RF Electromagnetic Energy Harvesting for Smart Sensors in Smart Communication Systems- A Review

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Abstract:- In the smart communication era, advancements in miniaturization technology have led to the development of RF energy harvesting due to the ambient/dedicated RF energy availability. It contributes to the realization of more sustainable, autonomous, eco-friendly, and efficient sensor nodes in the far-field communication links. The deployment of RF energy harvesting system is confronted with a number of obstacles, including power transformation efficiency, DC output voltage, and sensitivity. In this work, a detailed review of antenna design, impedance matching, and rectification efficiency are discussed for the development of an energy-efficient RF energy harvesting system.

Keywords*:* Radio Frequency, Energy Harvesting, sensors, self-sustainable.

1. Introduction

From the past few years, usage of wireless communication has drastically increased due to development of wearable gadgets, 5G wireless devices, wireless sensor networks (WSN), Internet of Things (IoT), etc., where deployment of sensors at remote locations are required for potential communication between each node [1]. In this type of networks, sensors are dependent on battery sources for power. Usage of batteries are having many limitations like maintenance, replacement at regular intervals in unreached locations and unreliable for operating long duration. To overcome these limitations Energy harvesting (EH) is a promising idea which eliminates or reduces the pollution caused by the disposal of batteries in the environment [2]. EH technique provides green eco-friendly as well as self-sustainable systems.

Various ambient energy sources like thermal, wind, solar, electromagnetic and vibration energies are available in the surroundings is depicted in the table-1. Absorbing these energies and transforming into electrical energy to drive low power sensor nodes in the IoT and WSN communication systems is a vital task. Electromagnetic energy and thermal energy are continuously present while solar energy is available during day time only. Thermal and solar energy harvesting requires larger aperture area where as amount of radio frequency (RF) energy harvesting depends on distance and availability of RF source [3]. Researchers shows more interest towards RF-EH to eliminate the need for battery, due to its potential to make the device to operate unlimited lifespan because they are freely available from the RF sources like Digital TV broadcasting, radio stations, internet devices, satellite stations and mobile base stations.

RF-EH technique harvests the available RF energy present in the environment and convert into DC voltage. Receiving antenna, matching network and rectifier are the key modules of the RF-EH method and its block diagram is depicted in figure-1. The receiving antenna harvest the RF AC power from the surrounding and transfer to the next stage. Matching network has important task to match the impedance between receiver and that rectifier so that all the received RF AC power will be transferred to rectifier without any loss. The rectifier will transform the RF AC power to useable DC power [4].

Table 1: Comparison between various accessible ambient generators in the surrounding

Ambient Sources	Sensors Used	Availability	Power Density	Output Voltage
Thermal	Thermoelectric converters	Continuous	40μ-100μ W/cm^2	10-100MW
Wind	Wind turbines	Continuous	3.5mW/cm^2	100MW and above
Solar	Photovoltaic solar panels	Day Time	1500μW/cm^2 outdoor day light	0.5V-1V
Vibration	Piezoelectric	Activity dependent	3.8μ-500μW/cm^2	10-25V
Electromagnetic (EM)	Rectenna	Continuous	0.02μ-1μW/cm^2	3-4V

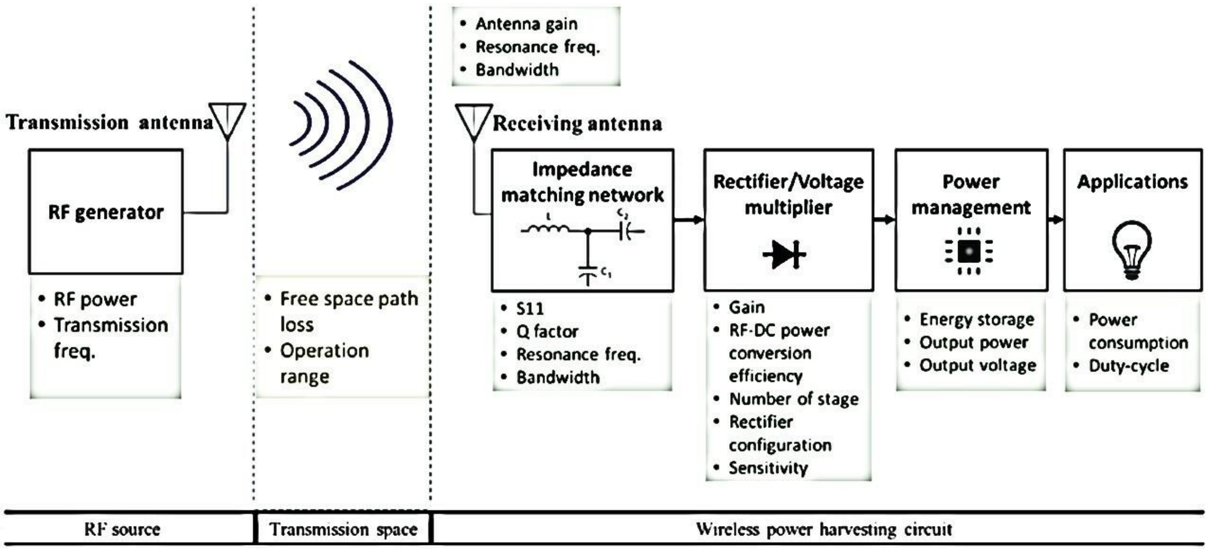


Figure 1: Block diagram of RF-EH system [4].

The remaining portion of the paper is structured as follows. In section 2, various receiving antennas based on various parameters influencing reception of RF energy. Section 3 address the challenges faced during matching network design. While section 4, discusses the mechanism of rectifier circuit and finally section 5 conclusion.

2. Selection of Receiving Antenna

In RF-EH systems, antenna is the front end which absorbs the incident RF AC power from the environment and transfer to rectifier circuit for electromagnetic AC to DC conversion. The received electromagnetic AC power by the antenna varies according to the frequency, distance and gain of the antenna. The attenuation of signal strength in space is characterised by free space path loss which depends upon distance between receiving and transmitting antenna. The received power is expressed as [5]

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi r)^2} \tag{1}$$

Where P_r is the receiving antenna power, P_t is the transmitting antenna power, G_t and G_r are the transmitting and receiving antenna gain in dBi, λ is the transmitting signal wavelength and r is the distance between transmitting and receiving antenna.

From the P_r equation, free space power loss L_p in the far field is expressed as

$$L_P = \frac{(4\pi fr)^2}{(G_t G_r C^2)} = \frac{4(\beta r)^2}{G_t G_r} \tag{2}$$

$$L_{P_{dB}} = 20\log_{10} r + 20\log_{10} f - G_t - G_r + 32.44 \tag{3}$$

The above equation indicates the RF power strength at far field region.

Electromagnetic field (EMF) emission is limited by the International Electro Technical Commission and FCC for safety measures in different applications indicating in view of health hazards caused by high frequency (above 10GHz) such as skin burns and eye cataracts [6] if EMF density is above 1000W/m^2 and the tissues damage by energy absorption at low frequencies (between 1MHz to 10GHz) due to penetration of EMF waves. Due to limitations and safety guidelines by FCC set for EMF exposure controls the available incident RF power density in the environment which in turn controls the available harvesting power for RF-EH systems [7].

Increasing requisition for compact devices, antenna with small size is the area of interest for researchers where microstrip antennas are the suitable candidate for RF-EH in WSN and IoT applications due to its conformal nature, less cost, low profile and easy of fabrication. The performance of the receiving antenna is categorized by its operating frequency, impedance bandwidth and antenna gain. The gain of the antenna is given as the ratio of power density of transmitting divided by receiving antenna in specific direction to the isotropic or omnidirectional antenna. The antenna gain is given by the formula [5]

$$G(\theta,\phi) = \frac{S(\theta,\phi)}{S_{isotropic}} \tag{4}$$

Where S(θ,Φ) is the power/unit area as a function of maximum radiation direction and $S_{isotropic}$ is for isotropic antenna power/unit area in the same direction. There is a trade-off exists between antenna gain and bandwidth which is extracted from the antenna Q-factor given by

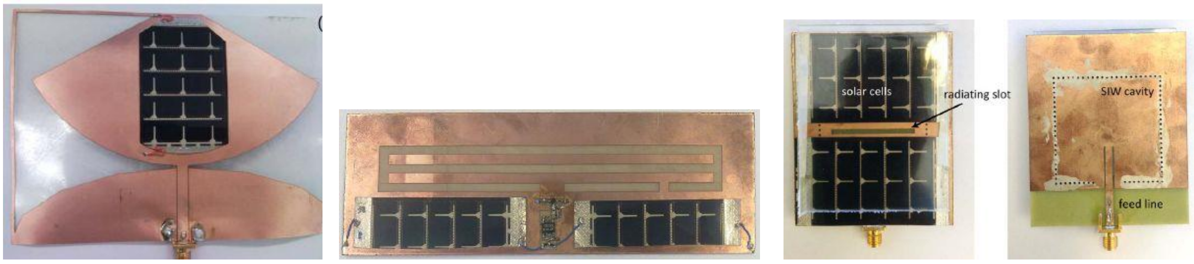
$$Q = \frac{f_r}{BW} \tag{5}$$

Where f_r is the operating frequency and BW is bandwidth of the antenna. As Q increases, BW becomes narrow and as antenna gain decreases, Q decreases hence BW increases.

In the surrounding, the ambient RF energy commonly found on frequency bands such as GSM 900MHz/1800MHz, Wi-Fi (2.45GHz, 5.5GHz), 3G (2110MHz-2170MHz), 4G (2300MHz-2400MHz), etc. In the past few years, antenna designers of RF-EH are paying more interest towards the characteristics of the antenna like frequency and polarization [8]. Based on frequency the antenna design is categorized as single band [9], multi band [10],[11] and wide or broad band [12] receiving antennas. In [13], single band compact fractal antenna is designed to harvest Wi-Fi energy with sensitivity of -20dBm and highest power transformation efficiency (PTE) of 52% at 2.45GHz with 0dB input. A quad band antenna is proposed to harvest WiFi, WiMAX, LTE, 3G and 4G energy with an antenna efficiency of 92.49% at 0.2mV of transmitted power [14]. A dual-band antenna for RF-EH over WiFi bands 2.45GHz and 5GHz is designed with peak gain of 4dBi in the operating band [15]. A dual band antenna with high gain of 10.2dBi and 8.94dBi at WiMAX and WiFi bands is proposed [16]. In [17] slotted wideband antenna with defected ground is proposed to harvest energy in the frequency range 5.336-6.194GHz with a gain of 6.189dB at 5.8GHz.

Antenna polarization plays a vital role in the reception of signal strength. Polarization is defined in the direction of electric field component orientation. For RF-EH systems the receiving antenna must harvest all the incident RF energy without any polarization loss. In this regard circularly polarized antenna [18],[19] are the best solution to eliminate polarization loss which receives both circularly and linearly polarized RF signal and improves the power conversion efficiency by increasing received RF signal energy at the first stage in the RF-EH system. In the opposite case only half of the RF power is received by the linearly polarized antenna when compared with the circularly polarized one. The only drawback in circularly polarized antenna is its narrow bandwidth.

Hybrid energy harvesting are also need due to fluctuating RF signals available in the environment. In [20], consists of solar cells placed on patch where field distribution is weaker so that performance of the RF antenna is not degraded as depicted in the figure 2. A hybrid solar-RF EH system is designed to operate electrical wheelchair using maximum power tracking with boost converter to make the charging system stable [21]. In [22], combination of RF energy and thermal energy harvester is presented for body area networks, internet of things applications in which rectenna is modelled for RF EH and thermal sensor for harvest human thermal energy by using harvesting protocol.



(a) **(b)** **(c)**

Figure 2: a) UWB printed monopole solar antenna. b) CPW folded slot solar-to-EM converter c) SIW solar cavity-backed slot antenna

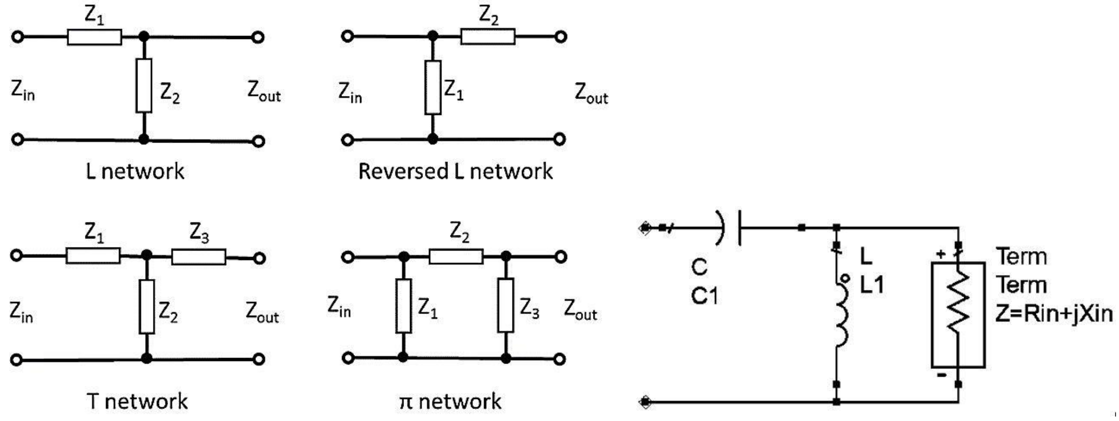
3. Matching Network

In RF-EH system, PCE is also improved only when all the RF harvested energy from the antenna is delivered to the rectifier without any transmission loss, for this purpose impedance matching network (IM-N) is placed between antenna and rectifier to match the impedance of both. If any impedance mismatch occurs between antenna and rectifier that leads to reflections and reduction of PCE. A matching network makes sure that load impedance should be complex conjugate of receiver impedance for maximum power transfer between receiver and load. IM-N also acts as low pass filter and rejects higher order harmonics generated by the non-linear components of the rectifier network to reach the antenna. Designing IM-N for wide band frequency range is very complex task because impedance of the antenna changes with input power and load [23]. IM-N should have wide bandwidth of operation because the rectifier impedance varies for varying the input power as well as the load. IM-N for RF-EH system is designed using distributed microstrip lines components [24] (radial stub, short and/or open stubs) or lumped elements. Using lumped element design of the matching circuit have less quality factor (Q) and wider BW, but due to parasitic effect at higher frequencies greater than 1GHz they are not recommended. Basic lumped components matching circuit are classified into L, inverted-L, Pi and T impedance matching circuits is depicted in figure3(a). Most commonly used lumped network for IM at low power is L-section with two components which provides minimum loss with good IM. With source impedance of 50 ohms the L-section IM-N is depicted in figure3(b). With components L^1 and C^1 which are calculated using the following equations [25]

$$L^1 = \frac{R_{in}}{\omega_0 \left(Q + \omega_0 C_{in} R_{in} \right)} \tag{6}$$

$$C^1 = \frac{R_{in}}{L^1 \left(R_{in} - R_s \right)} \frac{1}{\left(\omega_0^{\,2} - L^1 C_{in} \right)} \tag{7}$$

Where Q is quality factor, ω_0 is resonant angular frequency, R_s is source resistance, R_{in} and C_{in} are input resistance and capacitance



(a) (b)

Figure 3: (a) Basic Impedance matching networks (b) L-section IM-N with L & C components

At high frequencies, distributed microstrip lines are preferred, but it has narrow bandwidth with high Q factor. Therefore, multiband or wideband IM-N are required for IM over broad range of input power levels and frequencies. In [26], a dual band IM-N is designed using modified pi-section matching circuit which consists of open and short-circuited stub transmission lines to make frequency dependent and a detailed analysis is presented.

4. Rectifier Network

Rectifier module is the important part of RF-EH systems, which converts the harvested RF energy into usable DC energy delivered to the load. The strength of the incident RF power at the antenna aperture is very low hence power amplifier with RF to DC converter is required to drive the load continuously [27]. Diodes are the important ingredient of the rectifier circuit but due to non-linear behaviour it produces inter-modulation and harmonic terms which intern increases losses and results in reduction of overall efficiency of the system [28]. Choosing proper diode in designing the rectifier circuit is the primary importance because its performance determines the power conversion efficiency of the system.

At high frequencies the performance of the diode is determined by the series resistance (Rs), zero-bias junction capacitance (C_{j0}), diode breakdown voltage (V_{br}), switching speed of the diode and less threshold voltage. For RF-EH applications, the diode must have less threshold voltage, less series resistance, low junction capacitance and large breakdown voltage [29]. Based on the above specifications there are some commercially available diodes are listed in the table-2.

Table 2: Comparison of Spice parameters for commonly used surface mount Schottky diodes in RF rectifier circuits

	Parameters	Units	HSMS-285X	HSMS-286X	HSMS-282X	SMS-7621	SMS-7630
Breakdown voltage	BV	V	3.8	7.0	12	3	2
Zero bias junction capacitance	CJ0	pF	0.18	0.18	0.7	0.10	0.14
Energy band-gap	EG	eV	0.69	0.69	0.69	0.69	0.69
Current at Breakdown voltage	IBV	A	3E-4	10E-5	1E-4	1E-5	1E-4
Reverse saturation current	IS	A	3E-6	5E-8	2.2E-8	4E-8	5E-6
Ideality factor	N		1.06	1.08	1.08	1.05	1.05
Series resistance	RS	Ω	25	5.0	6.0	12	20
Junction potential	VJ	V	0.35	0.65	0.65	0.51	0.34
Saturation current temp. exp	XTI		2	2	2	2	2
Grading coefficient	M		0.5	0.5	0.5	0.35	0.40

Different types of topologies of the rectifier circuits are listed in the literature like, Cockcroft-Walton voltage doubler [30], Dickson charge pump [31], Greinacher rectifier [32] and differential drive voltage multiplier [33] are depicted in the figure 4. In all this topology single stage voltage doubler network is most commonly used, because it provides high efficiency and

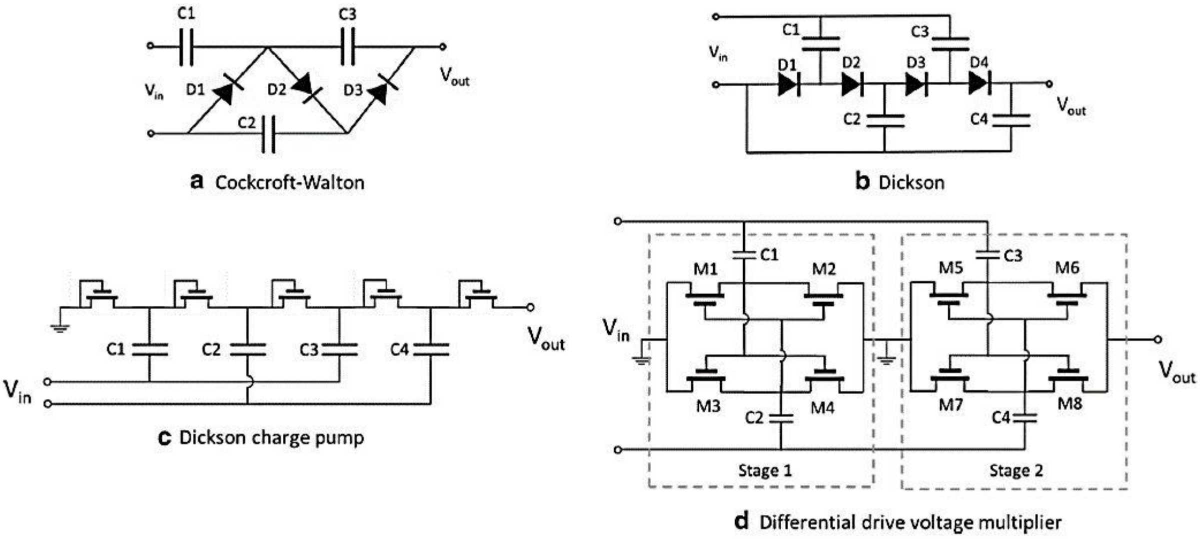


Figure 4: Cockcroft Walton voltage multiplier, Dickson voltage multiplier, Dickson charge pump using CMOS, Differential drive voltage multiplier

high V_{out} at low Vin. Its circuit diagram is depicted in the figure 5. and is working principle is as follows, during '-ve' half of the Vin, D_2 is forward biased and D_1 is off, no current flows through it and C_2 is charged to peak value of the Vin voltage. During positive half of the Vin, D_2 is reverse biased, D_1 is on and C_1 is charged to maximum value of the Vin and during next period the charge stored in C_2 is transferred to C_1, which appears across the load R_L twice that of Vin minus drop across diodes [34]. Voltage doubler, voltage tripler, voltage quadrature these are different forms of the voltage multiplier circuit. In [35], rectifier circuits for deep brain simulating module are presented and the author designed and fabricated prototype of delon voltage doubler, Greinacher voltage tripler, voltage quadrupler and two stage charge pumped rectifier with maximum efficiency of 78%, 75%, 73% and 76% respectively at -5dBm input power with 10KΩ load. As number of stages of the rectifier increases, the output voltage also increases but voltage drop across each diode also increases which intern reduces the PCE of the network. Hence trade-off between number of stages of the rectifier and PCE must be wisely chosen.

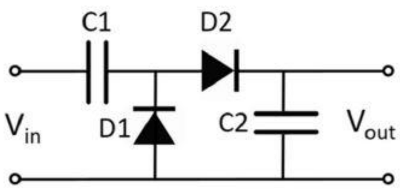


Figure 5: Voltage Doubler Circuit

Rectifier network with single band [36] [37], dual band [38], triple band [39], quad band [40] and six band [41] rectifier consists of single diode, double diode with single stage or multistage rectenna available in recent literature are some of them tabulated in the table 3.

Table 3: Comparison of different single band, dual band, triple band, quad band and six band rectenna designs.

S. No	Antenna/ substrate	Frequency	BW	Polarization	Gain (dBi)	Impedance Matching Network (IMN)	Rectifier	Rectifying component	Efficiency (%) @ i/p, RL
13	Fractal/FR4	2.45GHz	110MHz	NA	2.2	T-Microstrip line	1-Voltage Doubler	HSMS2852	52% @ 0 dBm, 4KΩ
15	Novel Dual Band antenna/RT Duroid5870	2.45GHz, 5GHz	80MHz, 100MHz	NA	4, 7	NA	7-stage voltage doubler.	SMS7630-079LF	1.3V @ 10dBm, 60 cm distance
26	Dual-band inverted-F monopole/FR4	900MHz, 1800MHz	150MHz, 200MHz	NA	0.62, 2.36	Modified п-section	1-Diode with shunt capacitor	HSMS2850	12.93%, 8% @ -30dBm, 4.5KΩ
16	Multilayer with aperture-coupling feed/ RTDuroid5880	3.5GHz, 5.8GHz	NA	NA	10.2, 8.92	Parallel inverted L-micro strip line	Parallel 1-Diode with shunt capacitor	SMS7630	44%, 29% @ 0dBm, 0.5KΩ
37	2×3 Koch fractal patch / Taconic RF35+ FR4	5.2GHz	NA	NA	NA	Adaptive MN	6 Parallel 2-Diode with shunt capacitor	HSMS2862	67% @ 20dBm
18	Fabry-Perot resonator antenna/ RT Duroid5880	34.8GHz	2GHz	Circular polarization	17	2 class-F DC pass filters	Microstrip line with shunt diode	MA4E1317	63.8% @ 77.3mW, 430Ω
19	Circular radiating patch/ F4B350	5.8GHz	100MHz	Circular polarization	6.3	NA	2 L shaped slots in series with diode	HSMS-286C	71.2% @ 18dBm, 400 Ω
40	Fractal/ FR4	0.9GHz, 1.8GHz, 2.5GHz, 3.5GHz, 5.5GHz, 7.35GHz	350MHz, 600MHz	Circular polarization	7.1	Radial stub, rectangular stub	Voltage Doubler	HSMS-2820	78% @ 12.5dBm
38	Square with spiral shaped, asymmetric cross slot loaded/ FR4	2.4GHz, 3.5GHz, 5.2GHz	600MHz, 800MHz, 850MHz	Circular polarization	4.8, 4.9, 5.1	1-rectangular stub, 2-radial stub	1-voltage doubler	HSMS282 E	85.6% @ -6dBm, 500 Ω, 3.5GHz
29	Insert fed Rectangular Microstrip/ FR4	2.45GHz	100MHz	NA	7.2	Inverted L MN	1-voltage doubler	SMS7630-061	5.9-27.7% @ 1-10μW/cm^2
17	Slotted patch antenna with Dumbbell-shaped DGS/ FR4	5.8GHz	858MHz	NA	6.189	3- LC ladder network	Greinacher voltage doubler	HSMS-285C	75% @ 10dBm, 1.5k Ω
39	self-complementary bow-tie cross dipoles/ FR4	0.89GHz, 1.83GHz, 2.19GHz, 2.45GHz	NA	Dual-Polarized	3.72, 4.59, 4.56, 4.86	Multi stubs microstrip matching elements (Radial stub, short and open stubs)	Combination of voltage doubler and novel half-wave Greinacher rectifier circuit	HSMS-285B and SMS7630	60% at 0.85GHz, 48% at 1.81GHz, 35% at 2.18GHz, 25% at 2.4GHz @ -20dBm, 1.5KΩ & 4KΩ
24	self-complementary log-periodic higher bandwidth/ FR4	0.9GHz, 1.8GHz, 2.15GHz, 2.45GHz	3GHz	NA	3.4, 6, 5.8, 5.4	4 band Modified T-network RF filter with radial stub.	differential dc doubler rectifier topology	HSMS2852	52% @ -20dBm, 6.18K-7.5KΩ

23	Patch Antenna/ Yarn with organza	2.45GHz	NA	NA	5	Shorted resonant transmission line	Single diode parallel with capacitor	SMS7630	70% @ 8dBm, 1KΩ
37	Double patch antenna array	1.8GHz, 2.45GHz	100MHz, 80MHz	NA	1.5, 1.8	matching T microstrip line	series half-wave rectifier	SMS7630-079LF	26% @ 10 dBm, 1.5KΩ
36	Directional circular patch/ Arlon DiClad 880	5.81GHz	340MHz	NA	8.4	matching T microstrip line with radial stub	two open ring stubs	BAT15-03W	69.4% @ 8.2dBm, 1.3KΩ
34	Square patch array	2.45GHz	175MHz	NA	6	L-type	Voltage doubler	HSMS-2850	77.6% @ -55.8dBm
9	Spiral antenna	2.5GHz	270MHz	circular polarization	NA	L-type	Diode	SMS 7630, HSMS 2860	85% @ 0dBm, 1KΩ, 88% @ 10dBm, 1KΩ
28	Off-center-fed dipole antenna/ Rogers RT6002	0.9GHz, 1.8GHz, 2.4GHz	200MHz, 700MHz	NA	1.8, 3.5, 3.3	NA	single shunt diode rectifier	SMS7630, HSMS2850 HSMS2860 HSMS2820	60% @ 0 dBm, 65% @ 5 dBm, 70% @ 10 dBm, 75% @ 20 dBm, 0.2-2KΩ

5. Conclusion

In this paper the survey on RF-EH rectenna topologies based on single band, multiband receiving antenna, design complexity of compact IM-N and rectifier network. Study of each in RF-EH system corresponds to a RF receiving antenna, IM-N and rectifier module to obtain high RF-DC PTE is presented to pioneer the way towards the optimized RF-EH network at low RF input power density. Still there are many areas in compact wide band or multiband IM-N design and high PCE at compact RF-EH devices required to power up many low power sensors in Internet of things and body area networks in health care systems.

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