$P_R = \frac{P_T G_T G_R \lambda^2}{(4\pi D)^2} \qquad (1)$$

where, P_R is the power received at receiving antenna, P_T is the power transmitted from transmitting antenna, G_T and G_R are the transmitting and receiving antenna gain, respectively, λ is wavelength of electromagnetic

signal, D is the distance between transmitting antenna and the receiving antenna.

Using equation (1), the free-space path loss (L_p) can be calculated as:

$$L_p = \frac{P_T}{P_R} = \frac{(4\pi D)^2}{G_T G_R \lambda^2} \qquad (2)$$

By solving (2), L_p in dB can be expressed as:

$$L_p(dB) = 20\log_{10}(f) + 20\log_{10}(D) + 32.44 - G_T - G_R \qquad (3)$$

By using (3), it is possible to predict RF signal power in the far-field region. However, this equation is not sufficient to address all the factors that affect RF signal during the propagation such as absorption, diffraction, and reflection etc.

There are several parameters that decide the overall performance of the RF energy harvester and these parameters are needed to be evaluated. These parameters are power conversion efficiency (PCE), sensitivity, operation distance between source and RF energy harvester, and output power. The PCE of the RF energy harvester can be defined as the ratio of the power harvested by the RF energy harvester to the RF input power received by the receiving antenna. Generally, PCE of the RF energy harvester defines the efficiency of the rectifier and energy storage element. If transmission loss in space is neglected, the PCE of the rectifier can be calculated as [12]:

$$\eta = \frac{P_{load}}{P_{RX}} = \frac{V_{OUT}^2}{R_L \cdot P_{RX}} \times 100\% \qquad (4)$$

where, P_{RX} is power received by the receiving antenna R_X, and V_{OUT} is the output DC voltage across load resistance R_L. There are many factors that determine value of the PCE of the rectifier such as parasitic effects of the printed circuit board (PCB) traces, bond wires, bond pads, leakage in the circuits, nonlinear threshold of electrical devices and design topologies.

The sensitivity of the RF energy harvester can be defined as the minimum value of P_{RX} required to perform the operation of the RF energy harvester. It can be formulated as [38].

$$Sensitivity(dBm) = 10\log_{10}\left(\frac{P}{1mW}\right) \qquad (5)$$

where, P is the minimum power required by system to perform the task. The sensitivity of the RF energy harvester is affected by the threshold voltage of the CMOS technology. The CMOS with low threshold voltage is more sensitive but also results in more leakage current which eventually reduces the overall PCE of the RF energy harvester. The output power of the RF energy harvester is the DC power that is characterized by load voltage V_{OUT} and load current I_{load} across load resistance R_L. The importance of V_{OUT} and I_{laod} varies depending upon the load conditions. If sensor acts as a load at the output of the RF energy harvester, V_{OUT} is more important than I_{load} while in applications like LED or electrolysis, I_{load} is more dominant than V_{OUT}.

3. ANTENNA AND MATCHING NETWORK

A. ANTENNA DESIGN

An antenna captures the RF signals. The performance of the antenna is characterized by its gain, bandwidth and resonance frequency. High antenna gain and miniaturized size are the main attributes of antenna technology. The antenna can be classified as isotropic antenna (radiates energy equally in all directions) or directional antenna (radiates energy more effectively in one direction than others). The antenna gain is defined as the ratio of power density of an antenna in a specific direction to the power density of an isotropic antenna. This parameter tells how well the antenna sends or receives a signal in a specific direction. Technically, antenna gain is the produce of efficiency and directivity. Efficiency measures the losses of the antenna due to surface coating irregularities, dielectric, VSWR, manufacturing faults, or any other factor while directivity measures the concentration of the radiations of the antenna in a specific direction. Authors in [59] reports different antenna topologies for RF energy harvesting. A comparative study about several antenna topologies has been proposed in [60]. Authors in [61] compare the structures of existing antennas. Antenna array for effective RF energy harvesting has also been studied in [62], [63]. Antenna arrays effectively increase the capability at low input power. However, there is a trade-off between the performance and size of the antenna. Narrow-band antenna designs (up to tens of MHz) have been implemented in [64], [65], [66], and [67]. Similarly, dual-bands are designed in [68], [69]–[71]. Moreover, recent work have been focused on broadband antenna [72]–[75].

B. IMPEDANCE MATCHING NETWORK

The main purpose of the impedance matching network is to maximize the power transfer from the receiving antenna to the rectifier circuit and increases the RF input voltage level for the rectifier [76]. In WPT applications, the receiving antenna and the rectifier are considered as source and the load, respectively. In DC circuits, it is acknowledged that optimum power is transferred when resistances of the circuits, impedance is considered instead of the source and the load are identical. However, in RF respectively. In DC
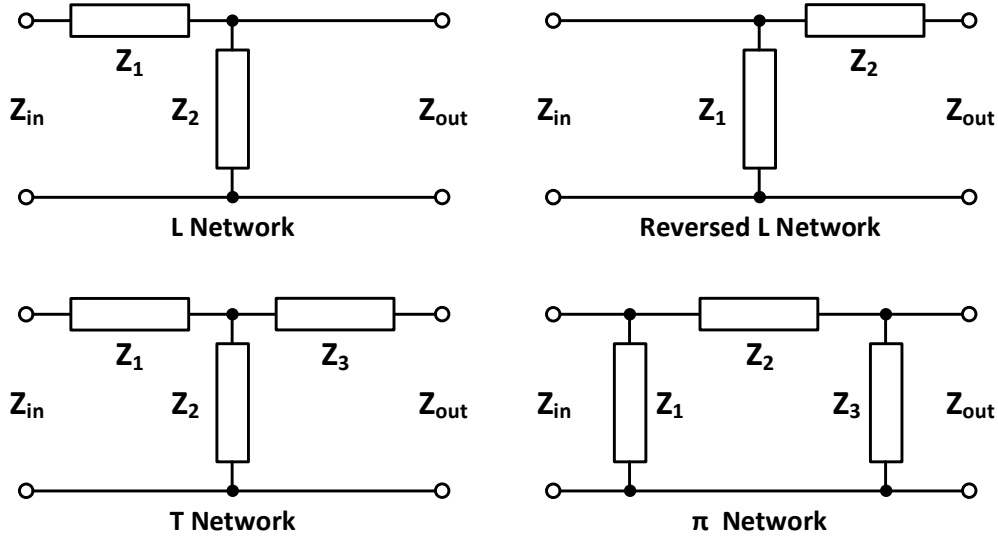
Figure 5. Common impedance matching networks configuration.

circuits, it is acknowledged that optimum power is transferred when resistances of the source and the load are identical. However, in RF circuits, impedance is considered instead of the resistance due to reactance of the inductance and the capacitance. If impedance mismatch occurs between the source and the load, some part of incident power is reflected back to the source (referred as reflection co-efficient) that reduces the efficiency of the system. Therefore, an impedance matching network is required between the receiving antenna and the rectifier to ensure maximum power transfer between them. A matching network is usually composed of reactive components such as capacitors and inductors that do not dissipate power [77].

There are three main types of matching network for RF energy harvesting i.e. L-type, π-type, and T-type matching networks [38] as shown in Figure 5. The commonly used matching network is the L-type as it has two components to simplify the designing process. The quality factor (Q) of the circuit is not changed in the L-type matching network. So, Q cannot be chosen freely as it is fixed by the matching factor. This is the main constrained in the L-type matching network. To overcome this constraint, π-type and T-type matching networks are used. The Q is basically the measure of the energy that is stored in the reactance to that being dissipated by the resistance. Mathematically,

$$Q = \frac{\omega . Energy}{Power_{lost}} \qquad (6)$$

For a lossless reactance, Q is equal to infinity. For an inductive reactance, the Q is given by:

$$Q = \frac{\omega(LI^2/2)}{(R_L I^2/2)} = \frac{\omega L}{R_L} \qquad (7)$$

The Q of the capacitive reactance is calculated by:

$$Q = \frac{\omega(I^2/2\omega^2 C)}{(R_C I^2/2)} = \frac{1}{\omega.C.R_C} \qquad (8)$$

The π-type and T-type matching networks are more complex than the L-type matching network and Q of the circuit is changed in these matching networks. These matching networks are useful in boosting the RF input voltage levels for the overdrive voltage of the transistors in the rectifier circuit. The π-type matching is basically the cascaded of two back-to-front L-type matching network. When two L-type networks are combined, a π-type network with higher Q is obtained. The T-type matching network is the dual of the π-type matching network.

The decomposition of T-type network results into a cascade of two back-to-front L-type networks. The resultant Q is higher than the single stage matching network. The π-type and T-type matching networks are two stage networks that can boost the Q of the network. In most of the applications, low network Q is desirable especially in broadband applications. Because, low Q is not only less susceptible to process variation but also lowers the network loss.

4. RF-DC CONVERTERS

This section discusses the approaches used for hardware circuit designs of the RF-DC converters. An RF-DC converter, being the main block in an RF energy harvesting system, converts the RF power captured by the receiving antenna into useable DC power. A number of techniques have been carried out

Table 4. Performance summary and comparison of some recent rectifier designs

Reference	Year	Technology	Frequency	Output voltage @ RF input power	Peak PCE @ RF input power
Diode Technology					
[94]	2019	MA4E1319-1	5.8 GHz	34.2 V @ 27 dBm	73.1% @ 27 dBm
[91]	2019	SMS-7630	2.45 GHz	12 V @ 13 dBm	37.5% @ 13 dBm
[95]	2017	HSMS-2860	5.8 GHz	5.2 V @ 14.77 dBm	71% @ 14.77 dBm
[96]	2017	HSMS-286C	5.8 GHz	5.1 V @ 24 dBm	64.1% @ 24 dBm
[43]	2014	HSMS-2852	900 MHz	1.3 V @ -10 dBm	75% @ -10 dBm
[44]	2013	HSMS-2850	2.45 GHz	0.55 V @ -15 dBm	N. A.
[45]	2013	HSMS-286B	13.56 MHz	1.9 V @ -30 dBm	55% @ -30 dBm
[48]	2013	HSHS-2852	900 MHz 2.4 GHz	2.2 V @ -10 dBm 0.4 V @ -20 dBm	N. A.
[46]	2012	SMS-2852	915 MHz	1 V @ -10 dBm	10% @ -10 dBm
[47]	2012	SMS-7630	2.45 GHz	30 V @ 40 dBm	85% @ 40 dBm
CMOS Technology					
[14]	2020	180 nm CMOS	902 MHz	3.23 V @ -8 dBm	33% @ -8 dBm 20% @ -18 dBm
[49]	2019	130 nm CMOS	896 MHz	N. A	51% @ -11 dBm
[10]	2019	180 nm CMOS	900 MHz	3.32 V @ 0 dBm	48.2% @ 0 dBm 31.8% @ -20 dBm 41.1% @ 20 dBm
[92]	2019	65 nm CMOS	2.45 GHz	N. A	48.3% @ -3 dBm
[50]	2017	65 nm CMOS	900 MHz	2.3 V @ -10 dBm	36.5% @ -10 dBm
[97]	2017	180 nm CMOS	433 MHz	1 V @ -17 dBm	65.3% @ 15.2 dBm
[98]	2017	180 nm CMOS	915 MHz	1 V @ -14.8 dBm	26% @ 0 dBm
[99]	2017	130 nm CMOS	953 MHz	3.5 V @ -12 dBm	73.9% @ 4.34 dBm
[100]	2016	250 nm CMOS	13.56 MHz	N.A	72% @ 1 $V_{p\text{-}p}$
[101]	2016	180 nm CMOS	2.4 GHz	1.25 V @ -22 dBm	38.4% @ 0 dBm
[90]	2016	130 nm CMOS	2.40 GHz	N.A	30% @ 10 dBm
[51]	2015	130 nm CMOS	915 MHz	3.2 V @ -15 dBm	32% @ -15 dBm
[52]	2014	130 nm CMOS	915 MHz	2.2 V @ -16.8 dBm	22.6% @ -16.8 dBm
[53]	2014	90 nm CMOS	868 MHz	1 V @ -27 dBm	40% @ -17 dBm
[93]	2014	180 nm CMOS	2.4 GHz	1.3 V @ 8.9 dBm	46% @ 8.9 dBm
[54]	2013	90 nm CMOS	868 MHz	1 V @ -26.3 dBm	31.5% @ -15 dBm
[55]	2013	130 nm CMOS	868 MHz	2 V @ -16 dBm	58% @ -3 dBm
[56]	2012	130 nm CMOS	868 MHz	2 V @ -17 dBm	60% @ -10 dBm
[57]	2011	90 nm CMOS	915 MHz	1 V @ -24 dBm	11% @ -15 dBm
[58]	2009	130 nm CMOS	2.2 GHz	1 V @ -25.5 dBm	N. A.

for circuit implementation of the RF-DC converters such as technology-based techniques and CMOS-based techniques. Traditionally, technology based techniques employ HSMS diodes and Schottky diodes for their low threshold voltage for circuit design of the RF energy harvester. Moreover, tunnel diodes, spin diodes, and MIM diodes with recent advancements in this technology make it more mature. For instance, tunnel-diodes with their low parasitic elements can operate at very high frequency. Similarly, MIM diodes can now be integrated with CMOS process which was impossible for the Schottky diodes. Moreover, spin diodes show lower threshold voltage than HSMS diodes and Schottky diodes. While choosing a diode for rectifier design, some parameters are needed to be considered. For example, at microwatt input power level, Schottky diodes show high zero-bias junction resistance which degrades the PCE of the rectifier [39]. However, courtesy recent development in this technology, if the input power level is less than 1 μW,

W-Band ZBD and SMS-7630 diodes are used because of their low parasitic losses [40].

Recently, a lot of literature work and publications have been carried out towards CMOS technology because of their custom assistance in designing and offering high sensitivity at low input voltage than the Schottky diodes. The CMOS technology uses two approaches such as active-circuit approach and passive-circuit approach. The active-circuit approach requires an external battery for the operation of the circuit and mostly used in active RFID or active sensors. The rectifier reported in [41] employs active approach to generate a bias voltage using an external battery. The bias voltage is applied to each transistor (used as rectifying device) to reduce the threshold voltage and improves the performance of the rectifier. However, the external battery results in the increased cost and maintenance and makes the active technique inappropriate for long-term harvesting applications. In contrast, passive-circuit approaches do not require an
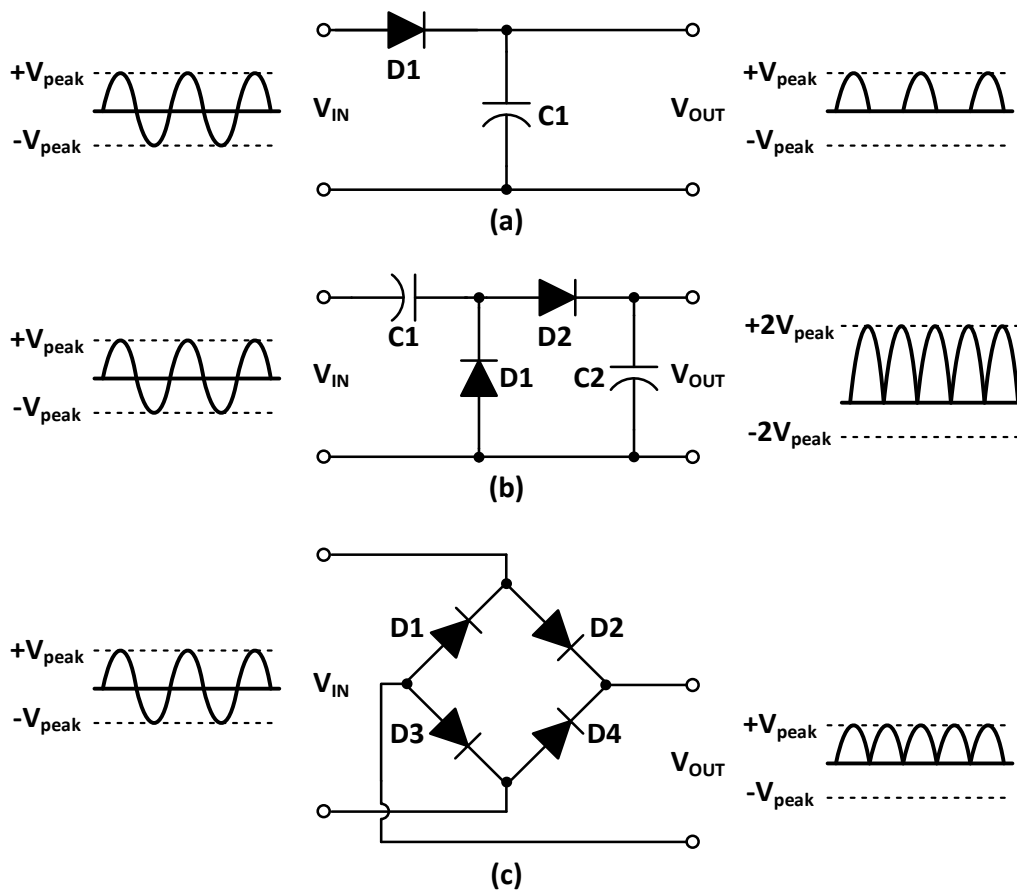
Figure 6. Basic topologies of the rectifier. (a) half-wave, (b) full-wave, and (c) bridge rectifier.

external source for threshold voltage compensation of the rectifying devices, but they require additional circuits. The rectifier reported in [42] generates threshold compensating voltage using an auxiliary block. The auxiliary block, consisting of transistors and capacitors, generates compensating voltage for rectifying devices in the main rectification chain.

The performance of the rectifier is strongly affected by the threshold voltage of the rectifying devices. Threshold voltage is the minimum voltage required to turn-on the transistor to enable the operation of the rectifier. Therefore, number of stages of the rectifier must be chosen wisely because it directly affects the performance of the rectifier. Though output voltage of the rectifier can be increased by increasing its number of stages, PCE of the multi-stage rectifier is decreased because of more voltage drop across the transistors. Thus, there is a trade-off between PCE and the number of stages of the rectifier. Higher the number of stages of the rectifier, lower is the PCE of the rectifier and vice-versa. A number of solutions have been proposed to reduce the threshold voltage of the transistors to enhance the performance of the rectifier. Table 4 summarizes the performance of some recent circuit designs using technology-based technique and CMOS-based technique.

The main issue in scavenging RF power from ambient sources is its limited signal strength at the input of the rectifier. This signal strength is limited due to path loss, unpredictable attenuations in the signal strength over the distance [78], presence of hurdles/obstacles between rectifier and power source, limited maximum signal strength allowed by regulatory bodies [35], antenna orientation, and the transmission medium in which rectifier is utilized. As a result, the overdrive voltages generated by RF voltage levels are not large enough for the rectifying devices in the rectifier to have low conduction losses even after boosted by impedance matching circuit. Consequently, the rectifier fails to harvest the maximum possible energy and its performance degrades. Therefore, designing a rectifier to generate a battery-like voltage from low input RF power is the major challenge.

Generally, there are three main configurations for a rectifier namely (a) diode-based [79] (b) bridge of diodes [80] and (c) voltage multiplier [81]. The diode is the key element of a rectifier circuit. The performance of the rectifier mainly depends upon the junction capacitance, saturation current and conduction resistance of the diode [82]. The performance of the diode determines the PCE of the

rectifier circuit. Silicon Schottky diodes are the most commonly used diodes for rectenna. The most basic topology for the rectifier circuit is half-wave. The half-wave rectifier is composed of only one diode as shown in Figure 6(a). The half-wave rectifier allows only positive half-cycle of the RF signal to pass (converts it into pulsating DC voltage) and blocks the negative half-cycle. Despite having the simple structure, half-wave rectifier is not efficient because large amount of power is wasted. Moreover, half-wave rectifier fails to produce a steady and smooth DC output voltage. To overcome this drawback, a full-wave rectifier is proposed as shown in Figure 6(b). The full-wave rectifier converts both half-cycles (positive half-cycle and negative half-cycle) of the RF signal into pulsating DC signal. The working principle of full-wave rectifier is explained as: During negative half-cycle of the RF signal, diode D1 is conductive while diode D2 is non-conductive. The coupling capacitor C1 is charged to the peak value (V_{peak}) of the RF signal. By using Kirchhoff's voltage law in negative half-cycle, the voltage developed across C1 is:

$$V_{C1} = -V_{peak} + V_{D1} \qquad (9)$$

where, V_{peak} is the peak amplitude of the RF signal and V_{D1} is the voltage drop across D1.
During the positive half-cycle, D1 is non-conducting while D2 is conducting and the charged developed across C1 (during negative half-cycle) is transferred to capacitor C2. Using Kirchhoff's voltage law during positive-half cycle, the output voltage (V_{OUT}) can be written as:

$$V_{OUT} = V_{peak} - V_{C1} - V_{D2} \qquad (10)$$

where, V_{D2} is the voltage drop across D2. By putting (12) in (13), V_{OUT} can be calculated as:

$$V_{OUT} = 2V_{peak} - V_{D1} - V_{D2} \qquad (11)$$

If D1 and D2 are considered as ideal diodes, then V_{OUT} is twice the V_{peak}. The full-wave rectifier is more efficient and more stable than the half-wave rectifier. There is also another type of the rectifier that is called bridge rectifier as shown in Figure 6(c). The main feature of the bridge rectifier is that it keeps the same polarity of the output voltage regardless of the polarity at the input.
Voltage multiplier is basically a cascade of rectifier units that generates output voltage higher than the input voltage. The most fundamental configuration of the voltage multiplier is Cockcroft-Walton multiplier which is also referred as Greinacher multiplier [83] or Villard multiplier [84]. The Cockcroft-Walton multiplier is composed of cascaded rectifier units of

diodes and coupling capacitors to couple the charge through the diodes from clock. The multiplier operates by successively charging and discharging of the coupling capacitors during each phase of the clock and charge is transferred along the diode chain. However, coupling capacitor C must be larger than the diode's parasitic capacitance with the increase in number of stages to have efficient voltage multiplication. To eliminate this limitation, Dickson voltage multiplier has been proposed as shown in Figure 7(a) [85]. In Dickson voltage multiplier, the input is coupled through the coupling capacitor in parallel instead of series. Dickson multiplier achieves efficient multiplication as compared to Cockcroft-Walton multiplier even with relatively high parasitic capacitance value. Dickson topology is very suitable for low power applications and voltage multipliers for RF energy harvesting are generally based on this topology. Though Schottky diodes are widely used in rectifier design due to their small junction capacitance, small series resistance and low-turn on voltage. However, these diodes are not available in standard CMOS technologies. Moreover, they require additional fabrication steps which result in increased production cost and prevent rectifier integration with CMOS integrated circuits.

As it is discussed earlier that a lot of research is being carried out on CMOS technology for not only their assistance in custom designing but also offering high sensitivity at low input voltage level than the traditional Schottky diodes. Conventional Dickson multiplier is also known as "charge pump". A self-compensation scheme based on Dickson topology [85] is reported in [57], [86]. The circuit is composed of diode-connected NMOS transistors as shown in Figure 7(b). The circuit is modified by applying input signal at φ_1 and grounding φ_2 for low power harvesting applications [87]. The modified self-compensation circuit where gate terminals of diode-connected NMOS transistor are connected to later stages to generate compensating voltages as shown in Figure 7(c). The overall output voltage is increased by cascading the several rectifier stages. The variation of threshold voltage between the different stages is reduced by individual body biasing provided by the triple-well diode connected NMOS transistors. However, these triple-well NMOS transistors are not always compatible with other circuits. Moreover, triple-well structure introduces parasitic capacitance at each node causing more losses. Also, dummy NMOS transistors at later stages are not threshold compensated resulting additional power loss. Differential voltage multipliers (Figure 7(d)) are widely used due their low leakage current. However, differential circuits require a PCB balun for conversion of single-ended to differential or differential antenna which results in additional cost and large area on the PCB board. A detailed explanation and analysis of differential multipliers are
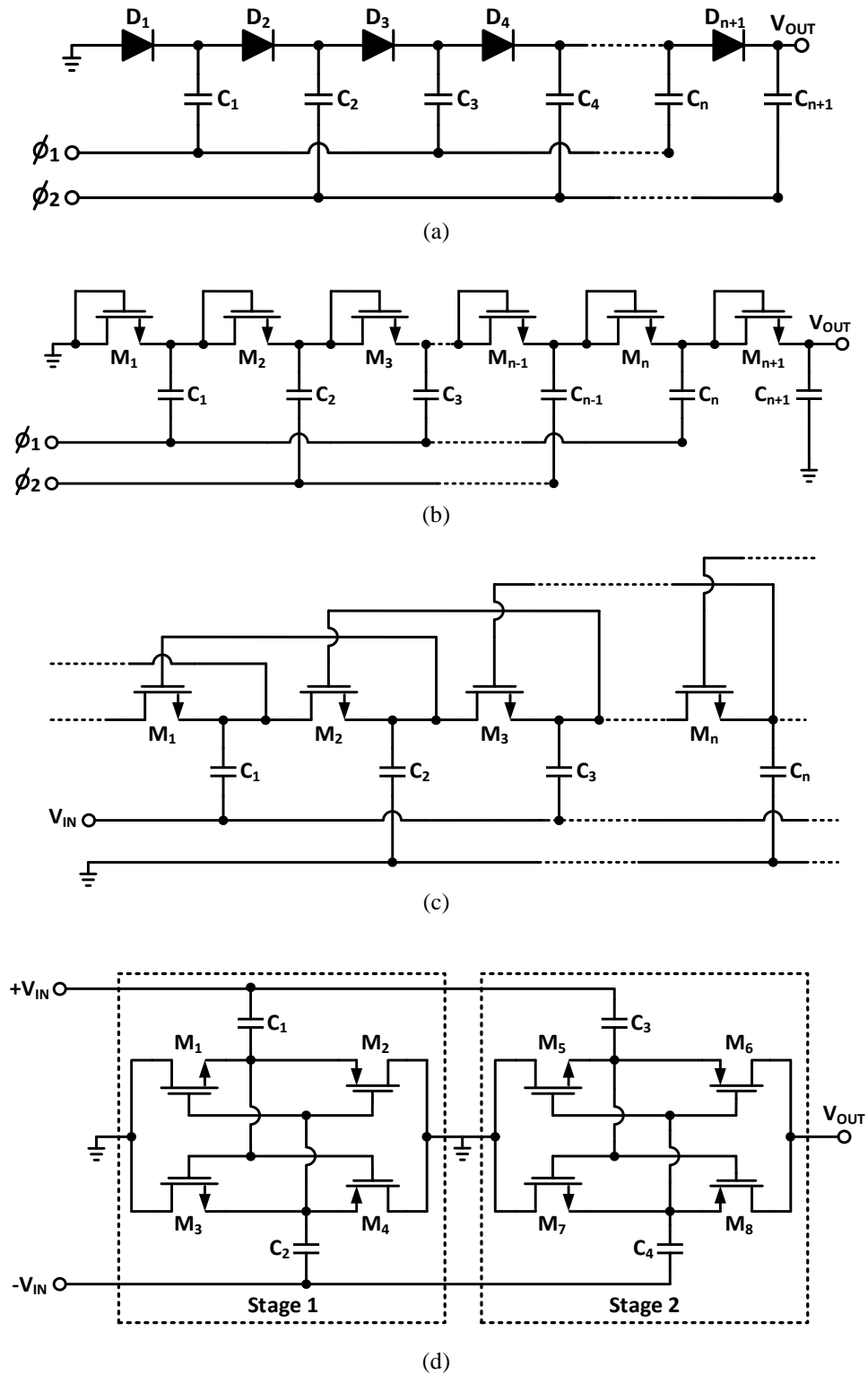
(a)

(b)

(c)

(d)

Figure 7. (a) Dickson voltage multiplier, (b) Diode-connected NMOS Dickson voltage multiplier, (c) Forward-compensated NMOS transistors, and (d) Two-stage differential voltage multiplier.

reported in [88], [89]. Since performance of the rectifier is rectifying devices. A number of solutions (using active-circuit approach or passive-circuit approach) have been proposed to reduce the threshold voltage of the rectifying devices. However, reducing
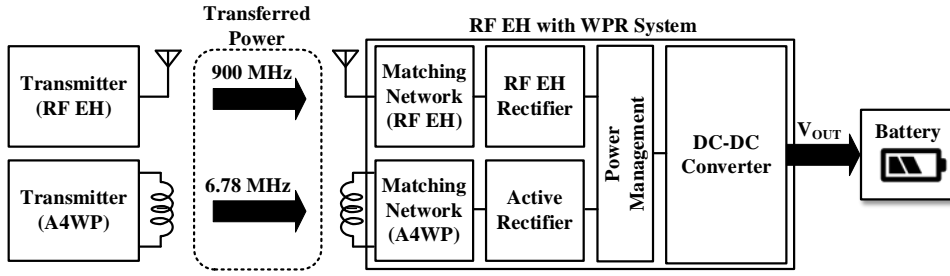
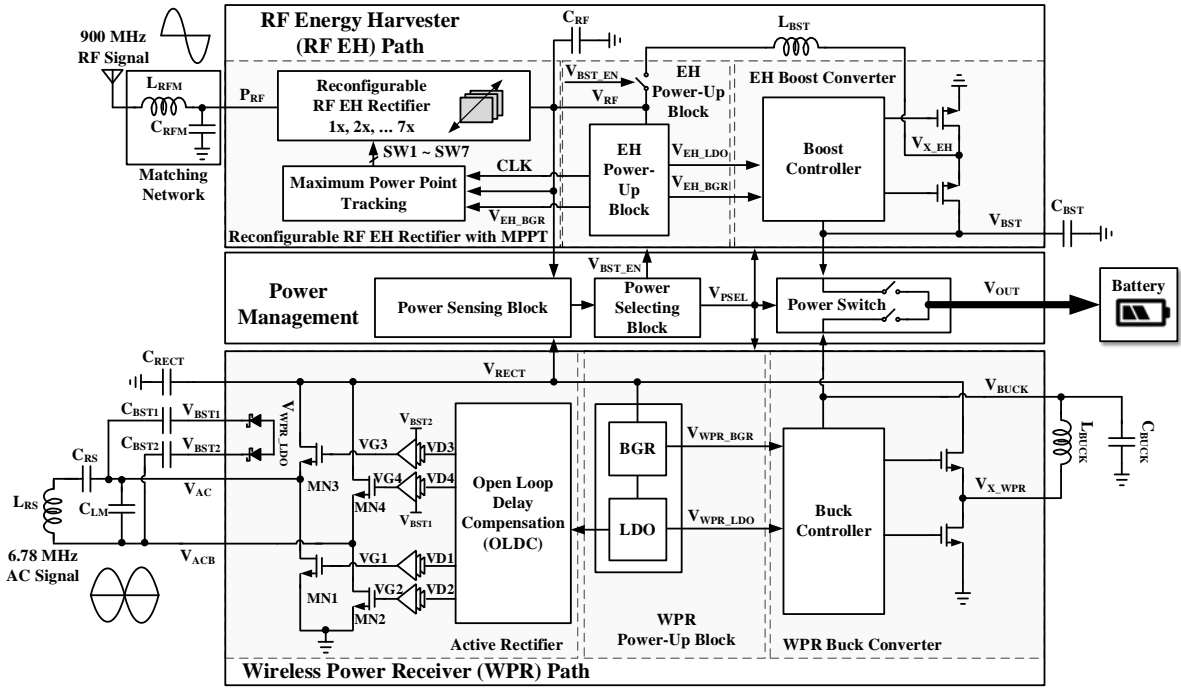Figure 8. Block diagram of RF energy harvesting with A4WP WPR.

Figure 9. Block diagram of the proposed RF energy harvesting with A4WP WPR.

threshold voltage causes flow of leakage current that decreases the overall performance of the rectifier. Therefore, state-of-the-art rectifier designs are required that compensate threshold voltage of the rectifying devices and maintain high PCE of the rectifier over wide input RF power range.

Authors in [10] report a 900 MHz reconfigurable RF energy harvester operating over wide input power range and merge with alliance for wireless power (A4WP) wireless power transfer (WPT). Figure 8 shows the block diagram of the RF energy harvesting with A4WP WPT system. The basic conceptual idea behind this architecture is to increase the power levels and charging distance at the same time. In the environment where A4WP transmitter is deployed offers high power for wireless power receiver (WPR) system and when distance of transmitter from receiver is far, RF energy harvester is utilized to scavenge the such systems have significant effect in terms of power delivery over distance. Figure 9 shows block diagram of the proposed WPR system that is composed of two

power paths i.e. RF energy harvesting (EH) path and A4WP WPR path. The RF energy EH path is composed of a reconfigurable RF-DC converter using maximum power point tracking (MPPT) algorithm, EH power-up blocks and EH boost converter. The reconfigurable RF-DC converter implementing MPPT converts RF power into dc power while maintaining high PCE over extended RF power range. The proposed reconfigurable converter is composed of seven stages for continuously storing the output voltage (V_{RF}) on the storing capacitor (C_{RF}). The V_{RF} is connected to the EH boost converter through the signal V_{BST_EN} from the power management. The output voltage (V_{SBT}) of the boost converter is connected to the battery by power switch. On the other hand, the A4WP WPR path is made up of an active rectifier, WPR power-up block, and WPR buck converter. The high efficient active rectifier converts the AC power received by the receiver coil (L_{RS}) into dc power. An open loop delay compensation (OLDC) in the active rectifier compensates the reverse leakage
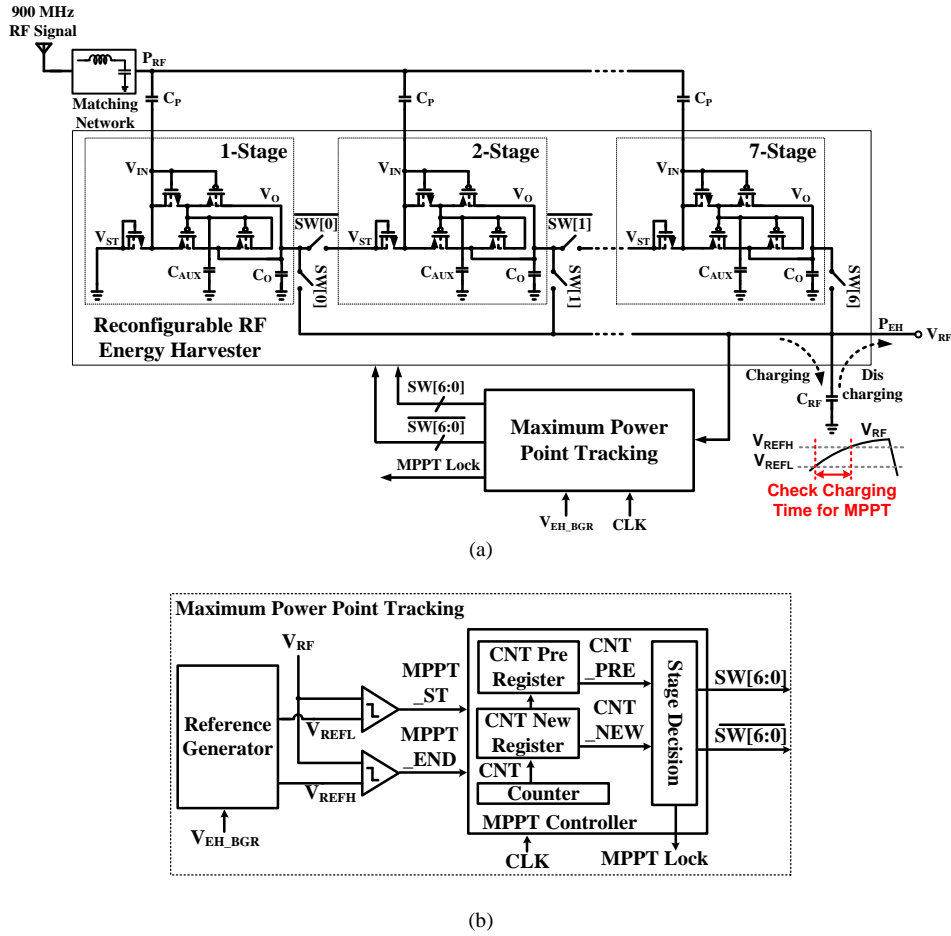
(a)

(b)

Figure 10. Block diagram of (a) proposed reconfigurable RF-DC converter using MPPT for RF EH, and (b) MPPT
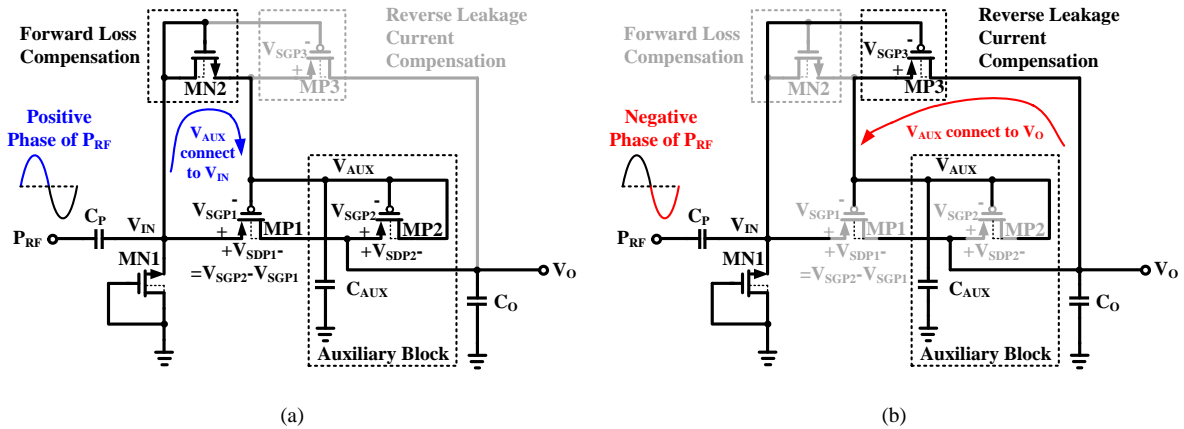

Figure 11. Proposed RF-DC converter for RF EH (a) positive phase, and (b) negative phase.

current caused by the switching frequency of A4WP standard. The output voltage (V_{BUCK}) of the WPR buck converter is connected to the battery by power switch. Figure 10(a) shows the block diagram of the proposed reconfigurable RF-DC converter using MPPT for RF EH. The MPPT is proposed to select optimum number of stages of the RF-DC converter based-on input RF power level by adding and

controlling the switches. Figure 10(b) shows block diagram of the proposed MPPT that is composed of MPPT controller, reference generator, and comparators. In the proposed MPPT, the output voltage is calculated by the charging time of the output capacitor (C_{RF}). The MPPT controller determines the number of stages of the converter based on the charging time. Figure 11 shows the proposed RF-DC
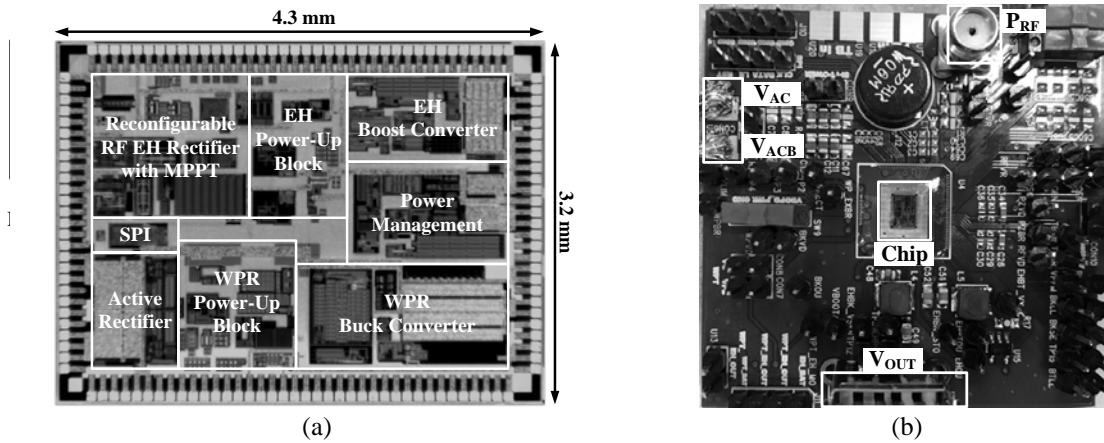
(a)　　　　　　　　　　　　　(b)

Figure 12. (a) Chip microphotograph. (b) Measurement environment of the RF EH with WPR.

(a)　　　　　　　　　　　　　(b)

Figure 13. Measured (a) transient waveform, and (b) Efficiency of the reconfigurable RF-DC converter for RF EH with MPPT at input power of 0 dBm with respect to the number of stages.
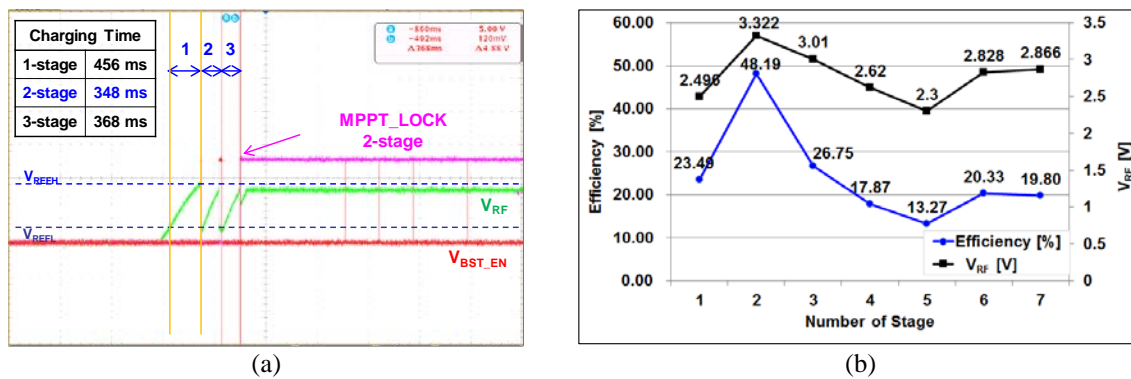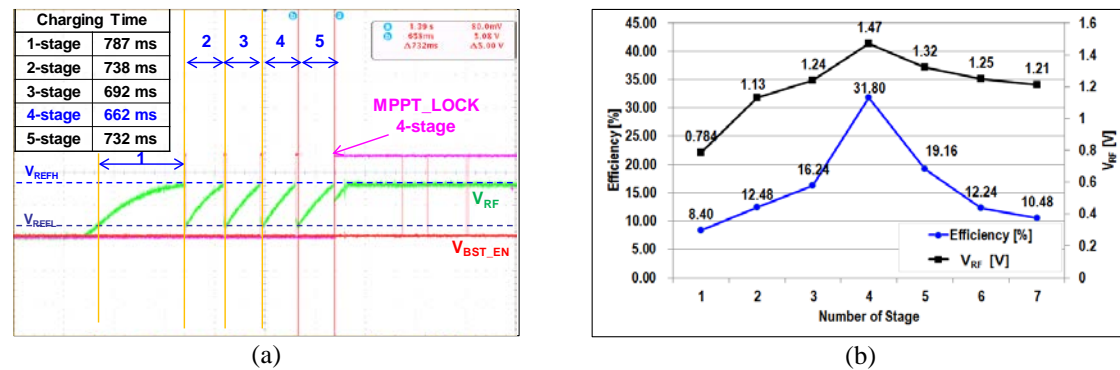

(a)　　　　　　　　　　　　　(b)

Figure 14. Measured (a) transient waveform, and (b) Efficiency of the reconfigurable RF-DC converter for RF EH with MPPT at input power of -20 dBm with respect to the number of stages.

converter using internal threshold voltage compensation (IVC) technique for RF EH. The auxiliary transistor (MN2 and MP3) compensate the threshold voltages of the rectifying devices (MN1, MP1 and MP2) in the main rectification chain by controlling their gate-source voltages.

RF power from the environment. Consequently, Figure 12(a) shows microphotograph of proposed EH with WPR. The die size is 4.3 mm × 3.2 mm including electrostatic discharge with 1P6M 0.18 µm

CMOS. Figure 12(b) shows the measurement setup of the EH with WPR. In the test board, the operations of EH and WPR are measured through the test ports at the output of the EH with WPR (V_{OUT}), the inputs of the EH (P_{RF}) and WPR (V_{AC}, V_{ACB}).

Figure 13(a) and (b) show the measured transient waveforms and efficiencies, respectively, of the RF-DC converter for RF EH when the input power level is 0 dBm. Figure 13(a) shows that when the input power is 0 dBm, RF-DC converter for RF EH locks to

the two-stage by the MPPT operation, achieving maximum efficiency. Figure 13(b) shows that the RF-DC converter for RF EH has the maximum efficiency at two-stage when the input power is 0 dBm. Figure 13(a) and (b) show that the optimum number of stages are two for the input power level of 0 dBm, where corresponding efficiencies are 48.19%.

Figure 14(a) and (b) show the measured transient waveforms and efficiencies of the RF-DC converter for RF EH when the input power level is –20 dBm, respectively. Figure 14(a) shows that when the input power is –20 dBm, RF-DC converter for RF EH locks to the four-stage by MPPT operation, achieving maximum efficiency. Figure 14(b) shows that RF-DC converter for RF EH has maximum efficiency at the four-stage when the input power level is –20 dBm. Figure 14(a) and (b) show that the optimum number of stages are four for the input power level of –20 dBm, where corresponding efficiencies are 31.8%. The performance summary of the reference [10] is reported in Table 4.

5. DESIGNING AND OPTIMIZATION OF ENERGY HARVESTING SYSTEM

The efficiency of the wireless energy harvesting (WEH) system is the integration of efficiencies of individual circuits together. Therefore, efficiency of the WEH system can only be improved by maximizing the efficiency of each individual block. Figure 15 explains the work flow of designing a WEH system [38]. There are several adjustments needed to be done for an optimized WEH system. For instance, operation frequency for harvesting RF energy from environment (to meet requirements of the applicant) significantly affects the efficiency of the WEH system. Secondly, operation range must be specified. For instance, far-field WPT requires high frequency such as 900 MHz, 2.45 GHz, and 5.8 GHz etc., while near-field WPT requires electromagnetic waves of kHz frequency range. Thirdly, the output dc power determines the type of RF energy harvester's topology. Based on these requirements, circuit design especially designing of the rectifier/voltage multiplier is very critical. Circuit analysis with detailed features of different rectifiers have been discussed in the previous sections.

6. CONCLUSION

This survey paper summarizes RF energy harvesting (EH) technology that is being considered a promising alternative for replacing the batteries. A basic EH unit is composed of three modules; an antenna, an impedance matching network, and a rectifier/voltage multiplier. The RF energy is abundant in space due to deployment of the wireless systems. These features make RF energy a reliable source of energy and enabling the low-power wireless devices to be self-sustaining and eco-friendly by harvesting RF energy.

In this paper, a detailed literature on RF energy harvesting technology has been provided to guide for the design of RF energy harvesting circuits. Despite progressive accomplishment in the past recent years, there are still many areas needed to be optimized in RF energy harvesting technology such as adaptive impedance matching network and high PCE of the RF energy harvesters especially at low input RF power level.

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