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Simulation and Performance Analysis of a Dual GSM Band Rectifier Circuit for Ambient RF Energy Harvesting

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Abstract: In this article, an intelligent rectification circuit capable of collecting radio frequency (RF) from dual GSM bands for small DC power applications is proposed. The RF energy harvesting system (RFEH) is designed to gather RF energy at GSM 900 MHz (950 MHz band) and GSM 1800 MHz (1850 MHz band) carrier signals. The RFEH system comprises an impedance matching network (IMN) and a voltage multiplier circuit (double rectifier). Conventional IMNs are made up of passive components such as inductors and capacitors. However, these components degrade at high RF due to their material characteristic behaviour. The IMN based on distributed element or also known as stubbing configuration is presented to maximize the output DC power generated by the voltage multiplier circuit which boosts up the overall RFEH circuit performance. The circuit performance was analyzed with the Advanced Design System (ADS) simulation software to find the optimum RF power conversion efficiency of several input power levels. The propositioned RFEH circuit achieves utmost effectiveness for RF-DC conversion at 43.514% and 25.985% for the 950 MHz and 1850 MHz bands, respectively, for a low input RF power of -10 dBm with an optimum load of 25 kΩ. These results present a promising RFEH circuit network, making it a good candidate for low-level RF input power applications that allow wireless sensor network circuits or devices.

Keywords: Agilent ADS; Efficiency; GSM band; Radio frequency energy harvesting; Voltage multiplier.

1. INTRODUCTION

Presently, several exciting kinds of research are conducted in harvesting ambient energy, especially for operating portable electronic devices and low-power applications technology. Over the past decades, self-powered wireless remote sensing networks designed for the Internet of Things (IoT) are becoming the centre of attention [1]. Due to the increasing demand for wireless products, wireless communication has advanced rapidly and widely spread, along with the development of wireless sensor networks (WSN) [2]. WSN is a highly crucial part of the Industrial Revolution 4.0 and is widely used in factories, industrial complexes, and urban areas. The functions of WSN are to monitor ambient conditions such as pressure, temperature, humidity [3], the surrounding situations, infrastructure management, energy management, safety management, transportation, user applications, and other networking.

Nevertheless, the WSN system increasingly used batteries as the primary source of energy, inducing a few drawbacks, such as more astronomically immense contrivance weight and size and regular maintenance due to the constrained battery lifespan [4]. The environment naturally produces various forms of energy that could be utilized, for instance, radio frequency (RF)/microwave, wind, solar and kinetic energies. However, these energies are only accessible depending on several environmental factors including the time, setting, as well as type of weather [5]. Energy harvesting from the resource of RF signals has immense potential in supplying power for low applications via wireless methods without being utterly dependent on batteries' consumption.

Numerous research fields have benefitted from the use of RF energy because of this condition. The energy harvested can be reused to power low power applications, low power circuits, and WSN sensors and devices. Besides, it can substitute batteries as the primary source, which is a significant contribution, by saving the maintenance expenditure. The RF energy harvesting (RFEH) system can convert electromagnetic field waves into functional electrical domains, which many researchers in this field find challenging. The most critical feature in the RFEH system is the ambient RF power density, which is low and the main drawback is that it would penalize the conversion efficiency from RF to DC [6]. The aptitude of an energy harvesting system from RF waves has a solution for battery substitution in secluded locations with difficult accessibility. These settings are usually sited at bridge areas, hill peaks, and locations that are highly exposed to radioactive substances, particularly near chemical implants. As an example, energy generated through solar cells or generally, environmental energy essentially unsteady and constricted.

Alternatively, in wireless telecommunication systems, RF energy has great potential in renewable energy harvesting. An RF-based energy harvesting system is involved in cooperative transmission for simultaneous data and power in wireless networks study [7]. The process in the RFEH system involves: (i) the incident RF signal is received by the antenna, (ii) the power transfer from the receiving antenna is maximized by an impedance matching network (IMN) to the rectifier, and (iii) the incoming RF signals are converted into an output DC voltage [8]. Additionally, the impedance matching could also be categorized as filters that serve to eliminate any distortions and harmonics or the unwanted noise that cause interruption during the transmission of energy. Five types of IMN are relevant in matching the impedance value of port antenna (R_s) with load impedance (R_{load}) such as half-wave lines, single stub, inductor-capacitor of a transmission line, inductor or capacitor of a transmission line and a quarter-wave transformer. A single stub IMN configuration is introduced a new efficient technique that comprises shorted or opened segments of the line, connected in parallel or series with the line at an appropriate distance from the load. Stubbing network matches are widely used to match any complex load to a transmission line mainly, for a high frequency of more than 1 GHz [9].

This study emphasizes the IMN design using an efficient single stubbing technique to maximize the low input RF signal. A single stubbing matching technique is appropriate in coordinating any complex load to characteristics impedance using a 50 Ω transmission line equally for the mainline and stub [10]. The multiple input signal RF sources add opportunity for higher energy collection rates and thus more output power. In previous studies [11-13], the RFEH system used passive components to make up the IMN subsystem. However, due to its characteristics behaviour at high RF, passive components have failed to give high-performance efficiency. IMN single stubbing network based on the distributed elements is a relevant topology to increase the input signal by matching the input antenna impedance with the voltage multiplier circuitry to the load impedance. In this paper, the RF energy harvesters having two different frequencies that are GSM band (900 MHz and 1800 MHz) are analyzed for the voltage multiplier having a different number of stages, load impedance, input frequencies, and input RF power level using the Advanced Design System (ADS) software [14]. An integrating dual-band RF energy harvester, capable of generating energy in the aforementioned frequencies, is designed. Thus, optimum parameters for an effective RF energy harvester are determined. Furthermore, battery consumption demonstrates several drawbacks. For instance, the limitation of battery use is its limited life expectancy and the exorbitant cost of periodic replacement. Even severer is the need for battery disposal, which is a perilous act leading to environmental pollution. Likewise, the related incurred cost can greatly exceed the cost of endorsing the development of WSN devices. The finest alternative for the previously stated concerns is to conserve the RF waves and convert them into electrical energy. This option is intended to substitute the batteries to establish the application system of the device. Even though the RF waves exhibit very-low-density energy compared to the energies which are powered directly by the sun, the waves are constantly projecting radiation. Hence, the harvesting of energy waves from RF is hypothetically the most fitting solution, which guarantees and provides the sustainability of energy resources for the future.

2. MODELLING OF RFEH SYSTEM

In this paper, an overview conceptual of the RFEH system is illustrated in Figure 1, which comprises of three fundamental subsystems. The receiving antenna, which is the primary subsystem is exclusively accountable for obtaining the entire RF vitality sources. The conventional dipole antenna had been employed as a receiving antenna to acquire the input signal sources. Therefore, the 950 MHz and 1850 MHz bands were used as an RF power source to energize the low application system, i.e., WSN circuits or devices.

The band selection is sourced from the tower downlink in mobile communication, which is the signal coming from a cell tower into a cellular device. GSM 900 MHz (transmitted data from 880 MHz to 960 MHz) and GSM 1800 MHz (transmitted data from 1710 MHz to 1880 MHz) are the spectrum carrier band signals that are approved for use by Telco companies in mobile communication. As the second subsystem, the impedance matching networks act as a filter and voltage amplification to amplify the low RF input signal. The third subsystem is the rectification circuitry (RF to DC). It is recognized as the voltage multiplier circuit to amplify and effectively transform the low input power variance into a consistent DC yield output voltage.

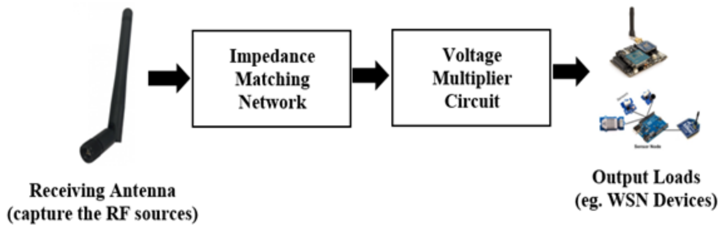

Figure 1. Conceptual block diagram of the RFEH system

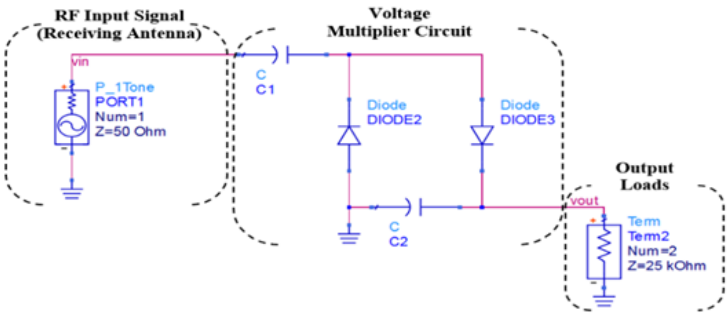

Figure 2. A single stage Villard voltage multiplier circuit

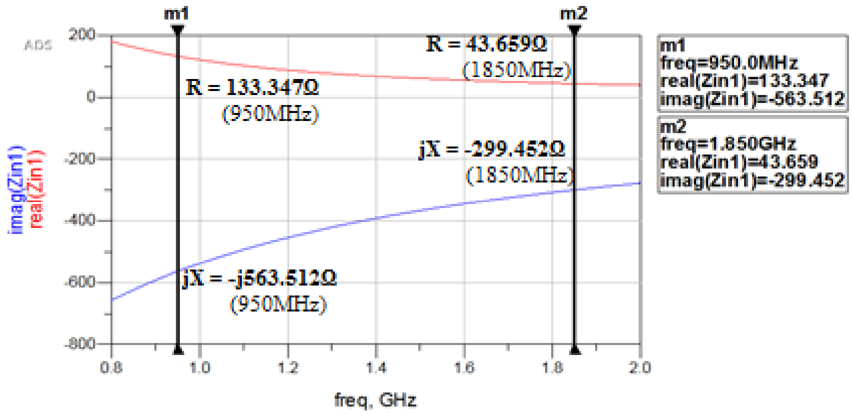

Figure 3. Input impedance of a single-stage voltage multiplier circuit

2.1 Designing a Voltage Multiplier Circuit

The most crucial block of the RFEH system is the RF voltage multiplier/rectifier converter. It converts the incoming AC RF signal obtained by the antenna into a constant DC signal. The source of ambient RF signals usually has a low level of power. Thus, the voltage multiplier circuit is needed to rectify the AC voltage to DC voltage and increase the voltage gain. Usually, the AC signal output from the receiving antenna is not consistent because the power received from the ambient is low and have distortion. Therefore, a voltage multiplier circuit (VMC) is used to boost up the signal. By increasing the number of stages of VMC, a higher DC voltage could be obtained depending on the end-use applications. However, increasing the number of stages could decrease circuit efficiency performance due to the number of diodes and capacitors involved. Hence, the selected number of stages for VMC design is also significant. In this study, a single-stage VMC is employed to simulate and analyse the designed RFEH system.

There are numerous types of voltage multiplier including the Cockcroft Walton, Dickson, Mandal-Sarpeshkar, and Villard circuit [15]. In this paper, the Villard voltage multiplier circuit is employed to realize the RF to DC power conversion to produce maximum DC output for WSN sensors and other low-power applications. A single-stage RF voltage doubler rectifier circuit comprises two capacitors and two diodes is depicted in Figure 2.

The SMS-7630 Schottky diode was used in the voltage multiplier circuit since it has a high switching speed and low cut-off voltage, which is efficient in rectifying low-power high-frequency signals. ADS simulation software from Agilent Technologies was used to design and simulate the RFEH circuit. The modelling parameters of the diode are given as series resistance, $R_S = 20\ \Omega$, zero bias capacitance, $C_{j0} = 0.14$ pF, reverse breakdown voltage, $B_V = 2$ V, saturation current, $I_s = 5 \times 10^{-6}$ A, current at reverse breakdown voltage, $I_{BV} = 1 \times 10^{-4}$, and emission coefficient, $N = 1.05$ [16]. Besides, the capacitor values are not arbitrary in the RFEH system. From one stage, a fairly low output AC voltage will be produced from a high capacitance value. Thus, a low capacitance value will trigger a voltage decline during the switching causing the improper function of the rectifier. Such value is determined by the diode selection as the diodes could be stimulated by the AC voltage. The capacitor value used for this circuit that maximizes the rectifier efficiency was found to be 100 nF.

There are two cycles of the AC signal: positive half and negative half cycles. The rectification of the RF input signal is performed in both half cycles. However, the voltage across the input capacitor, C_1 in the half cycles is only transmitted to the output capacitor, C_2 in the next succeeding half-cycle. Therefore, the voltage in the output capacitor is twice the peak voltage of the RF source (excluding the diode's turn-on voltage). The rectifier circuit has first gone through a simulation without matching the networks to acquire input impedance at distinctive frequencies of 950 MHz and 1850 MHz. The Smith Chart plot of simulation outcomes and the input impedance attained at both frequencies are displayed in Figure 3 while the return loss coefficient is shown in Figure 4.

The rectangular plot in Smith Chart utility in ADS is used for matching the complex load impedance, $Z_L = 133.347 - j563.512\ \Omega$ at 950 MHz and $Z_L = 43.659 - j299.452\ \Omega$ at 1850MHz with 50 Ω input antenna port impedance. In the simulation, the standard antenna port impedance is fixed at 50 Ω and consequently, each matching network was designed to transform every rectifier's complex input impedance to a 50 Ω antenna impedance. The 50 Ω is the optimal antenna impedance

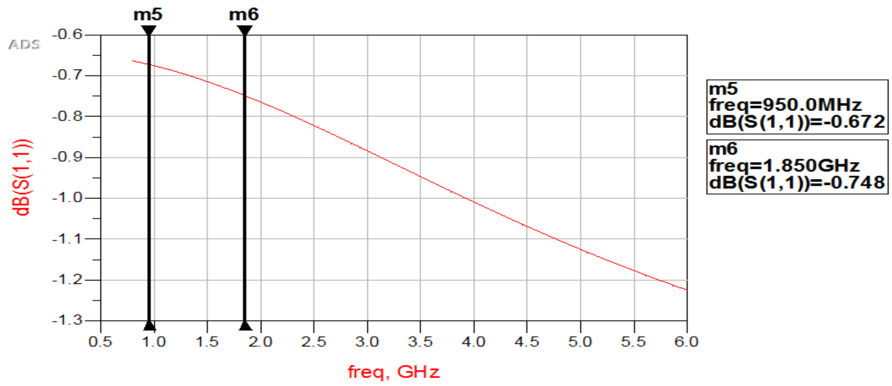

Figure 4. Return loss coefficient (S_{11}) response of VMC before matching

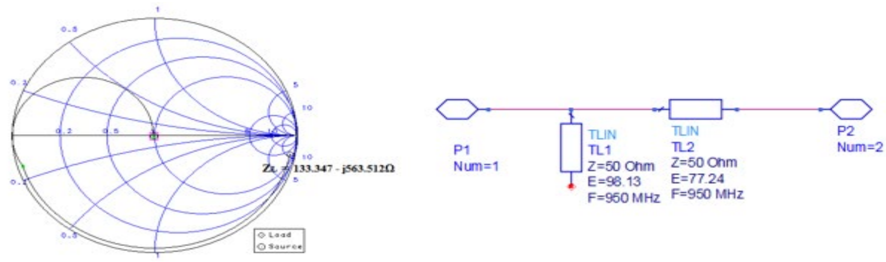

Figure 5. Smith chart for designed open parallel stub IMN at 950 MHz

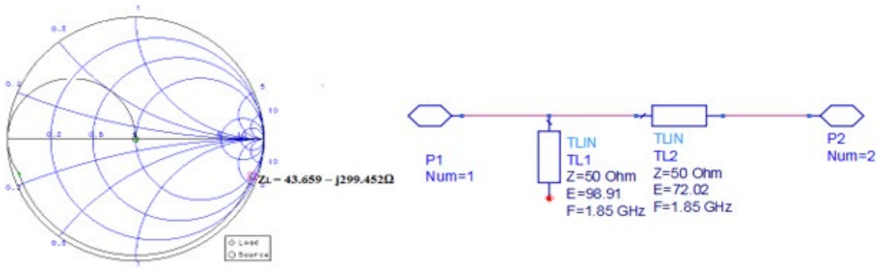

Figure 6. Smith chart for designed open parallel stub IMN at 1850 MHz

to have low losses for a transmission line and maximum available power in the subminiature version-A (SMA) coaxial cable use in the communication industry [17]. The impedance definition is the relation between *E* and *H* fields for TEM (transverse electromagnetic mode). In the communication field, 50 Ω is generally used in industrial RF generators and instrumentation while 75 Ω and 300 Ω are usually used for a cable TV and twin lead cables. Matching the antenna's input impedance to 50 Ω is mandatory in ensuring that from the RF circuitry, the maximum power is transmitted from the antenna to the load.

2.2 Designing the Impedance Matching Network

When the source and load impedances are identical, the maximum power strength is transmitted to the load as elaborated in the power transfer theorem. The input circuit and the source need to be equivalent, whereas the output circuit and the load need to be equivalent to supply maximum power to the load. As the supply and load impedances become each other's complex conjugates, the glide of power to the load for reactive elements is highly inflated [18]. The real and imaginary components should be compared with each other for the different RFEH systems, sources, and loads, as well as resistive and reactive impedances. Therefore, the perfect IMN must be employed to aid the estimated operating frequency and input power level estimation [19]. In the RFEH system, there are two types of IMN coordinating arrangements, which are lumped component-based (configured by an inductor and a capacitor) and distributed component-based (transmission line) as shown in Figures 5 and 6.

Although the lumped component-based IMN is typically compact [20], they are not favoured in-circuit working at high RF. The intrinsic loss relating to lump factors has triggered the abovementioned matter. The actual lump component is the self-resonant frequency, in which the capacitor becomes the inductor and on the other hand, the inductor becomes the type of capacitor. In matching the two impedances among the receiving antenna and the VMC, a single open parallel stub-matching network was chosen for the contribution to this paper [21]. Insertion loss and return loss of IMN are paramount for the RFEH system since it decreases the circuit's efficiency in general. The IMN is made up of transmission lines and open parallel circuited stubs (T_{L1} and T_{L2}) with the role of transforming the complex impedance of the voltage multiplier to a 50 Ω.

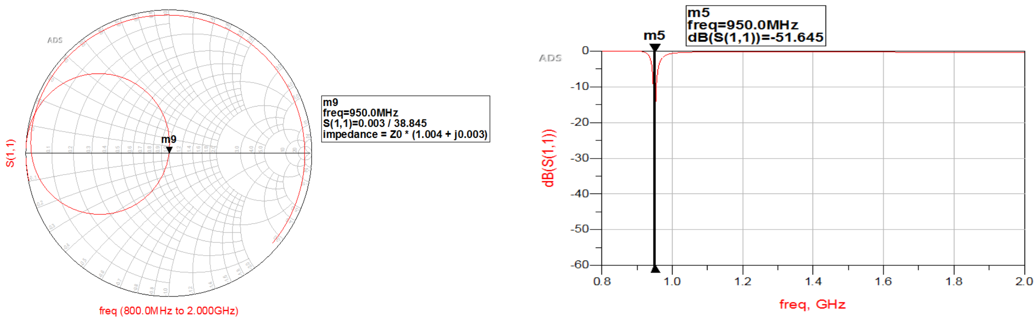

Figure 7. Return loss coefficient (S_{11}) response at 950 MHz frequency after inserted IMN

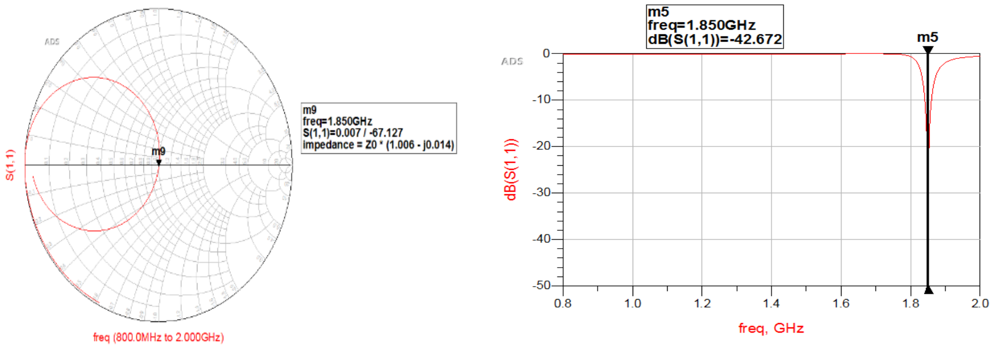

Figure 8. Return loss coefficient (S_{11}) response at 1850 MHz frequency after inserted IMN

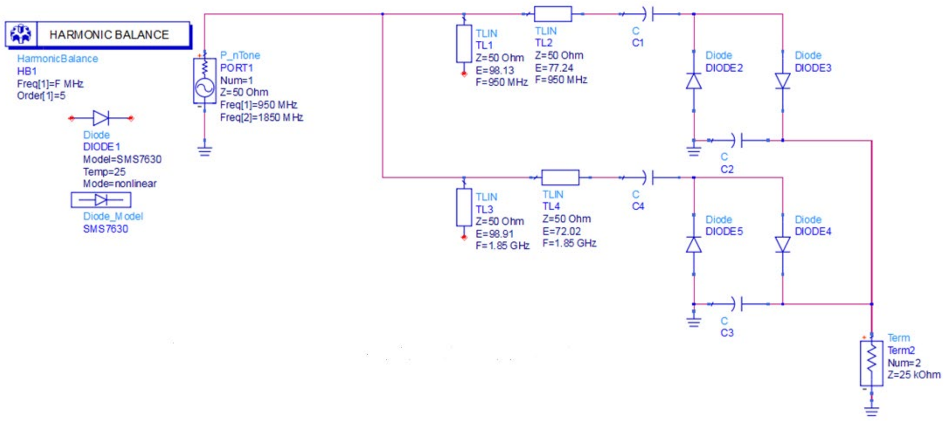

Figure 9. Dual GSM bands RFEH circuit

The simulated return loss coefficient, S_{11} at the IMN input once optimizing the transmission lines' lengths and widths are illustrated in Figures 7 and 8. Evidently, from the findings, the matching at the desired frequency of these bands has been established. The open parallel stub IMN is added between the receiving antenna and the VMC to decrease the value of the reflected power and to increase RF system effectiveness at the targeted frequency. Additionally, it also ensures the transfer of the maximum power to the load from the source. The open parallel stub IMN is done using the ADS Smith Chart Utility tool (Figure 5), to match the standard input antenna impedance, $Z_s = 50\ \Omega$ with $Z_L = 133.347 - j563.512\ \Omega$ and $Z_L = 43.659 - j299.452\ \Omega$ at 950 MHz and 1850 MHz respectively. The Z_L value is the real part and the imaginary part because the voltage multiplier circuit has a capacitor that depends on the frequency. The complete RFEH circuit in Figure 9 is made up of a single-stage VMC and a single IMN at 950 MHz and 1850 MHz.

Essentially, IMN needs to fine-tune the impedance match of the receiving antenna with the VMC so that the transmission loss could be reduced and the voltage gain could be increased. It also eliminates any noise and interference outside the frequency band used. Therefore, the power can be transferred from the source to the load to increase the RFEH efficiency system.

Table 1. Return loss coefficient of dual-bands RFEH

Frequency (MHz)	Return Loss (S_{11})	
	Without Matching (dB)	With Matching (dB)
950	-0.672	-51.645
1850	-0.748	-42.675

Table 2. Simulated result of DC voltage for difference input power signal

Input Power (dBm)	Input Power (mW)	DC Output Voltage (V_{out})	
		950 MHz	1850 MHz
-30	0.001	0.059	0.049
-20	0.01	0.313	0.259
-10	0.1	1.043	0.806
0	1	1.895	1.879
10	10	1.907	1.908
20	100	1.909	1.907
30	1000	1.908	1.906

3. SIMULATION RESULTS AND DISCUSSIONS

For acquiring the output voltage for various levels of input power from -30 dBm to 30 dBm, the circuit is simulated with Harmonic Balance (HB) simulation in ADS. The intensity of power indicated from the antenna is represented by S_{11} named the reflection coefficient (known as gamma or return loss). Return loss is the valuation of the signal amount reflected in the source using decibels (dB) as its unit of expression. Additionally, this measurement parameter is constantly a positive number. A satisfactory measurement parameter would be a high return loss, and commonly, this is correlated to a low insertion loss. To be specific, an infinite return loss would occur if all power is transferred to the load. Contrariwise, all of the power would return with no return loss if there is an open or short circuit termination. As an example, if $S_{11} = 0$ dB, the antenna reflects all of the power, and nothing will be radiated. For the best value for *S*-parameters and also in developing an RFEH system, S_{11}, which is also known as return loss (R_{loss}), should have a smaller value than -10 dBm. If an RF energy harvesting system has a return loss of -40 dB, it means that the RFEH system gives a better performance than -10 dB in terms of return loss.

In the RF world, discontinuities and impedance mismatches are the two main reasons for return loss in the network. Discontinuities happen at connections where the cable has been dismissed to plugs or jacks and within the plug/jack connection itself. Situations including a cable being bent too much, kinked, or broken could also trigger a discontinuity. A return loss or echo will occur once a transmitted signal pulse strikes a form of the structural discontinuity. Secondly, the impedance mismatches can be small-scale between the antenna port and the voltage multiplier circuit. Small mismatches are usually component-to-component related especially for receiving antenna and voltage multiplier designing. For example, if the antenna port network averages 50 Ω impedance and the voltage multiplier circuit is 60 Ω, each 10 Ω mismatch also causes a return loss reflection.

The IMN is an important subsystem in RFEH to eliminate the mismatch between antenna and voltage multiplier impedance. Besides, IMN also increases the power gain transferred from the input antenna to the load. The simulation result in Table 1 shows the return loss coefficient when IMN was applied to the RFEH system in two conditions before and after adding impedance matching to the VMC. The return loss of IMN has tremendously lowered the S_{11} value to –51.654 dB, and -42.672 dB as compared to the case before IMN was inserted which were -0.672 dB and -0.748 dB at 950 MHz, and 1850 MHz respectively. Therefore, IMN is vital in designing the RFEH system. Apart from that, the IMN has proven that the sum of harvested power could be maximized from the limited energy source.

The full RFEH system circuit in Figure 9 was effectively simulated with the HB simulator in ADS to acquire constant DC output voltage (V_{out}) at various input signal power starting from -30 dBm to 30 dBm. The simulation results are tabulated in Table 2 for the targeted carrier frequencies of 950 MHz and 1850 MHz, at a 25 kΩ load resistance. This load value has been a standard for various WSN sensor devices [22].

Table 2 demonstrates the simulating results for the constant output DC voltage for several input power signal levels. The results show a direct proportionality of the DC output voltage to the small RF input power level. With the increase in the input power signal in the RFEH circuit system, the output voltage is also automatically increased due to the VMC's ability to boost the input signal. These data were plotted in Figure 10 which clearly shows the relationship between the output voltage and input power levels. It shows that the DC output voltage is maximum when the input power is equal or greater than 0 dBm. It is also found that things are different when the input power is less than 0 dBm. However, the circuit still able to produce a significant DC voltage for such a small input power of -20 dBm.

Furthermore, the conversion efficiency performance of the RF input to the DC output is given by [22]:

$$\eta(\%) = \frac{P_{out}}{P_{in}} \tag{1}$$

and

$$P_{out} = \frac{{V_{out}}^2}{R_L} \tag{2}$$

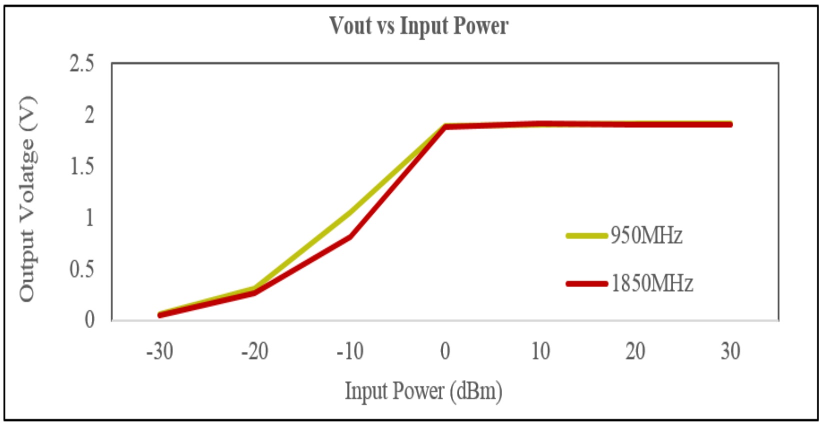

Figure 10. DC output voltage at difference input power signal

Table 3. Power conversion efficiency at several RF input power signals

Input Power (dBm)	Input Power (mW)	Efficiency (%)	
		950 MHz	1850 MHz
-30	0.001	13.924	9.604
-20	0.01	39.188	26.214
-10	0.1	43.514	25.985
0	1	14.364	14.122
10	10	1.455	1.456
20	100	0.146	0.145
30	1000	0.145	0.014

Table 4. Efficiency versus output load impedance at -10 dBm

Input Power (dBm)	Output Load Resistance (kΩ)	Efficiency (%)	
		950 MHz	1850 MHz
-10	5	47.629	41.405
	10	54.464	40.069
	25	43.514	25.985
	50	28.850	14.620
	100	16.926	8.723
	500	3.942	1.944
	1000	2.019	0.988

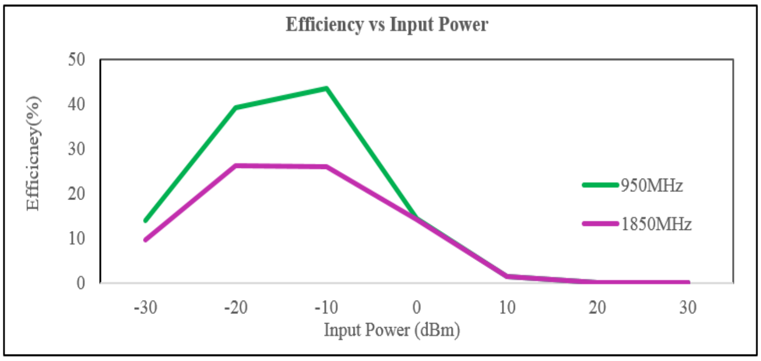

Figure 11. Efficiency of RFEH systems at difference input power signals

where P_{out} , P_{in} ,$V_{out,}$ and R_L are respectively the DC output power, RF input power, DC output voltage, and output load resistance. The power conversion efficiency (PCE) for several levels of RF input power that range between -30 dBm and 30 dBm is calculated using Equations (1) and (2) are presented in Table 3. The results demonstrate that the highest efficiency is achieved when the IMN between the source impedance and the load impedance is established. Furthermore, when the circuit resonates at the desired frequency, the IMN improves circuit efficiency [13]. The efficiency slowly declines when the input power increases to the highest level which is caused by the IMN that is incompatible with the high input signal.

The functionality of the IMN is appropriate with the low input signal. This network's main features amplify the antenna's low signal before the voltage multiplier circuit boosted that signal. Figure 11 exhibits the relationship between the PCE and RF input power levels. We observed that the efficiency of the system dropped as the input power signal inclined to start from 0 dBm. The efficiency increased when the input signal power at -30 dBm until -10 dBm, therefore proved the impedance matching is well suited to the low input signal conversion. Moreover, it is shown in Figure 11 that at the input power of -30 dBm, the lowest efficiency could be observed, while the efficiency is greater for higher levels of input power. The highest efficiency for both 950 MHz and 1850 MHz bands for input powers of -10 dBm is 43.514%, and 25.985% respectively. Besides, the simulated conversion efficiency of the RFEH versus input power levels at seven output loads of different resistance can be seen in Table 4. The efficiency over the output load resistance of interest has been satisfactorily sustained for load values that range between 5 kΩ and 25 kΩ.

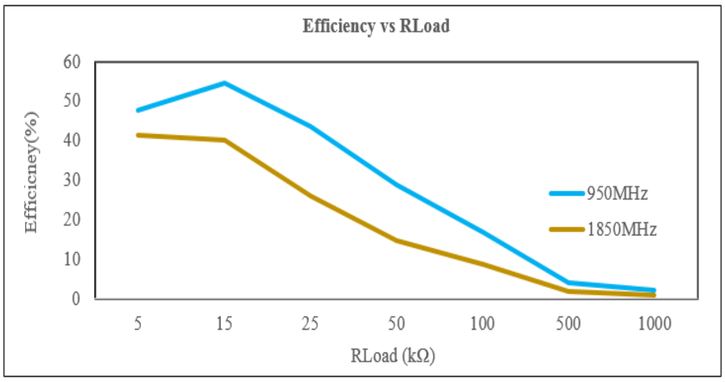

Figure 12. Efficiency of RFEH system at -10 dBm with variant output load

Figure 12 shows the simulated RF to DC conversion efficiency of the RFEH circuit system at seven respective output load values with an input power level at -10 dBm. Also, the conversion efficiency of the RFEH circuit highly depends on the load resistance, which is seen in Figure 12. Various output load values are considered in the HB simulations and a 25 kΩ load resistance is selected as a fairly higher efficiency is acquired at -10 dBm, which is the optimal value for WSN sensor devices [22].

4. CONCLUSION

A dual-band RFEH circuit functioning at the carrier frequency of 950 MHz and 1850 MHz is proposed. The VMC was simulated and its performance was analyzed with impedance matching and without impedance matching. The circuit was simulated by Agilent ADS software, and its performance was analyzed. IMN has been established over all of the assigned standard frequency bands through a microstrip stubs configuration. The circuit simulations are important to optimize the whole RFEH system. The output DC voltage is simulated for single-tone input signals with input power levels ranging between -30 dBm and30 dBm. The results indicate an incline in the output voltage as the input power levels are increased. Essentially, the RF-DC conversion efficiency has been simulated over the frequency for various levels of input power. The optimum efficiency was obtained at an input signal of −10 dBm as 43.514% and 25.985%, for 950 MHz and 1850 MHz, respectively. Noticeably, the proposed RFEH system can still deliver an adequate DC output voltage at low incident of RF input power. The return loss S_{11} has tremendously lowered to –51.654 dB, and -42.672 dB at 950 MHz, and 1850 MHz compared to before IMN was inserted. Therefore, IMN is vital in designing the RFEH system. Apart from that, the IMN has proven that the sum of harvested power could be maximized from the limited energy source.

The proposed circuit designed is relevant for various low-power applications and thus, can be utilized to numerous battery-less WSN circuits and devices. Therefore, the simulation process is an important part of modelling and constructing the RF harvester circuit. For further study, a power combiner/splitter circuit will be employed to separate the input signal power into various output ports. The power combiner arranges for ideal input and output port matching, high isolation, and low loss in an exceptionally narrow band. The role of the power combiner circuit is essential in the communication systems like the transceivers, phased arrays, and power amplifiers, for their practical design and good performance.

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