Wireless Charging of Mobile Battery via Optimization of RF Energy Harvesting System

Taushif Raja Ansari, Asif Khan and Imran Ansari

Abstract— RF energy harvesting is a field whose time has come and its possibilities need to be explored. RF energy is everywhere. We are being bombarded with Radio Frequency energy which is emitted by sources that generate high electromagnetic fields such as TV signals, wireless radio networks and cell phone towers. Even it is new idea, many researches have been done for the optimization of RF energy harvesting system. Many of the works are related with regard to the optimization of antenna, some are with matching network and voltage doubler circuit. Those research in which matching network is concern, the author has done matching without considering the diode in the circuit, i.e. only considering capacitor and resistor because matching the diode is not straightforward. What we have done is matching the circuit with considering diode in the circuit in the Agilent ADS software. With regard to RF-DC conversion, voltage doubler, we have used Greinacher voltage doubler circuit and simulated it in ADS software up to 9 stage circuit. For the optimum stage of voltage doubler, it should be greater than 4 (n>4) and first stage capacitor should be double of the rest capacitor. With regard to the result for this paper, we have used 5 stage voltage doubler so as to trade-off between output voltage and output current. The simulated result is, at 0 dBm V_{out} is 1.8 V and I_{out} is 0.1814 mA, at 10 dBm V_{out} is 7.77 V and I_{out} is 1 mA and at 20 dBm V_{out} is 17.88 V and I_{out} is 2 mA.

Moreover, it can be concluded analysing the effect of distances between Tx and Rx antennas on the RF energy harvesting system and on the output by Friis Transmission Equation, which is that at 10 cm, the small battery can be charged in a day.

Index Terms— RF Energy, Voltage Doubler, Matching Network, RF - DC Conversion, Friss Transmission Equation, Rectenna, Schottky diodes.

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1 INTRODUCTION

Scientists or engineers have done many researches on how power can be generated and transmitted. The common means of generating power are through hydro, nuclear, solar, biomass etc. However, the major challenge is how can we generate and transmit uninterrupted power to power critical remote devices such as satellites in the orbits. Also, the researchers have shown that the use of cell phone and other miniatures devices has exponentially increased in developing countries, however some of these countries are experiencing interrupted power supply and most time charging these devices has become burden on the users.

RF energy harvesting is an idea whose time has come [1]. RF energy is everywhere. We are being bombarded with Radio Frequency energy which is emitted by sources that generate high electromagnetic fields such as TV signals, wireless radio networks and cell phone towers [2]. Today there are over 5 billion cell-phones (there are 7 billion people), 44,000 radio stations, thousands of TV stations, and countless home Wi-Fi system irradiating RF energy into the atmosphere [3].

The work presented in this research paper is in the area of Radio Frequency (RF) energy harvesting and its optimization. This project addresses needs felt across many sectors of industry. As the demand for energy increases, the need for energy efficiency grows in long step. Modern microcontrollers can operate on less than 200 micro-amps of current, and this is already considered “ultra low” current. Despite the already “ultra low” label, the bar continues to be lowered every year. How low power consumption can go will be determined by future hands, but the power supply that can run these super-ultra-low consumption devices is already at our fingertips [1].

Portable electronic devices are very popular nowadays. As the usage of these portable electronic devices is increasing, the demands for longer battery life are also increasing. These batteries need to be recharged or replaced periodically. It is a hassle to charge or change the battery after a while, especially when there is no power outlet around.

So we are presenting a prototype for wireless charging system for mobile. This wireless battery charger is expected to eliminate all the hassles with today’s battery technology. It would be convenient not having to worry about charging or changing the batteries and still have a working device. The advantage of this device is that it can wirelessly charge up the batteries which can save time and money in a long run for the general public [3].

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2 SYSTEM ARCHITECTURE

The system architecture for designing RF energy harvesting system consists of two components namely RF signal transmitter and RF signal receiver where the RF signal generator generates RF signal acting as a prototype which then is transmitted via transmitter and received via receiver and then it moves algorithmically to other components which are discussed further.

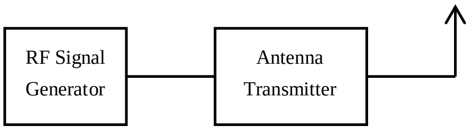


Fig. 1. RF Signal Transmitter.

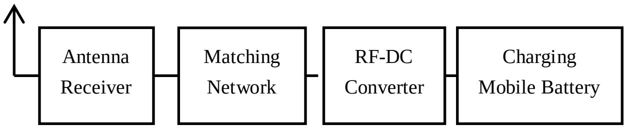


Fig. 2. RF Signal Receiver (Harvesting System).

3 ANTENNA

The author D. W. Harrist (2004) in [4] has used the monopole antenna because of its relative ease of use, after discussing different types of antenna for wireless mobile charging. A monopole antenna basically consists of a piece of copper wire with one end connected to the circuit, and the other left open. Probably the best reason for using an antenna such as this is that it fits nicely into the chosen stands. The wire is attached to the circuit and then wound once around the inside of the case; making sure that it does not touch any other part of the circuit or itself. Another good quality of this type of antenna is that its operating frequency range is fairly large. For this research, this is helpful because precise tuning of the antenna is not required.

The wire that was wound around the stand functioned as an antenna and was power efficient at 915 MHz, which is the frequency of choice.

There are other antennas like Quarter-wave Whip Antenna, 9 db gain Yagi Antenna, Dipole Antenna, etc. Here, we have used monopole antenna because of its comparative advantage to our work. The comparative advantage of monopole antenna are listed below [6]:

a) Well suited to be adapted to general dual band applications.
b) Has a flexible design where required impedance can be achieved by altering length and geometries of the microstrip lines. Return loss achieved is -25dB.
c) Helps provide the ability to operate at more RF bands and harvest energy for remote power applications.

4 MATCHING NETWORK

The maximum power transfer theorem, states that for DC circuits, the maximum power will be transferred from a source to its load if the load resistance is equal to the source resistance. In AC, the same theorem states that the maximum transfer of power, from a source to its load, occurs when the load impedance (ZL) is equal to the complex conjugate of the source impedance (ZS).Thus, if the source impedance is ZS= RS + jX, thus, its complex conjugate will be ZS = RS - jX [7].

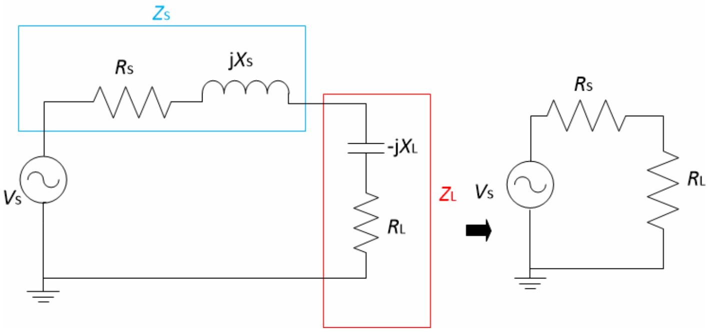


Fig. 3. Matching Network Scheme [7].

Impedance matching is needed to provide maximum power transfer between the source or RF energy and its load. This is especially important if you deal with low amplitude signals. Imagine a radio or TV antenna. To get a good reception every bit of this signal needs to be used and the designer cannot afford any signal loss – a perfect match is desired. So the first reason for matching is just power efficiency.

The second reason is device protection – If RF circuit is not matched we get reflected power. This reflected power builds standing waves on the transmission line between the source and load. Depending on the phase between the forward and reflected both waves can either subtract or add. Because of that on the line we can get places where the voltage is the sum of both voltages and eventually places where the voltage equals zero (maximum current). If the standing wave is positioned in such a way on the transmission line so that the maximum voltage or current is applied to the power FET's they can be destroyed [11].

There are several numbers of possible networks that could be used to perform the impedance matching function. So the researchers have used five types of matching network. They are

a) A shunt inductor.
b) An L – Network.
c) A transformer.
d) A pi – Network.
e) A T – Network.

Nahida Akter et al. (2014) in [8] have implemented a T-Network as a matching network for voltage boosting in RF energy harvesting system. Since the energy harvesting circuit consists of diodes, which are nonlinear devices, the circuit itself exhibits nonlinearity. This implies that the impedance of the energy harvesting circuit varies with the amount of power received from the antenna. Since the maximum power transfer occurs when the circuit is matched with the antenna, the impedance matching is usually performed at the particular input power. The impedance matching network performs impedance transformation to assure maximum power delivery. A matching circuit that operates at 950 MHz and input impedance of 50 Ω and load resistance of 100 KΩ was made.

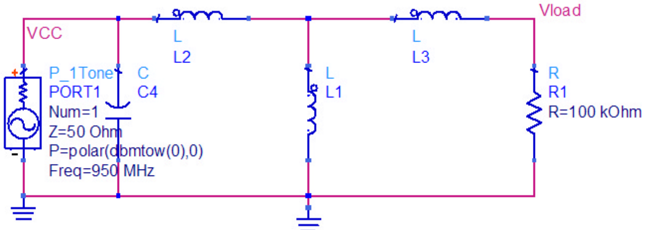


Fig. 4. Matching Circuit [8].

In this circuit design, zero bias Schottky diodes (V_i = 0.35 V) HSMS-2850, and HSMS-2822) from Agilent were used.

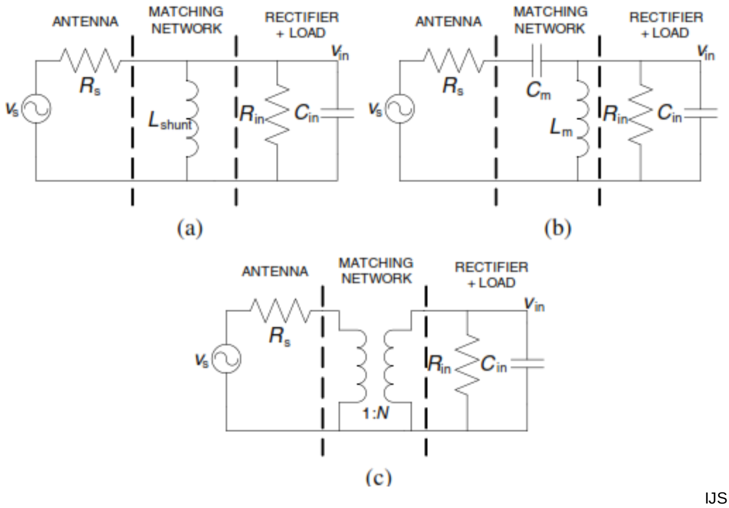
Anchustegui-Echearte et al. (2013) in [12], in fig.4, have shown different types of matching networks where Vs and Rs model the antenna and Rin and Cin model the input impedance of the rectifier plus the ensuing load (e.g., autonomous sensor) to be powered. An antenna can be roughly modelled as an AC voltage source (Vs) with a series impedance. The series impedance basically comprises a radiation resistance (Rs), a loss resistance and a reactive part. The amplitude of the voltage generated on the antenna is given by

$$Vs = 2\sqrt{2RsPAV} \quad (1)$$

Or,

$$PAV = Vs2/8Rs \quad (2)$$

Where, P_{AV} is the available power at the antenna. As can be deduced, lower values of P_{AV} lead to lower values of Vs.



(a) (b) (c)

Fig. 5. Three types of matching networks: (a) shunt inductor, (b) L network, (c) transformer [12].

5 RF – DC CONVERSION

RF-DC conversion is nothing but the conversion of RF energy (AC) captured through antenna to DC i.e. a rectifier. There are three option to perform RF-DC conversion:

a) A diode (together with the antenna i.e, rectenna).
b) A bridge of diodes.
c) A voltage rectifier multiplier.

Rectenna has been used in many of the research paper. Basically rectenna means combination of rectifier and antenna. It does rectification after capturing RF waves through antenna.

Olakanmi O. Oladayo (2012) in [9] has implemented full wave rectifier as RF-DC conversion in his prototype. The author has chosen full-wave rectifier for the prototype due to its simplicity and efficiency in converting the AC signal. Since the power received by the receiver will be relatively low and the signal frequency is high, the diodes are required to have a very low turn on voltage and operating frequency at 900 MHz. Therefore, a Schottky diode by Skyworks is used for the prototype (SMS3929-021 Bridge Quad Schottky Diode).

In many recent work on RF-DC conversion, voltage doubler or multiplier circuit is used. The voltage rectifier multiplier provides an output voltage that doubles the input voltage amplitude. Those research papers which have used 10 stage or 7 stage voltage doubler, the amount of current decreases with the increase of stage, although the voltage is optimized, which is not sufficient to charge the mobile.

TABLE 1
COMPARISION OF RECTIFIERS [6]

Type of Rectifier	Structure	Rectifier Topology
Basic Rectifier	A diode connected in series with a load. A capacitor acted as a filter to smoothen the ripple in the output. Commonly called as single -stage rectifier.	Half wave and Full wave Rectifier
Voltage Doubler	Uses two stages to approximately double up the DC voltage.	Villard circuit, Greinacher circuit, bridge circuit, Dickson charge pump voltage - doubler
Voltage Multiplier	Converts RF energy into DC voltage using a network of capacitors and diodes.	Villard cascade voltage multiplier, Dickson multiplier, Cockroft Walton voltage multiplier

5.1 Selection of Diodes

One of the crucial requirements for the energy harvesting circuit is to be able to operate with weak input RF power. For a typical 50 Ω antenna, the −20 dBm received RF signal power means an amplitude of 32 mV. As the peak voltage of the AC signal obtained at the antenna is generally much smaller than the diode threshold [14], diodes with lowest possible turn on voltage are preferable.

Moreover, since the energy harvesting circuit is operating in high frequencies, diodes with a very fast switching time need to be used. Schottky diodes use a metal-semiconductor junction instead of a semiconductor-semiconductor junction. This allows the junction to operate much faster, and gives a forward voltage drop of as low as 0.15 V. We have 2 different diodes from Agilent Technologies, HSMS-2822 and HSMS-2852. The former has the turn on voltage of 340 mV while the latter is at 150 mV, measured at 1 mV and 0.1 mV, respectively. Consequently, HSMS-2852 is suitable for LPD used in the weak RF environment, while HSMS-2822 is preferred for HPD in the strong RF environment.

Saturation current is another critical parameter that impacts the efficiency of diodes. It is desirable to have diodes with high saturation current, low junction capacitance and low equivalent series resistance (ESR). Moreover, diodes with higher saturation current also yield higher forward current, which is beneficial for load driving. However, higher saturation current is usually found in larger diodes, which have higher junction and substrate capacitance. The latter two parameters can introduce increased power loss, where the benefit of higher saturation current is lost [15]. So, HSMS-285x is chosen for our research.

5.2 Half Wave Rectifier

The half wave rectification is done with HSMS 285x diode. This circuit produces a lot of ripple, or noise, on the output DC of the signal. The voltage decreases in relation to the inverse of the resistance of the load, R, multiplied by the capacitance C.

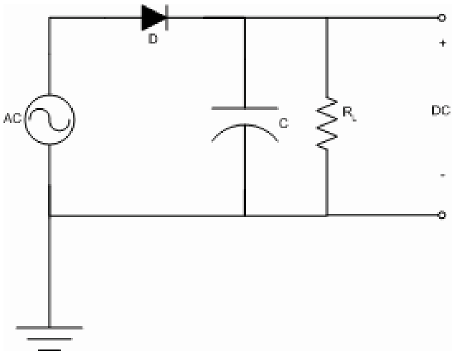


Fig. 5. Half wave Peak Detector [4].

5.3 Full Wave Rectifier

From this figure, we see that in the positive half of the cycle, D1 is on, D2 is off and charge is stored on the capacitor. But, during the negative half, the diodes are reversed, D2 is on and D1 is off. The capacitor doesn't discharge nearly as much as in the previous circuit, so the output has much less noise, as shown in Figure 6. It produces a cleaner DC signal than the half-wave rectifier, but the circuit itself is much more complicated with the introduction of a transformer.

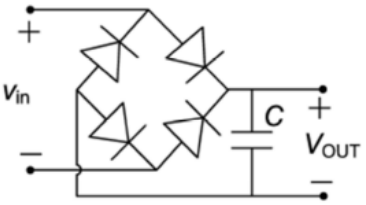


Fig. 6. Full wave Rectifier [9].

5.4 Greinacher Voltage Doubler

For RF-DC conversion, we have chosen Greinacher voltage doubler because it does two work, first it rectifies RF-DC and secondly it amplifies the voltage according to the stages of doubler circuit. We will simulate 4, 5, 6, 7, 8 and 9 stage Greinacher voltage doubler circuit. The load chosen is 10 kΩ.

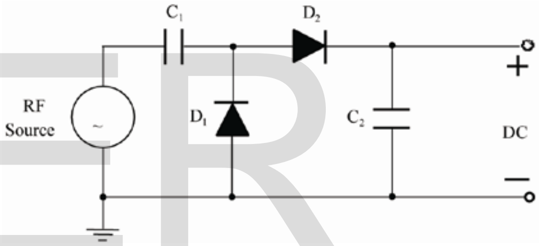


Fig. 7. Greinacher Voltage Doubler [9].

5.5 Number of Voltage Doubler Stages

The number of rectifier stages has a major influence on the output voltage of the energy harvesting circuit. Each stage here is a modified voltage multiplier, arranged in series. The output voltage is directly proportional to the number of stages used in the energy harvesting circuit. However, practical constraints force a limit on the number of permissible stages, and in turn, the output voltage. Here, the voltage gain decreases as number of stages increases due to parasitic effect of the constituent capacitors of each stage, and finally it becomes negligible [15].

It is proven in [16] that for the optimum number of stages in a Cockroft-Walton cascade circuit for maximum output voltage for a given load current, supply frequency and input voltage, is more than 4 stages.

6 RESULT AND DISCUSSION

In this section, simulation result of RF energy harvesting system is shown which is done in Agilent Advanced Design System (ADS) 2009 software. We have used S-parameter analysis for matching network and harmonic balanced analysis (a frequency domain method) for RF-DC conversion.

6.1 Source

We have generated RF wave of 915 MHz by using Surface Acoustic Waves (SAW).

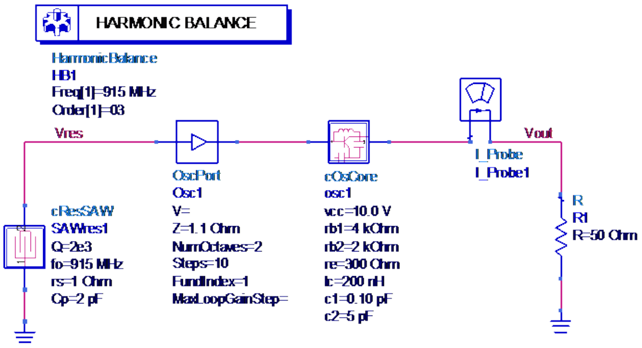


Fig. 8. Fixed frequency Oscillator by SAW.

In Surface Acoustic Wave devices, a surface acoustic wave travels on the surface of the piezoelectric materials used. Piezoelectric materials are used for as electrical signals need to be transformed into the surface acoustic wave. Piezoelectric materials become deformed when an electrical field is applied. With this effect, waves can be generated by forming comb-shaped electrodes, and applying signals to them.

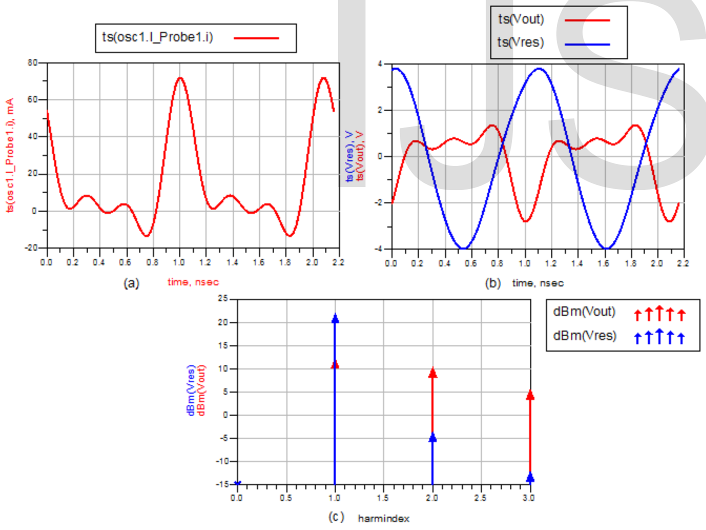


Fig. 9. Output across the antenna (resistive load): (a) output current, (b) output voltage, (c) output power in dBm.

As we can observe from above output, the voltage is nearly 1.5 V which is 10 dBm. Here an antenna is roughly modelled as an AC voltage source (Vs) with a series impedance. We have used power source, P_1Tone (Power Source, Single Frequency), which is an Agilent device in ADS software.

Fig. 10. Aligent power source with single frequency.

The source input is taken from -20dBm to 20dBm (0.01mW to 100mW) which means the amplitude of voltage generated at receiving antenna is from 0.06V to 6.32V, done by the equation (3), also shown below for convenience.

$$Vs = 2\sqrt{2RsPAV} \tag{3}$$

At 0dBm, P_{AV} = 1 mW. So Vs = 0.63 V, which is very small.

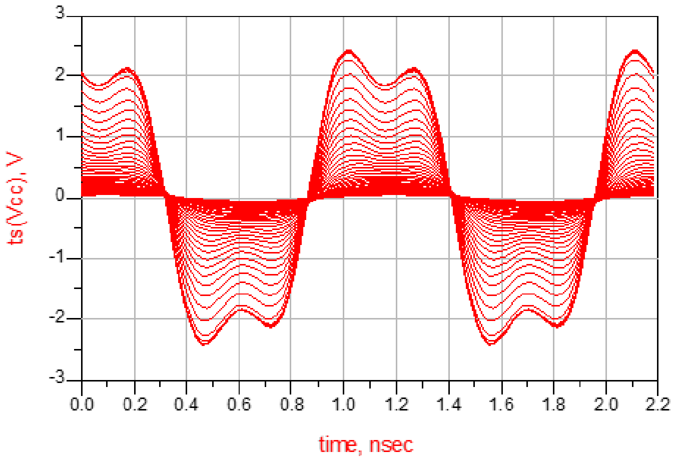


Fig. 11. Input RF wave of order 3.

6.2 Diode

Since the energy harvesting circuit is operating in high frequencies, diodes with a very fast switching time need to be used. Schottky diodes use a metal-semiconductor junction instead of a semiconductor-semiconductor junction. This allows the junction to operate much faster, and gives a forward voltage drop of as low as 0.15 V. We have used schottky diode HSMS285X.

6.2 Matching Network

We have simulated matching network by using smith chart utility which is shown below.

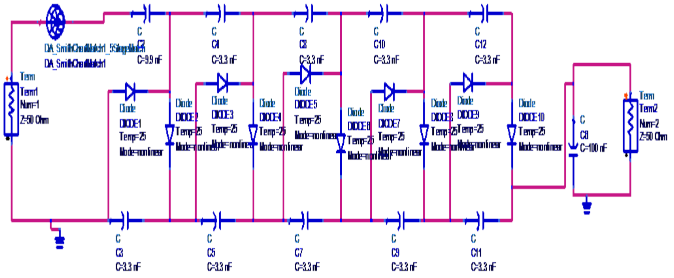


Fig. 12. Schematic diagram for Matching Network.

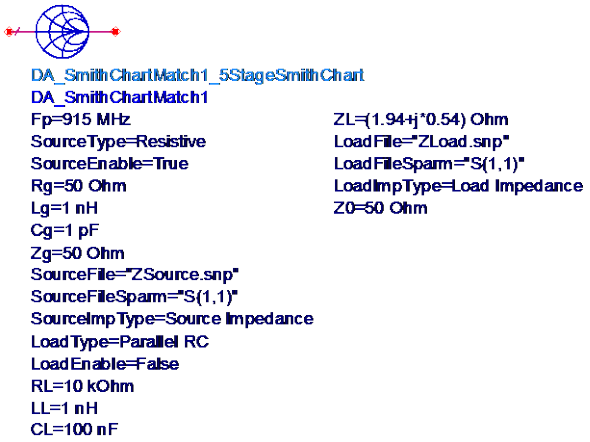


Fig. 13. Build ADS Matching Network.

6.3 Greinacher Voltage Doubler

Here we have simulated 4, 5, 6, 7, 8 and 9 stage Greinacher voltage doubler circuit. We have shown the simulation results of only 4 stage voltage doubler and made a comparision with others.

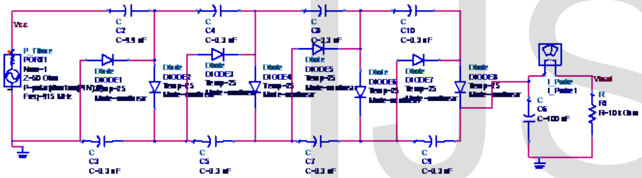


Fig. 14. Greinacher 4 stage voltage doubler.

In 4 stage voltage doubler, at 0 dBm, the output voltage is 1.813v which is very low for small device. Hence, higher order of the Greinacher voltage doubler is used.

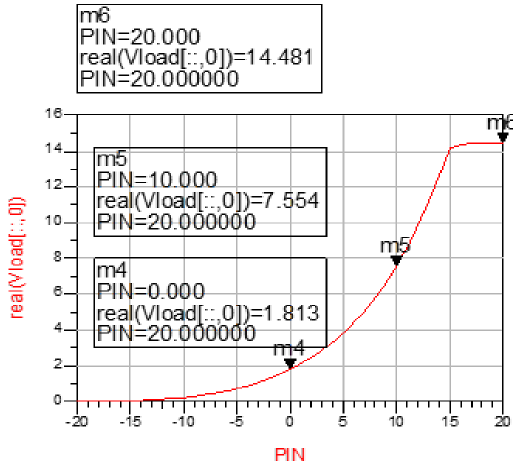


Fig. 15. Voltage Output.

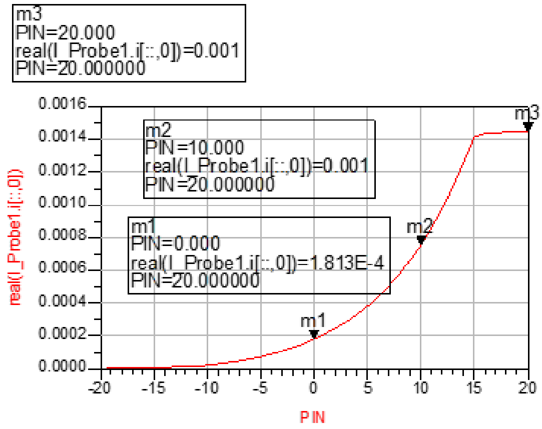


Fig. 16. Current Output.

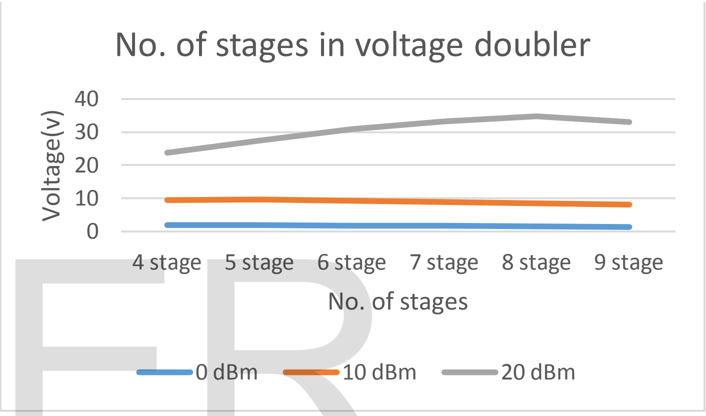


Fig. 17. Line graph representing voltage at different power level.

As we can see from above output voltage and current curve, output voltage increases till 7 stage voltage doubler, and decreases from 8 stage voltage doubler, and vice versa with current.

So for this research, we have chosen 5 stage voltage doubler for battery charging, to trade-off between voltage and current.

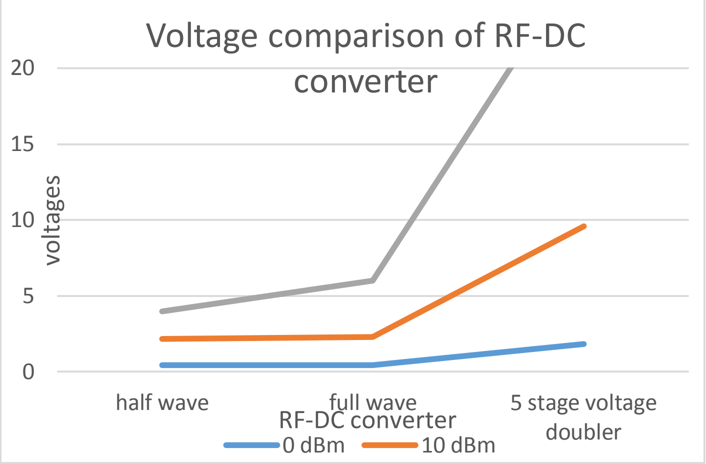


Fig. 18. Line graph representing voltage comparision of RF-DC Converter at different power level.

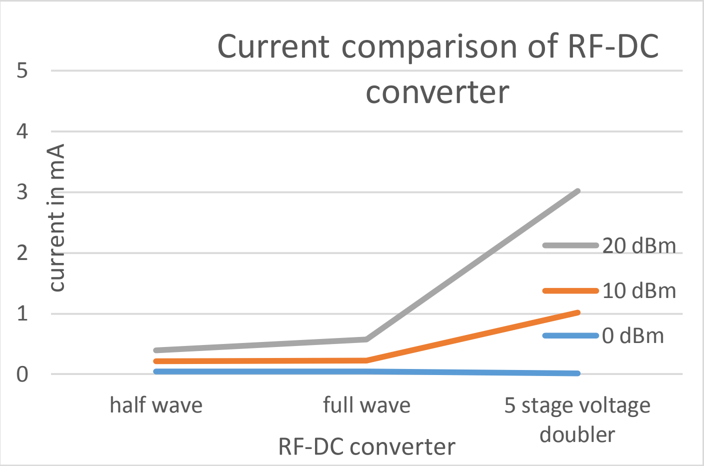


Fig. 19. Line graph representing current comparision of RF-DC Converter at different power level.

The above line graphs depicts the voltage and current comparison between different types of RF- DC converters such as half wave rectifier, full wave rectifier and 5 stage voltage doubler. As we can see, the voltage and current value is very low in all RF- DC converter. Nevertheless, 5 stage voltage doubler has good amount of voltage and current than others.

Therefore, we have chosen Greinacher voltage doubler for this research so as to make it efficient for RF – DC conversion because both voltage and current level is low in half wave rectifier and full wave rectifier.

6.4 Power Vs Distance between the Tx and Rx antenna

We are using Friis Transmission Equation for this purpose. The Friis Transmission Equation is used to calculate the power received from one antenna (with gain G1), when transmitted from another antenna (with gain G2), separated by a distance R, and operating at frequency f or wavelength lambda [17].

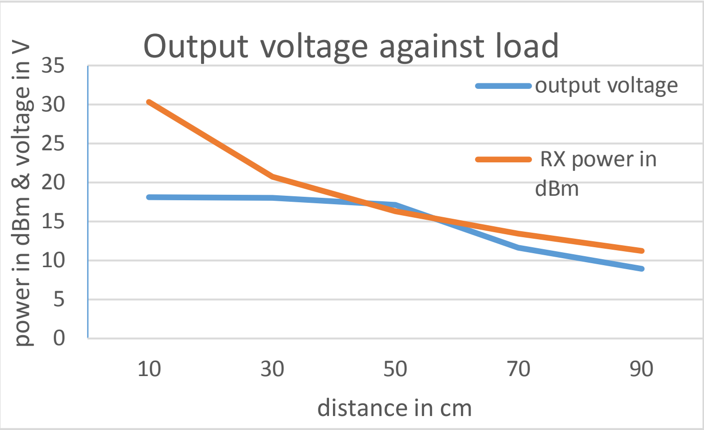


Fig. 20. Line graph representation of output against distance.

TABLE2
OUTPUTS AGAINST DISTANCE WHEN LOAD IS 10 KΩ

Distance from Tx antenna (m)	Received power on Rx antenna (dBm)	Output voltage (v)	Output current (mA)
0.10	30.3298	18.122	2
0.3	20.7874	18.059	2
0.7	13.4278	11.602	1.3
1.1	9.5020	6.795	0.9
1.5	6.8080	5.171	0.7
1.9	4.7547	3.90	0.5
2.1	3.8854	3.38	0.4
2.5	2.3710	2.501	0.25
2.9	1.0818	2.136	0.2136
3.1	0.5026	1.732	0.1814
5.1	-3.8216	0.875	0.1064
10.1	-9.7566	0.279	0.0278
19.9	-15.6473	0.054	0.005418

TABLE3
OUTPUTS AGAINST DISTANCE WHEN LOAD IS 100Ω

Distance from Tx antenna (m)	Received power on Rx antenna (dBm)	Output voltage (v)	Output current (mA)
0.10	30.3298	2.4137	24
0.3	20.7874	0.797	8
0.5	16.3504	0.431	4

From the above table, at 30.32 dBm, Vo = 2.4137 V and Io = 24 mA
Then, power = 57.84 mW i. e. 17.622 dBm.
So, for charging a battery of 1.2 V and 600 mAh, the time required is T = (Q / I) = (600 / 24) = 25 hour.

25 hour is very long time and which is taking longer than usual source. This time is not desirable, but it desirable to charge small sensors.
Efficiency, at 10 cm distance, and at Power input 30.32 dBm and power output 17.62 dBm, across 100 ohm load is only 5.37%.

Finally, we can say that, at 10 cm of distance between antennas, small batteries can be charged reluctantly.

7 CONCLUSION

7.1 Result Analysis

In this paper, we finally optimized the RF energy harvesting system to be able to charge the batteries and also power wireless sensor network. The whole work is done in the software called as Agilent ADS software where we have optimised the matching network and voltage doubler by choosing Agilent schottky diode HSMS285X.

The design system with the experimental results have shown an alternative means of charging hand held devices like mobile phones. The base stations of some of the telecommunication companies can replace the transmitter section of the prototype, and the receiver section can be incorporated in a silicon chip that can be embedded in any power critical device.
We have also analysed the effect of distances between Tx and Rx antennas on the RF energy harvesting system and on the output by Friis Transmission Equation, which is that at 10 cm, the small battery can be charged in a day.

7.2 Limitations

Although RF energy harvesting is an effective means to tackle the power problem with regard to WSN, autonomous sensors and charging battery, it needs further deep study and improvement regarding efficiency. It can charge battery easily but with maximum time, which is not desirable. Power efficiency at 0dBm of RF energy harvesting can be increased by full wave rectifier instead of voltage doubler because result reveals that.

7.3 Future Work

The work presented in this paper are matching network and RF- DC conversion. So, work on antenna and its optimization is reaming which will be future work. The right choice of RF – DC conversion is also important topic for future work. For dedicated source, the system is sound with respect to distance, but for ambient source the system is not desirable. As of now, there are no known companies developing the RF source battery charger, this implies a very good market opportunity for this product, as people will be willing to spend more money for convenience.

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