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REVIEW ARTICLE

RF energy harvesting systems: An overview and design issues

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Abstract
One of the main challenges in implementing sensor devices for internet of things (IoTs), is the means for the operating power supply. RF energy harvesting (RFEH) presents a promising solution as RF power is a suitable choice particularly for cases where solar harvesting is not feasible. However, in spite of RF communication system design being a well-established, there are several challenges poised for the implementation of the RFEH systems especially for harvesting the ambient RF signals. The challenges can be widely categorized as the overall conversion efficiency, bandwidth, and form factor. In this article, an exhaustive survey on the different RFEH system that is reported is carried out and discussed. Important design issues are identified with insights drawn. First, we have presented the challenges in designing antennas for RFEH systems. This is followed by rectifier circuits and matching networks, and eventually a general frame work for designing of ambient RFEH systems is deduced.

KEYWORDS
IoT sensors, RF energy harvesting, rectennas, rectifier, matching circuit

1 | INTRODUCTION

Recent advances in technology has led to the development of Internet of Things (IoT), Wearable Electronics, 5G Wireless Systems, etc, which requires widespread deployment of sensors often positioned at remote places[1] with the capacity of communicating wirelessly with each other. Power is often the limiting factor, as we have to depend on battery sources. This leads to the tedious task of disposing and replacing enormous number of batteries causing environmental pollution.

Energy harvesting (EH) provides a green as well as sustainable solution to this challenge. This involves absorbing ambient energy and converting it into electricity to power up the battery/sensors.[2] Various sources of ambient energy are solar energy, wind energy, tidal energy, electromagnetic energy, thermal energy, mechanical energy, etc. The block diagram of a typical EH system is shown in Figure 1. An energy harvester converts the incident ambient energy into electrical energy. Power management unit (PMU) conditions the electrical energy into a form suitable for a particular application. Solar energy, even though the most abundant of the sources, suffers from intermittent supply.[3] Due to its continuous availability, radio frequency (RF) source is an alternative. However, it suffers from low incident power levels. This can be improved by using a dedicated source and an efficient RF to DC conversion circuit. Low power consumption in the sensors and a widespread availability of RF power makes it as a tangible option for energy harvesting.

The RFEH process involves harvesting electrical energy from RF signals (which could be from a dedicated, ambient, or unknown RF source). The power density from the various RF sources ranges from 0.1 (ambient RF) to 1000 (dedicated RF) $\mu W/cm^2$. The various RF energy sources are, namely, WiFi, WLAN, Digital TV, AM, FM, Bluetooth, etc. Due to its ubiquitous nature, it can be used to power wireless sensor nodes,[4] wireless body area networks,[5] wireless charging systems,[6] and RFID tags.[7] The loss in signal strength is characterized by free space path loss. It depends on frequency of transmitting wave, antenna gain, and distance between transmitter and receiver.[8] For a transmitter and receiver, the power received by the receiving antenna is governed by the Friis transmission formula (Equation (1)).

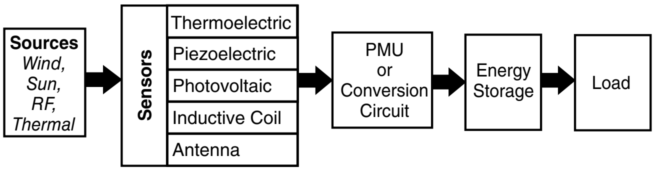


FIGURE 1 Block diagram of energy harvester

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

where, P_R is the received power, P_T is the transmitted power, G_T is the transmitting antenna gain, G_R is the receiving antenna gain, λ is the wavelength of transmitting wave, and R is the distance of separation between transmitting and receiving antenna. The free space path loss is given by,

$$P_L = \frac{(4\pi R)^2}{G_T G_R \lambda^2} = \frac{(4\pi f R)^2}{G_T G_R c^2} \quad (2)$$

$$P_L(dB) = 32.44 + 20\ \log_{10}(f) + 20\ \log_{10}(R) - G_T - G_R \quad (3)$$

where, P_L is the free space path loss, f is the frequency of transmitting wave.

International standards and frequency limits for safe operation of electromagnetic field devices, set by the Electro-technical Commission,[9] has to be adhered to while using these devices for biomedical application to limit the radiation exposure to human body. Frequency range between 1 MHz and 10 GHz penetrates through human tissue and results in an increased temperature as a result of energy absorption. Above 10 GHz, EM fields are blocked by the skin and cause damages like cataract, skin burn, etc., if the incident field is above 1000 W/m^2. To prevent such effects, FCC has set general limits for RF field exposure which in turn limits the incident RF power density available for RFEH systems.

The RFEH can be based on either near-field or far-field energy transfer and signals within the frequency range from 3 kHz to 300 GHz can be used. Near-field RFEH can be accomplished by either inductive coupling[10] or by magnetic resonance coupling.[11] The latter is based on energy transfer involving two coils resonating at the same frequency through magnetic coupling while the former uses two systems resonating at same frequency where the energy is transferred through evanescent wave coupling between them. Incident power density and conversion efficiency are the key features of such a system. However, coupling coefficient which determines the power conversion efficiency (PCE) is dependent on the distance between the coils.[12] Hence, power transfer is limited by distance. In addition, it requires proper calibration and alignment of coils at the transmitter and receiver. Inductive coupling is used for charging mobile phones, wearable electronics while magnetic resonance coupling is used for charging consumer electronics as well as for commercial applications.

TABLE 1 RF power transmission characteristics[15]

Characteristics	Far field transfer	Resonant coupling	Inductive coupling
Field	Electromagnetic (EM)	Resonance (electric, magnetic, or EM)	Magnetic method
Method	Antenna	Resonator	Coil
Efficiency	Low to high	High	High
Distance	Short to long	Medium	Short
Power	Low to high	High	High
Safety	EM	None (evanescent)	Magnetic
Regulation	Radio wave	Under discussion	Under discussion

The RF power transfer at a distance above $\lambda/2\pi$ is considered as far field energy transfer.[13] This enables devices distributed in a wide area to be powered by RF energy. However, incident RF energy is limited by the transmitter and receiver distance as well as low conversion efficiency for low input power.[14] Also, it lags behind in terms of the technology for harvesting ambient RF energy. Table 1 compares near-field and far-field energy transmission. The near-field transfer is used for powering home appliances while far field transfer is still posing many research challenges especially in improving its conversion efficiency.

Rectenna or rectifying antenna, capable of converting RF energy into DC, has been widely used for wireless power transfer (WPT) systems and are also applicable for RFEH systems.[16] It is the rectenna which primarily determines the overall RF to DC PCE. There are two approaches to achieve high PCE. Commonly used approach is maximum power absorption and its delivery to the rectifier circuit. It can be achieved by using large antenna arrays, broadband antennas, etc, but at the cost of large size. The other method would be to introduce a low pass filter in between the rectifier and antenna or by designing harmonic rejection antennas in order to avoid the re-radiation of the signals generated by the nonlinear elements present in the rectifier.

Key components of a rectenna are antenna, harmonic suppression filter, rectifier, voltages multiplier, matching circuit, and load as shown in Figure 2. The antenna receives ambient/dedicated RF signals and the matching circuit is used to match the antenna impedance to the remaining circuit to obtain high efficiency. It also acts as filters for removing re-radiated signals. The rectifier is used for converting AC signals into DC and the number of stages of multiplier circuit determines the output voltage. Since the amplitude of the dc output voltage is lower than the received RF signal amplitude, voltage multipliers are used to boost the output DC.

Main design challenge of the rectenna is its PCE which is the measure of the efficiency of a rectifier in converting

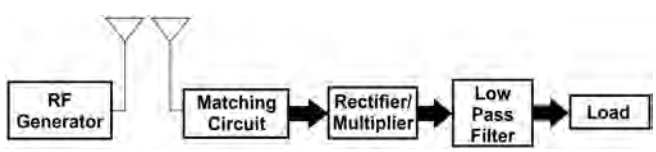


FIGURE 2 Block diagram of an RF-EH circuit

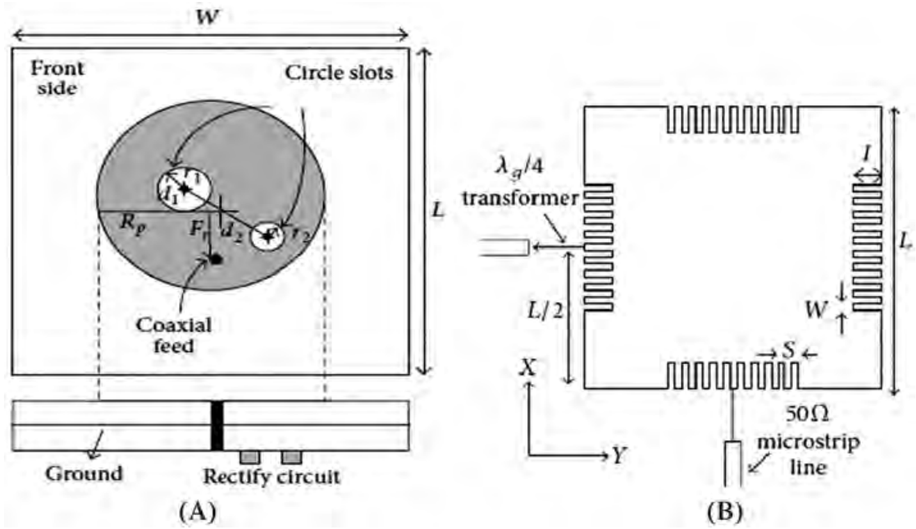


FIGURE 3 Patch antennas used in RF-EH system (A) circular patch with slots inscribed [20] and (B) meandered square patch[21]

received RF energy into DC current. The RF to DC conversion efficiency of the rectenna is given by

$$\eta_{RF-DC} = \frac{P_{DC}}{P_{RF}} \tag{4}$$

where, P_{DC} is the output DC power and P_{RF} is the input RF power. The voltage at the input of the rectifier varies according to frequency and strength of the incident wave which results in variation in the diode impedance leading to a reduced PCE due to impedance mismatch.

Some of the factors affecting the overall power conversion efficiency of RF-EH systems are as below,

- Unpredictable incident RF power availability
- Losses associated with each component
- Limited sensitivity of associated circuits
- Restriction on maximum radiated power
- Distance between transmitter and receiver
- High non-linear dependence of output voltage on the input at low input powers
- Antenna output impedance variations due to variation in incident power and frequency leading to mismatch losses
- Trade-off between bandwidth and efficiency due to miniaturization

The scope of this article is to discuss the various design issues related to the circuit topologies used for RFEH systems. Section 2 presents an overview on antennas used for RFEH system. Section 3 discusses the rectifier and matching networks which is followed by conclusion.

2 | DESIGN ASPECTS OF THE ANTENNAS SUITABLE FOR RFEH SYSTEM

Growing demand for compact devices needs antennas with small form factor. Hence, the printed/planar compact antennas are a suitable candidate. Owing to its low cost, low profile, conformal nature, and microstrip antennas are a good candidate for wireless communication. High PCE is the essential requirement of a good RFEH system. Along with it, some of the other desirable characteristics are miniaturization without degradation in efficiency, circular polarization for minimum mismatch loss, high gain, broad bandwidth, adherence to SAR rating set by FCC, and high tolerance to environmental effects.

2.1 | Antenna size, gain, and bandwidth

With advancement in VLSI technology devices are miniaturized in size and there is a demand for embeddable compact antennas. However, this is achieved at the cost of several features namely bandwidth, efficiency, beamwidth, and gain.[13] Fundamental limit on antenna size and efficiency was set by Wheeler in 1947.[13] He stated that the maximum dimension of electrically small antenna is less than $\lambda/2\pi$ and enclosed in a sphere radius of a with $ka < 1$. The minimum Q required by a compact antenna to have minimum loss is set by Chu as in Equation (5) as given below.

$$Q \geq \frac{1}{k^3a^3} + \frac{1}{ka} \tag{5}$$

Radiation efficiency and antenna size is a trade-off and needs intelligent designs for maximizing efficiency while minimizing size. Antenna Q-factor is given by,

$$Q = \frac{f_r}{\mathrm{BW}} \tag{6}$$

where, f_r is the resonant frequency and BW is the bandwidth. For high Q antenna, the BW will be narrow. If the antenna size is reduced, Q decreases and hence BW increases. But since antenna gain bandwidth product is a constant, increase in bandwidth is associated with decrease in gain. Hence a trade-off must be accomplished between all these parameters.

The main challenge lies in designing miniaturized antennas with minimum performance degradation. The simplest method to achieve this is the use of high dielectric constant materials with low loss. They enable patch size reduction as guide wave length is reduced but they also show narrow bandwidth and low gain due to excitation of surface waves in the substrate layer.[17]

Other methods for miniaturization are to use slots, slits, shorting posts, or geometric optimization. Figure 3 depicts slot/slit loaded patch antennas reported for RFEH applications. Inscribing slots on antenna is a widely used method for miniaturization where the slots are modeled as an equivalent RLC circuit that works according to the Babinet's principle.[18] Due to fringing at the slot ends, the surface current path is increased which leads to size reduction. Slots reduces antenna aperture and in turn the antenna efficiency.[19] In Figure 3A, unbalanced slots[20] at 45° relative to the feed location axis are placed diagonally on the patch. At the operating frequency of 2.45 GHz, it reports 12% size reduction compared with square patch operating at the same frequency.

Another means for achieving antenna miniaturization is meandering slit. Meandered square patch antenna[21] operating at 2.4 GHz reports a size reduction of 48% as shown in Figure 3B. Surface current distribution disturbed by the presence of meander slits force them to increase the current path resulting in the resonant frequency reduction. Impedance mismatch and narrow band operation results in efficiency degradation. Spacing between the turns is also an important criterion, since closely spaced turns can lead to cross polarization which further reduces the antenna efficiency.

High reactive impedance of electrically small antennas are compensated by implementing slots, slits, etc, which results in small radiation resistance. This results in huge impedance mismatch between source impedance and input impedance deteriorating efficiency. External matching circuit can be added to reduce this mismatch, which is achieved at the cost of increase in its form factor.

Narrow band designs are able to achieve high efficiency at resonance frequency but the amount of output power is limited to the narrow resonant frequencies. In comparison, a broadband/multiband design can accumulate more power over the wideband and hence produces more output. Broadband antenna requires complex matching circuits to match the antenna and load at varying input power and load impedances.[22] The simultaneous multi-band input power equals the sum of RF powers at each tone, which can be expressed by,

$$P_m = \sum_{i=1}^{n} P_{fi} \quad (7)$$

P_m is the multiband power, P_{fi} is the power at each tone, and n is the number of tones. The conversion efficiency is given by Equation (8).

$$\eta_m = \frac{P_m - P_{loss}}{P_m} \quad (8)$$

To overcome this limitation, artificial materials that have resonant frequency in the negative and zeroth-order modes, less than resonances obtained in normal material, can be used. So, it helps in size miniaturization without effecting antenna performance.

Metamaterials, Electromagnetic Band Gap (EBG) structures, and defective grounded structures (DGS) are alternative methods to design compact microstrip antennas with reasonable efficiency. Different structures introduced in the ground plane (DGS) of the antenna disturb the current distribution in the ground plane.[23] DGS surfaces are commonly modeled using equivalent LC and RLC circuit. Increase in equivalent inductive part due to the defect introduced leads to high effective dielectric constant and hence achieves a size reduction of patch radiator. It has the ability to act as band stop for certain range of frequencies, enabling increased gain since power from input port is distributed only in the fundamental frequency.[24] But cutting slots on the ground plane introduces back radiation leading to reduced gain in desired direction. Its effect on SAR needs to be considered while using them for wearable applications.

Metamaterials are artificial materials that can have negative permittivity and/or negative permeability at the microwave frequency range.[25] This is achieved by using elements whose size and spacing are small compared with the wavelength of operation. If both the parameters are negative, then it exhibits negative index of refraction. If the permeability and permittivity of the material is near zero they are known as zero indexed metamaterials. They are modeled using different combinations of inductance and capacitance depending on their structures which can be in parallel or series with antenna equivalent circuit. Changing the dimensions of the structure changes the impedance and hence the resonance frequency. Metamaterials as superstrate or using metamaterial surface in between ground and radiator provides higher gain compared with the structures with metamaterial ground due to back radiation. They are good choice for wearable as well as RFEH systems and are able to concentrate energy due to their lens like behavior which helps to increase the gain.

Metamaterial based isotropic electrically small sphere around a radiator increases the overall of efficiency of composite antenna as its impedance matches the antenna impedance with the source impedance[26] without additional matching circuits. An epsilon negative metamaterial which is inductive can be applied as a covering to electrically small dipole to form a composite resonant antenna system. The EBG structures,[27] are periodic structures that control the propagation of electromagnetic waves and suppress surface currents due to their high impedance.[28] This results in enhancing the antenna gain. Parameters like permittivity and dimensions of the EBG structure depends on the resonant frequency. Electromagnetic wave interaction with periodic dielectrics generates stop band and pass band which is an important feature of EBGs. Multiple band gaps are produced by these structures due to periodicity and individual resonances of each element. Macroscopic response like Bragg resonance is governed by these individual resonances while element characteristics are determined by Mie resonance. The process of reflecting all wavelengths when an electromagnetic wave is incident on the material due to its characteristics is known as Mie scattering. So the dielectric inclusions create displacement current based electric or magnetic resonance and occur when metallic inclusions are in contact with electromagnetic wave of larger wavelength. Maximum bandgap is obtained when Mie and Bragg resonance occurs simultaneously. It provides the advantage of suppressing and directing radiation resulting in enhanced efficiency. Mushroom like EBG based planar inverted- F antenna with metallic patches, ground plane and connecting pins operating at (2.1-2.4 GHz) was developed by Zhao.[29] The structure has 6 dB reduction in backward radiation compared with conventional PIFA.

2.2 | Antenna polarization

Capability to radiate as well as receive RF energy in any plane with minimum loss makes circularly polarized (CP) antennas an important candidate in RFEH system.[30] It improves the PCE by reducing polarization mismatch losses. But its limitation is that the methods used to achieve CP radiation results in narrow bandwidth.[31] Corner truncation, spur lines, slits, stub loading, and cross shaped slots, are the few methods used to achieve CP. For single feed techniques, the antenna is fed at 450 with respect to the perturbation for achieving CP radiation. It has the advantage of simple and compact structure.

Simplest method to achieve circular polarization is corner truncation, that is, truncating patch corners. It leads to asymmetric current path along the diagonal length that produces two different resonance frequencies at 900 phase difference generating CP[32] but at the cost of reduced bandwidth and efficiency. Stacked structures, artificial magnetic conductors, and metamaterials are commonly used methods to overcome the narrow bandwidth limitation and for achieving high gain.[33]

One of the widely used methods to improve bandwidth of a CP antenna is the stacked patch concept. In this method, parasitic patch element of same dimension as that of patch is used.[34] A wide bandwidth is achieved because of the electromagnetic coupling between the driven and the parasitic elements for generating resonances that are close to each other but the limitation is increase in the overall size.

The annular slot ring around a circular patch for CP is reported in Ref. 35 which achieves 25% RF to dc conversion efficiency at 0 dBm input power but it reduces drastically at −20 dBm input power. It uses thin and flexible substrate and suffers from bending losses which reduces it efficiency. Table 2 compares the miniaturized antenna designs[20,36–40] reported for RFEH systems. From Table 2, the metamaterial based patch antennas shows a better performance compared with other structures. Based on the discussions so far, we can conclude that metamaterial structures are a good candidate for RFEH as they are able to achieve CP and miniaturization without performance degradation.

2.3 | Harmonic rejection

Non-linear components in rectennas are responsible for generating the harmonics of the fundamental frequency[41] which are re-radiated and cause electromagnetic interference with the antenna and nearby circuits resulting in performance degradation. To overcome this low pass filters is added between antenna and rectifying circuit but at the cost of increased size. Several antenna designs with harmonic rejection called filtennas are proposed for RFEH systems. They maximize the power received at the desired frequency and suppressed harmonics through structural modifications, like stub, slit, DGS, etc. The method is selected based on current distribution on the patch radiator, desired gain, efficiency, etc.

The circular slot antenna[42] in Figure 4A is an example for harmonic rejection. The multi-frequency rejection is achieved by inscribing single slot on ground plane. The DGS structure is actually a resonant slot placed on the ground plane. This structure has its own resonant frequency which acts as a stop band rejecting the higher harmonics. Right angle slits inscribed in a circular patch[43] with peripheral cuts is shown in Figure 4B. The 4 right angled slits, arranged symmetrically at the patch center, elongates the current path by creating disturbance, and degrading higher order modes without affecting the fundamental mode.

2.4 | Re-configurability

Frequency diversity and polarization diversity in wireless communication led to the development of reconfigurable antennas for RFEH systems.[30] Re-configurability is achieved by changing the antenna structure which in turn changes its radiation properties. It allows for bandwidth enhancement and size reduction as single antenna can be operated at different frequencies.[44]

Re-configurability can be achieved by cutting slots on the radiator surface and connecting it by switches. Based on the bias provided, the electrical length of the radiator as well as its current distribution is changed enabling frequency and polarization diversity. Frequency reconfigurable patch antenna is achieved by inscribing slots in rectangular radiator and connecting the patch surface using PIN diodes.[45] It suffers from back radiation and so the gain is low in both resonating frequencies (1.6 and 2.4 GHz).

Shao et al. achieved wide impedance match using a 2 × 2 beam steered phase array.[46] Beam steering is achieved by changing the feed position mechanically as shown in

TABLE 2 Comparison of miniaturized antenna designs

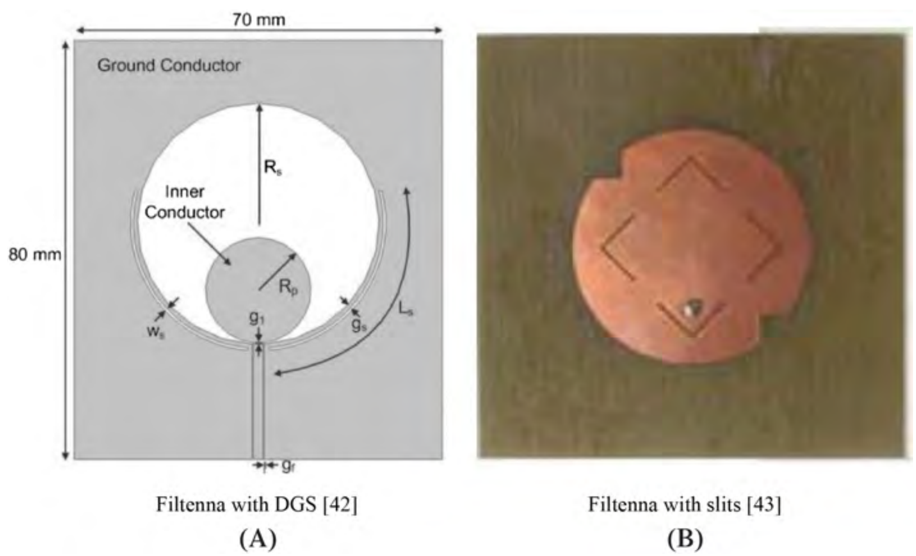
Antenna	Size reduction technique	Substrate	Frequency (GHz)	Gain (dBi)	Pol	BW (MHz/%)	Efficiency	Size (a × b mm^2)	% size reduction
Circular patch antenna[20]	Inscribed circular slots	FR4	2.45	3.36	CP	137	Efficiency degradation due to aperture reduction	60 × 60	12
Cross shaped slotted antenna[36]	Cross shaped slots inscribed along diagonal	Rogers R04003C	0.9	3.93	CP	<2%	Reduction in the efficiency due to larger cross perimeter to achieve CP	90 × 90	10
Circularly polarized slotted patch antenna[37]	Square ring slots placed symmetrically on diagonal of patch	Arlon AD 350	1.6	4.65	CP	90	High gain can be achieved at the high cost of substrate	35 × 35	22
Metamaterial based patch antenna[38]	Circular slotted corner truncated MSA with reactive impedance surface	FR4	2.45	4.6	CP	140	Better efficiency due to impedance matching and improved front to back ratio	35 × 35	22
EBG based printed patch antenna[39]	Modified mushroom based EBG structure	RT Duroid 5880	5.6	13.44	LP	31.75%	88.75%	16.4 × 16.4	89compared with mushroom EBG structure
Planar broadband monopole antenna[40]	Trapezoidal–elliptical radiator	FR4	10	5	LP	154.2%	82%	25 × 25	65compared with square patch operating at 2.45 GHz

Figure 5. By adjusting the wave traveling path inside the transmission line, phase difference between radiating elements are controlled. However, the impedance bandwidth is narrow and automatic beam steering is not achieved.

Table 3 compares some of the reconfigurable antennas with harmonic rejection capability[47–51] reported. From the table, it can be concluded that filtenna designs shows better efficiency, as most of the incident power is concentrated at the fundamental frequency, rejecting the harmonics that are re-radiated makes them suitable candidate for RFEH systems. So by combining metamaterial radiator with filtennas, it is possible to achieve high efficiency.

2.5 | Hybrid energy harvester

The hybrid energy harvesters are systems that can harvest energy from two different sources like sun and radio frequency energy.[52] They are developed to provide better output than a single energy harvester. Kyotori presents a solar/RF energy harvester which achieves a better power output than a narrow band RFEH system. Solar cells are placed on the patch where current distribution is minimum as shown in Figure 6. The dc connections of solar cell have significant effect on antenna performance. The amount of power obtained at the output decays depending on the variations in solar radiation and the size of the antenna is large compared



Filtenna with DGS [42]
(A)

Filtenna with slits [43]
(B)

FIGURE 4 Filtenna examples

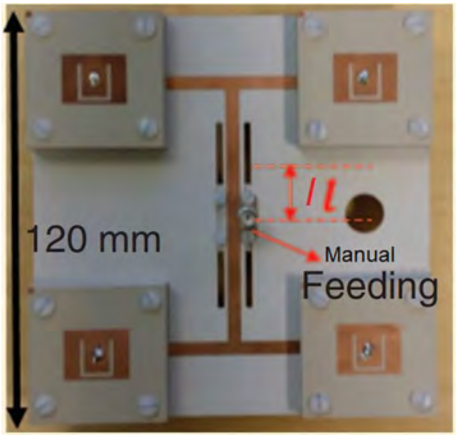


FIGURE 5 Beam steered array[46]

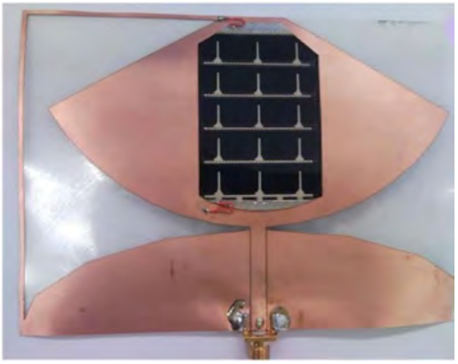


FIGURE 6 Solar/RF hybrid energy harvester[52]

with other harvesting circuits. The solar cells are also integrated with F antenna in Ref. 53 where they act as ground plane for the antenna. However, it shows a narrow band performance.

3 | DESIGN CONSIDERATIONS FOR RECTIFIER AND MATCHING NETWORK

The energy inefficiency in RFEH systems is mainly due to power leakage during transmission. Impedance matching network enables maximum power transfer between antenna and the load. Rectifier and remaining circuit is considered as load in the RFEH system. When there is an impedance mismatch, the incident wave gets reflected at the load which leads to reduction in efficiency. A matching network ensures identical impedance between the source and load. They can also act as a low pass filter to reject higher order harmonics generated by the rectifying circuit which can be re-radiated by the antenna creating loss.[54] Hence, a matched filter is desired between the rectifier and the antenna.

Non-linear devices are generally modeled using their small signal equivalent in order to approximate the behavior with linear equations.[55] This is not applicable to the RFEH system due to the presence of a large input signal without any DC bias, which makes the rectifier to operate in different regions of operation. This results in impedance variation of the rectifier for varying the input power as well as the load leading to degradation in PCE. Characteristics of the matching circuit are that they should be able to match the load impedance with the antenna impedance at any frequency, load resistance and input power. They should have a small form factor as well as wide bandwidth of operation. Main design challenge is that the antenna impedance changes with load as well as input power. Tuning circuits can be used to tune impedance to a desired value. Bandwidth improvement is provided by second order matching circuit than first order.[56] But bandwidth decreases rapidly if the order is increased beyond two. Lumped elements as well as distributed microstrip lines are used for implementing matching circuit. Compared with distributed line, lumped element based matching circuit has lower Q offering wider bandwidth. Due to the parasitic effects associated with lumped

TABLE 3 Comparison of re-configurable and harmonic rejection antennas

Antennas	Features	Pol	Harmonic rejection	Frequency (GHz)	Bandwidth (MHz)	Gain (dBi)/ efficiency (%)	Reconfigurable
Off center fed dipole antenna[47]	Dipoles are modified into bow tie stubs	CP	No	1.8, 2.5	0.7	3.5	No
Switchable Filtenna[48]	3 loop resonators in UWB antenna	LP	Yes	OFF state 3.2-11 ON state 3-3.5 4-5.7 6.2-11	7 0.5 1.7 4.7	OFF state 4.33, 96% ON state 3.8	Yes
Polarization reconfigurable monopole antenna[49]	Circular patch with reconfigurable feed antenna	One LP, two CP	No	5.07-5.86	0.79	3	Yes
Metamaterial based multiband antenna[50]	Antenna loaded with interdigital capacitor slots	LP	No	OFF state 7-8.5 ON state 3.8-4.2 5.5-6 6.8-8.5	OFF state 1.5 ON state 0.4 0.5 1.7	OFF state 1.93 ON state 1.78 1.63 2.32	Yes
T shaped slot wide band antenna[51]	T shaped conductor line connected to patch	CP	Yes	2-3.5	1.5	5.5	No

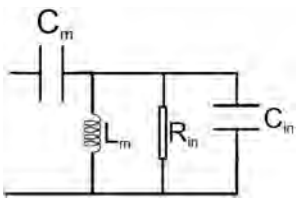


FIGURE 7 L section matching network

elements, they are not preferred at higher frequencies. Lumped circuits used for matching are commonly T network, pi-network, shunt inductor, L-network, gamma matching network, band pass filter, etc.

Commonly used matching network for low power regimes is simply two components L section matching network as shown in Figure 7 as they provide impedance match with minimal loss.[57] The inductor L also preboosts the input signal reaching the rectifier. Due to high quality factor Q they suffer from narrow bandwidth. Lm and Cm of the matching network are designed as follows. Source impedance is 50 Ω.

$$R_S = R_{in}\left(\frac{1}{1+Q^2}\right) \tag{9}$$

The quality factor, Q is given by

$$Q = \sqrt{\frac{R_{in}}{R_S} - 1} \tag{10}$$

The quality factor expressed in terms of imaginary part of impedance is

$$Q = \frac{Im(Z)}{Re(Z)} \approx \frac{R_{in}}{\omega_0 L_m} - \omega_0 C_{in} R_{in} \tag{11}$$

L_m of matching network is calculated as

$$L_m = \frac{R_{in}}{\omega_0 (Q + \omega_0 C_{in} R_{in})} \tag{12}$$

C_m is calculated by equating imaginary part to zero

$$C_m = \frac{R_{in}}{L_m (R_{in} - \mathrm{R_S})} \frac{1}{\left(\omega_0^2 - \frac{1}{L_m C_{in}}\right)} \tag{13}$$

L section matching network provides restriction on tuning of two components. This can be overcome by adding additional L to the circuit transforming it to T or Pi section network. Pi type matching network is shown in Figure 8 with diode replaced by equivalent impedance. Pi type networks are superior to L type networks since they provide an extra degree of freedom with greater amplitude of resonance. The output voltage varies rapidly with frequency compared with L section as shown in Figure 9A because of the presence of frequency dependent element.

Design equation for Pi-network is given below,

$$Z_{in} = \left\{\left[(R_L - jX_L) \parallel \left(\frac{1}{j\omega C_2}\right)\right] + j\omega L\right\} \parallel \left(\frac{1}{j\omega C_1}\right) \tag{14}$$

The parasitic losses associated with passive elements increase with frequency as well as capacitor behavior will be changed into inductance as frequency is increased. From Figure 9B, it can be observed that L value is changed drastically as Q is increased. So that high Q circuits can be easily implemented due to low L values.

The theoretical limitation of impedance matching bandwidth to parallel load impedance is provided by Bode[59] and Fano,[60]

$$\int_0^\infty ln \frac{1}{|\Gamma(\omega)|} d\omega < \frac{\pi}{R_{load} C_{load}} \tag{15}$$

For series load,

$$\int_0^\infty \frac{1}{\omega^2} ln \frac{1}{|\Gamma(\omega)|} d\omega < \pi R_{load} C_{load} \tag{16}$$

where, Γ is the reflection coefficient. Γ is ideally zero for the designed bandwidth range Δf and 1 for outside this bandwidth. Hence,

$$\Delta\omega ln \frac{1}{|\Gamma(\omega)|_{\min}} < \frac{\pi}{R_{load} C_{load}} \tag{17}$$

$$\Gamma = e^{-\frac{1}{2\Delta f R_{load} C_{load}}} \tag{18}$$

So according to Bode and Fano, efficient matching is achieved at the cost of bandwidth. Table 4 shows comparison of some matching networks.

Broadband impedance matching circuits with two branching sections are presented in Ref. 61. Radial stub, short stub and a 6 nH chip inductor are incorporated in the upper branch to obtain impedance matching around the frequency range from 1.8 to 2.5GHz. The compact rectennas can also be achieved by eliminating matching networks. Song et al., have developed a rectenna system without matching network.[47] It is achieved by changing antenna to a high impedance antenna that can directly conjugate match with the specific rectifier impedance. The antenna is an off center fed dipole antenna operating at (1.8-2.5 GHz) with imaginary part of impedance varying between 0 and 300 Ω in the desired band. The rectenna is able to achieve a conversion efficiency of 75% at 0 dBm input power which is high compared with other broadband rectennas reported so far.

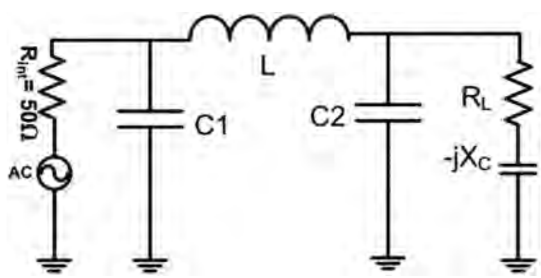


FIGURE 8 Pi section matching network

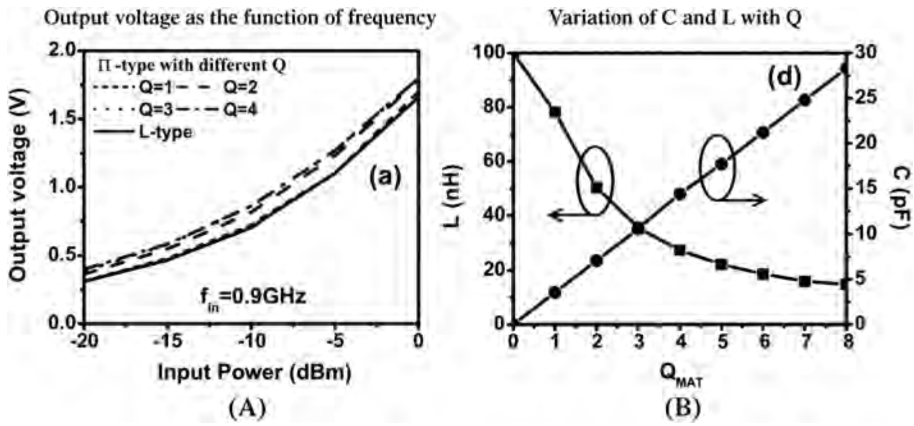


FIGURE 9 Comparison of L and pi networks[58]

The RFEH circuits are characterized by two metrics sensitivity and efficiency. The efficiency, expressed as PCE, is the measure of ability of a rectifier to convert the incoming RF energy into DC current. PCE of a diode changes with input power variations. The RF to DC conversion efficiency of the rectenna is given by Equation (4). The voltage at the input of the rectifier varies according to frequency which results in variation in the diode impedance leading to efficiency degradation due to mismatch.

Figure 10 gives the variation in efficiency with respect to input power. In low power regions, as shown in Figure 10, the efficiency is small because the forward drop of diode is greater or comparable to the voltage swing. PCE is also affected with the generation of higher order harmonics.[62] As the voltage swing exceeds break down voltage, V_{br} the efficiency deteriorates sharply. Break down voltage of the diode determines the critical input power given by $V_{br}^2/4R_L$, R_L is the rectenna load resistance.

Rectifiers are classified based on the components used as diode based and MOSFET based.

3.1 | Diode based rectifiers

Diode based rectifier circuits are most commonly used due to its low forward voltage drop compared with CMOS circuits. Single stage voltage doubler is a widely used circuit for high and medium power application. Schottky barrier diodes are commonly used in rectenna applications.[22] Diode with a lower forward voltage is the best choice since it can achieve higher PCE. High efficiency and high output power at low input voltage makes single stage voltage doubler rectifier a good choice for RFEH system. Figure 11 shows that for achieving high efficiency at low input power, low turn-on threshold is needed. However, low threshold voltage lowers the break down voltage. The maximum output power level can be increased with large reverse break down voltage. PCE depends on zero bias diode junction capacitance (C_{j0}), diode break down voltage (V_{br}), series resistance (R_s), switching speed of the diode, and low threshold voltage. It is also affected by losses in the substrate as well as with the transmission lines.

TABLE 4 : Matching network comparison

Matching network	Features	Application
L section	Simple structure with two components. Limited tunability.	RFID, sensor networks
Π section	Frequency dependent behavior	RFID, small impedance antennas
Transformer coil	Lower die area, robust	High impedance antennas

Single stage voltage doubler circuit is shown in Figure 12. During negative half cycle, the diode D2 is forward biased and it acts as a short circuit. So no current flows through D1, and energy is stored in C2. Series diode D1 rectifies the positive half cycle and energy is stored in C1. The energy is transferred from C2 to C1 during next period and discharged to RL. The output voltage is the difference between twice the input voltage and diode drop.

Cockroft Walton voltage doubler could produce an output voltage that is three times greater than the applied voltage.[64] The main disadvantage is the high coupling voltage drop which results in lower gain for the circuit. Since the output capacitors are holding a floating charge it is very difficult to store charge individually for other applications.

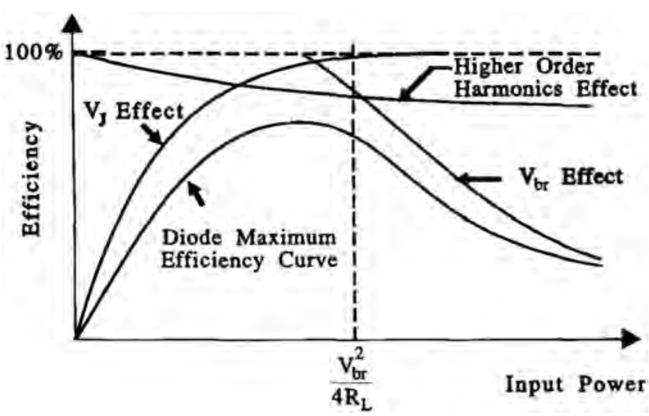


FIGURE 10 Input power versus efficiency[62]

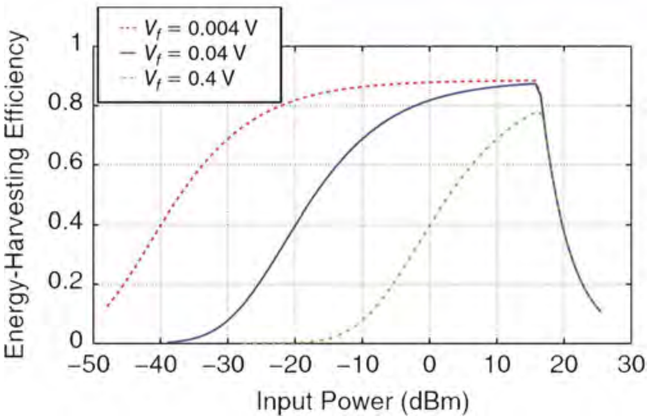


FIGURE 11 Performance variation[63]

Another type of charge pump is Dickson charge pump which is shown in Figure 13. It requires clock pulses as input for capacitors and is suitable for low voltage applications. The main drawback is the requirement of clock pulses for capacitors limiting its application in high voltage cases.

3.2 | MOSFET based rectifiers

Limitation of diodes can be overcome by MOSFET technology. Major advantage of MOSFET is the fast switching speed but is susceptible to thermal runaway and EMI. It also requires a high threshold voltage which limits the efficiency of EH circuits.[65] Many compensation methods are used to overcome this disadvantage. Dickson charge pump is also incorporated using MOSFETs is shown in Figure 14. They are fully compatible with CMOS technology. The voltage loss across MOSFET devices leading to low efficiency. This is further deteriorated by reverse leakage current. Another major disadvantage of MOSFET based circuits is that as frequency increases efficiency decreases due to increased power loss in the MOSFET occurring from the reverse leakage current.[66]

Harmonics and inter modulation products are produced by diodes due to its non-linear behavior reducing power conversion efficiency. Increased incident power levels reduces efficiency due to increased parasitic losses due to harmonic generation. So there is a tradeoff between all the above parameters. For low power handling applications, low threshold voltage diodes are preferred while high reverse break down voltage diodes are preferred for high power applications.

One method for threshold compensation is the cross-coupled technique[67] which is shown in Figure 15. It allows for simultaneous working in charging and discharging phase through control gate circuit. Higher efficiency is achieved through threshold voltage compensation. The main disadvantage is that to achieve high efficiency large number of stages is required which makes the circuit more complicated and bulky. Another method is cascaded cross-coupled voltage multipliers shown in Figure 16. It combines the voltage doubler with cross-coupled multiplier. The output DC voltage is given by $V_{OUT} = n(2V_{in} - V_{th})$. The output voltage ripple increases as number of stages increase leading to efficiency reduction. In Ref. 68, a rectifier is designed to power RFID tag. The RF signals are passed from a tag antenna into an impedance matching network. It uses a half wave rectifier of n stages. The incoming power is passed into next stage only during one half cycle. The system works well at a distance of 3 m from the source for a short duration. Its main disadvantage is that as number of stages increases the size of the circuit increases and leads to efficiency degradation. System works well only for high input power level applications.

To improve the efficiency of the entire system, an effective way is to use a passive network to boost the voltage amplitude at the input of the charge-pump circuit.[69] Buck boost converter is used in between antenna and rectifying circuit to improve efficiency. Input impedance can be made independent of load resistance and input power by using converter controlled by pulse oscillator circuit. Inductors, diode, switching elements, and capacitors are the main components that are used in discontinuous conduction mode to have stable input impedance. If energy is harvested using multiple antennas or rectennas a dc combining circuit must be used to get an overall DC output voltage.

Various rectifier topologies[44,70–86] are compared in Table 5. From this table, we find that diode based rectifiers provide better efficiency compared with MOSFET, as they suffer from high threshold voltage. Threshold voltage compensation in MOSFETs give rise to reverse leakage current

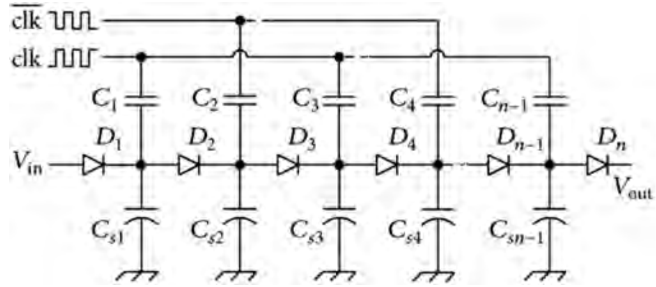


FIGURE 13 Dickson charge pump[64]

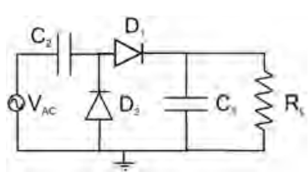


FIGURE 12 Single stage voltage multiplier[22]

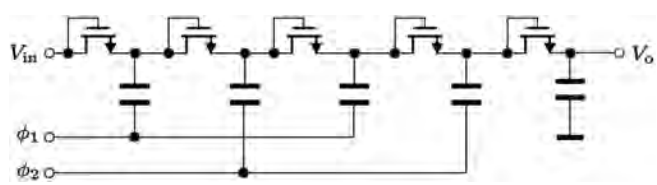


FIGURE 14 MOSFET based Dickson charge pump[66]

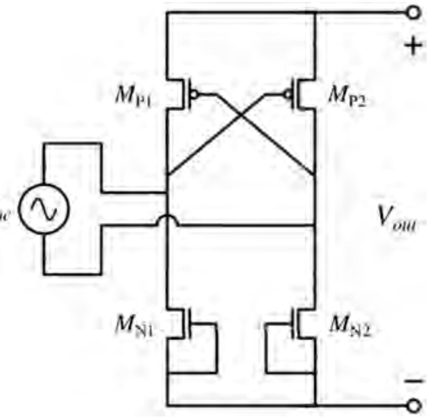


FIGURE 15 Cross-coupled voltage multiplier[67]

which further deteriorates efficiency. Most of the rectifier implementations are based on CMOS technology. Even though it can work with lower RF voltage compared with HSMS[87] and SMS[88] technology, efficiency is inferior to other technology. Using HSMS and SMS technology efficiency above 40% can be achieved at −20 dBm input power. Similarly, a single stage voltage rectifier circuit provides greater efficiency than multistage rectifiers because of less parasitic losses.

4 | RECENT TRENDS IN RECTENNAS

Most of the reported work is focused on ISM bands of 2.45 and 5.8 GHz due to the wide spread deployment of WiFi routers. Some are done for GSM 1800, GSM 900, and 2100 MHz frequencies. Due to growth in wireless communication and recent developments toward 5G, rectennas operating at 24 and 94 GHz enabling millimeter wave communications are also reported.

Commonly used antennas for rectennas are categorized into omnidirectional, compact, and high gain antennas like microstrip antenna, frequency independent antennas, substrate integrated waveguide antenna, dielectric resonator antennas which are modified further using artificial materials to achieve small form factor, wide bandwidth, and high efficiency. Most of the linearly polarized antennas are modified to obtain circular polarization to reduce mismatch losses. Low loss substrates like RT Duroid 5880, Rogers R4003C, glass, Arlon are used to fabricate rectenna to achieve higher efficiency compared with FR4. Planar bow tie cross dipole antenna with omnidirectional radiation pattern is proposed in Ref. 22. Dual linear polarization, wide bandwidth of 400 MHz, and bidirectional radiation pattern are its features. Bow-tie Antenna is further modified into frequency independent linearly polarized cross dipole antenna to achieve much wider bandwidth. The proposed rectenna is optimized only for an input power of −5 dBm and it does not consider load variations also. It operates in 2.45, 2.15, 1.85, 0.9, 0.7, and 0.55 GHz and achieves an efficiency of 67% at −5 dBm input power level. Two L-Probe microstrip patch antennas with single port is stacked back to back with adjacent ground fabricated on Rogers 3003 is proposed in Ref. 89. Patch is suspended over the ground with thick air gap in between them to improve bandwidth. L probe feed is used to easily integrate rectifier with the antenna. This structure resonates at 0.8-2.3 GHz. However, its rectifier circuit resonates at only 0.9, 1.8, and 2.4 GHz. It has maximum efficiency of 45% at −10 dBm input power for an operating frequency of 0.9 GHz.

Multiport rectenna concept is the latest trend as overall output voltage can be increased by combining multiple ports. Three port pixel rectenna operating at GSM 1800 MHz band proposed by Shen[90] achieved an efficiency of 19% at an input power of −19 dBm. It consists of rectangular grid with 15 × 15 square pixels fabricated on Rogers RO4003C substrate. DC combining from three ports enabled broad beam width making it possible to receive power from all directions while the overall size of the antenna is large as well as lesser efficiency at low input powers due to losses triggered by mutual coupling.

Differential rectenna operating at 2.1, 2.4, and 3.3 GHz achieved an efficiency of 53%, 31%, and 15.56%, respectively, at −15 dBm input power.[91]Two-layer square antenna that is electromagnetically coupled through slots achieved multiband characteristics. It is fed differentially at the bottom layer. A large reflector is used at the antenna backside to

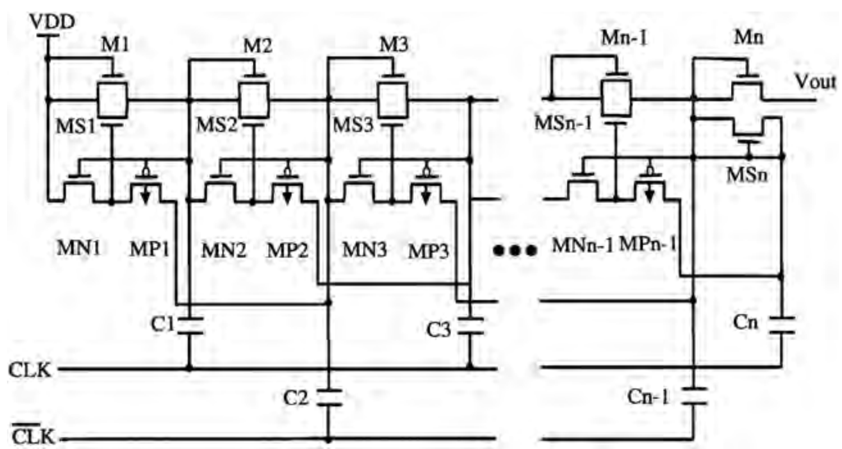


FIGURE 16 Cascaded cross-coupled voltage multiplier[68]

TABLE 5 Rectifier for RFEH

Rectenna	Rectifier	Frequency (GHz)	OLR (kΩ)	Output voltage (V)	Efficiency
Ref. 44	Diode based Grienarcher voltage multiplier	0.9, 1.8, 2.1, 2.45	11	1.5 at pin = −10 dBm	55% at pin = −10 dBm
Ref. 70	Single stage diode based voltage multiplier	2.45	Nr[a]	5.5	75% for pin = 19 dBm
Ref. 71	VD type rectifier	2.45	1	6.1	55% for R_L = 1 K
Ref. 72	Single stage diode based voltage multiplier	0.700-0.900 (broadband)	Nr[a]	0.5 at pin = −6 dBm	50% at −10 dBm input power
Ref. 73	Single stage diode based voltage multiplier	0.45-0.85 (broadband)	1.5	Nr[a]	25%at −20 dBm
Ref. 74	9 stage Dickson charge pump based on MOSFETs	0. 84-0 0.975 (broadband)	Nr[a]	2 at pin = −16 dBm	60% at pin = 10 dB
Ref. 75	5 stage MOSFET based rectifier for high power and 10 stage rectifier for low input power	0.9	Nr[a]	1.5	Nr[a]
Ref. 76	16 stage Cockroft Watson multiplier	0.45	1 M	3	10.94% at pin = 63.1 W
Ref. 77	Diode connected zero threshold NMOS transistor	0.9	500	1.52	13% at pin = −14.7 dBm
Ref. 78	Single stage shunt diode rectifier	1.8-2.5 (broadband)	0.5	Nr[a]	60% at pin = 0 dBm
Ref. 79	Schottky diode based rectifier	2.45	2.8	3 at pin = −15 dBm	60% at pin = −15 dBm
Ref. 80	Schottky diode based rectifier	2–18	0.1	Nr[a]	20% at pin = 0.1 mW/cm^2
Ref. 81	Full wave Greinacher circuit	1.8	1.2	1.8 V at pin = 10 μW/cm^2	60% at pin = 10 μW/cm^2
Ref. 82	0.18 μm CMOS	0.95	1	Nr[a]	Nr[a]
Ref. 83	0.18 μm differential CMOS	0.953	Nr[a]	1.8	67.5% at −12.5 dBm
Ref. 84	Bridge rectifier (HSMS2820)	0.9-2.45	200	6.5	78% at 23 dBm
Ref. 85	HSMS 285C	0.945	0.1	4.5	52% at −10 dBm
Ref. 86	Sub rectifier circuits with HSMS 2822 and HSMS 2860	2.4	0.82 and 1.2	Nr[a]	50% at 0-20 dBm

[a] Not reported.

achieve high gain but at the cost of increased overall size. Meander line-based stub along with butterfly stubs provided the impedance matching between antenna and rectifier circuit at these frequencies and for input power of −5 dBm.

Low radiation loss, low dispersion, and easy integration of active and passive devices makes CPW transmission lines a suitable candidate for rectenna feeding. It also helps to achieve wide bandwidth for antennas and can easily match rectifier impedance. Patch antennas are most preferred option for rectennas owing to their low cost, light weight, and easy integration compared with dipole and monopole antennas. Spiral or frequency independent antennas are preferred over YagiUda to make wide bandwidth antennas with an impedance variation independent of frequency. Slot antennas are used to achieve compactness as well as circular polarization. Metamaterial based antennas provide high efficiency due to their radiation concentrating capability and surface wave reduction.

5 | METHODS TO DESIGN EFFICIENT RFEH SYSTEM

The overall PCE of RFEH system is determined by individual component efficiency. So maximum efficiency can be obtained by maximizing each individual efficiency and consolidating them with minimum loss.

- Appropriate operation frequency and range determines the efficiency of the system. The required output power determines the rectifier topology to be selected.
- Highly efficient circularly polarized compact antenna with wide bandwidth and wide beam width for receiving maximum RF power with minimum loss.
- A compact matching network design that can match the antenna impedance with the remaining circuit irrespective of input power, frequency and load variation.
- Rectifier topology and number of stages must be determined depending on application and the required output voltage.
- If the input RF voltage is low, harvest power from multiple sources simultaneously or use a boost converter in between antenna and rectifier circuit. Use DC combining circuit if multiple antennas or rectennas are used to obtain combined DC output.
- If the output DC voltage is low, use a voltage booster to improve the output DC voltage

6 | CONCLUSION

Different antenna topologies for RFEH system has been compared based on different parameters. The antenna selection for energy harvesting depends on the type of application like 5G, WSN, RFID, etc. For IoT based sensors, compact antenna with high gain and wide bandwidth is preferred. For ambient RFEH system, an antenna with omnidirectional radiation pattern or an antenna array is preferred so it can receive signals from all directions improving PCE of the system. For wearable applications back radiations from antenna should be minimum demanding a perfect ground plane. From the above discussions, circularly polarized metamaterial based re-configurable antennas are preferred for RFEH system to achieve high conversion efficiency. Various rectifier configurations have been also compared and discussed various issues to boost the efficiency. The rectifier topology selected should be able to achieve high conversion efficiency even under load variations as well as input power variations.

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