RF Energy Harvesting System and Circuits for Charging of Mobile Devices

Hamid Jabbar *Student Member, IEEE*, Young. S. Song *Member, IEEE*,
Taikyeong Ted. Jeong*, *Member, IEEE*

Abstract— RF energy harvesting holds a promise able future for generating a small amount of electrical power to drive partial circuits in wirelessly communicating electronics devices. This paper presents the overview and progress achieved in RF energy harvesting field. A modified form of existing CMOS based voltage doubler circuit is presented to achieve 160% increase in output power over traditional circuits at 0*dBm* input power. A schottky diode based RF energy harvesting circuit performance is also studied with practical and simulations results.

Index Terms — RF Energy Harvesting, Ambient circuit, Schottky diode, CMOS design, Resonant circuit

I. INTRODUCTION

Finite electrical battery life is encouraging the companies and researchers to come up with new ideas and technologies to drive wireless mobile devices for an infinite or enhanced period of time. Batteries add to size and there deposition cause environmental pollution. For mobile and miniature electronics devices the answer is available in capturing and storing the energy from external ambient sources, a technology known as *Energy harvesting*. Other names for this type of technology are *Power harvesting, Energy scavenging* and *free energy,* derived from *Renewable energy*. History of wireless power is discussed in [1].

Energy harvesters take fuel from ambient sources present around us and thus are free for the user. Types of ambient sources considered and used for energy harvesting are wind, solar, vibration, electromagnetic, temperature gradient, thermoelectric, heel strike, push buttons, Radio Frequency (RF), acoustic etc [2] [3] [4]. Till present the electrical power generated by Energy harvesting techniques is small (usually less than few *milli-watt*), depending on techniques it is enough to drive small electrical or low power consumption devices. But energy harvesting technology presents a promotable future in low power consumer electronics and wireless sensor networks. Advancements in ultra low power or power-stingy electronics devices are also a major driving factor for this type of technology [5].

This paper focus is on the Energy Harvesting technique using the Electromagnetic (EM) energy specifically Radio Frequency (RF). Radio wave is ubiquitous in our daily lives in form of signals transmission from TV, Radio, wireless LAN, mobile phone, etc. Communication devices generally have omni-directional antennas that propagate RF energy in most directions, which maximizes connectivity for mobile applications. The energy transmitted from the wireless sources is much higher (kW in case of some Radio broadcast), but only a small amount can be scavenged in real environment, rest is dissipated as heat or absorb by other materials. RF Power harvesting technique is also used in RFID tags and implantable electronics devices [4].

Most commonly used wireless sensor nodes consume dozens µW in sleep mode and hundreds µW in active mode. A great factor contributing for Energy harvesting research and development is ultra-low-power components. Current COTS components power consumptions range is approximately, Microcontrollers: 160µA/MHz, sensor: 120µA, Transceiver (RS-232): 3mA, Transceiver (RS-485): 120µA.

This paper presents the overview of Ambient RF sources and available power in Section-II. Energy harvesting system is discussed in Section-III. Schottky diode based energy harvesting circuit is discussed in Section-IV and Section-V with experimental and simulation results. Section-VI presents the simulation results of CMOS based RF energy harvesting circuit.

II. AMBIENT EM SOURCES AND AVAILABLE POWER

Radio waves, a part of electromagnetic spectrum consists of magnetic and electric and magnetic component. Radio waves carry information by varying a combination of the amplitude, frequency and phase of the wave within a frequency band. On contact with a conductor such as an antenna, the EM radiation induces electrical current on the conductor's surface, known as the skin effect.

The communication devices uses antenna for transmission and/or reception of data by utilizing the different frequency ranges. Frequency ranges and power at different frequencies spectrum from 10kHz to 30MHz are given in detail in [6].

The output power of RF devices is limited by regulations, such as Federal Communications Commission (FCC), USA due to safety and health concern offered by EM radiations [7]. The maximum theoretical power available for RF energy harvesting is 7.0 μW and 1.0 μW for 900 MHz and 2.4 GHz frequencies respectively for a freespace distance of 40 meters. The pathloss of signals will be different in environment other than free space [8].

An average current up to 8µA has been obtained from a 1.584MHz amplitude modulated radio signal for WSN [9]. A loop antenna and a folded dipole was used as receiving antenna which receives the power of 1µWatt (-30dBm) with an impedance of 50 Ohm at 300 MHz [10].

H. Jabbar was MS student in the Dept. of Electronic Eng., Myongji Univ. Korea
Y. Song is with the Dept. of Material Science, Dankook Univ. Korea
T. Jeong is with the Dept. of Electronic Eng., Myongji Univ. Korea
(* Corresponding author; *ph*: +82-31-330-6775; *e-mail*: ttjeong@mju.ac.kr)

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A 1V/m electric field can yield power density of about 0.26µW/cm^2. Only when close to a powerful transmitter, field strengths of a few volts per meter can be measured [2].

RF emissions from 800MHz range mobile equipments are significantly stronger signal than others, such as 2.4GHz range, which is mostly used by wireless LAN. A preferable range for RF energy harvesting is between 500 megahertz and 10 gigahertz, in which many different radio communication signals lies.

109µW power is available at 800MHz as a part of research work done in Tokyo area [11]. An attempted to charge mobile-phone batteries by capturing RF energy at 915 MHz, 4mV/second charging time was observed by reference [12]. RF energy generation and delivery systems to provide energy to down-hole electrical equipment without wires using conductive pipes for radiating RF signals was done by [13]. An integrated circuit for RF energy harvesting studies for 868.3MHz implemented in a Silicon-on-Glass substrate transfer technology are also presented by [14] [15]. Circuit and system for both Solar and 900MHz RF power scavenging and management is developed for medical purposes [16]. Wireless sensor module on Paper-based inkjet-printed RF modules with 3-D "cubic" antenna scavengers is designed by [11] for 900 MHz band. Two energy Harvesting systems, *a)* Intel's Wireless Identification and Sensing Platform (WISP) and *b)* VHF or UHF energy harvester from TV towers are explained in [17], the second one is capable of harvesting 60µW of power from a TV station 4.1 km away. An RF-DC power conversion system is designed in a 0.25µm CMOS technology, at distance of 15 meters, 1 volt DC is measured with 0.3µA load current at 906MHz [8].

Using resistor emulation approach a system using 2.4 GHz dual-polarized patch rectenna backed by a ground plane harvesting 420µW to 8µW from a 6cm x 6cm rectifying antenna with incident RF power ranging from 70W/cm^2 to 30W/cm^2, respectively is implemented using discrete components [18]. A 2.45 GHz power conversion and data extraction circuit is designed for a wireless autonomous sensor platform [19].

III. Energy Harvesting and Charging System

Fig. 1 show the block diagram of the system, where RF signals generated by multiple RF sources are captured by antenna. Using matching circuits for the antenna along with a rectifier, generated DC power is used by charging controller to run mobile device terminal functions or recharge its battery.

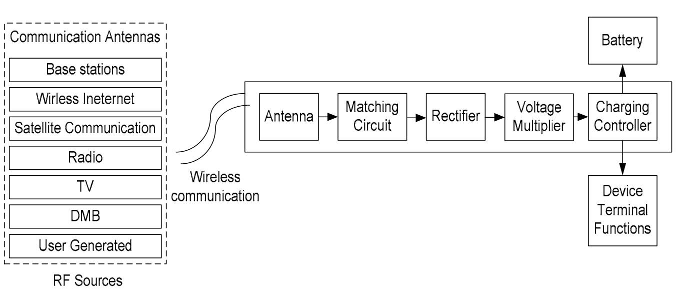

Figure 1: Wireless Charging System Architecture

This circuit will charge the battery by utilizing the ambient RF signal. Circuit will convert the RF signal to DC signal, and using the DC signal to charge the battery.

Complexities arise when we try to harvest energy from multiple RF sources. A RF energy harvesting system performance was demonstrated by [20] using maximum of four similar antennas in same space.

An energy harvesting system was studied through simulation and experimentally obtained data for practical design of the Smart energy harvesting circuit, as shown in the figure-2. The basic idea behind system was to use multiple antennas to harvest RF energy from different frequencies. The circuits need to be adjusted by using a controller to overcome the problem of frequency hopping and frequency tuning of signals. Also a wideband receiver antenna can be used which would be able to capture signals from multiple sources

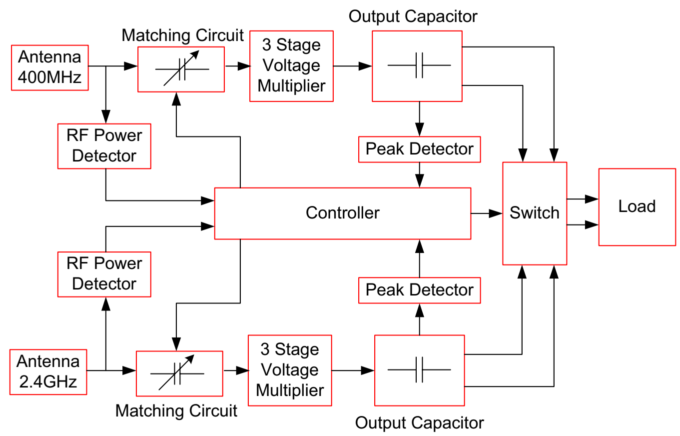

Figure 2: System diagram of Proposed Smart RF Energy Harvester

Using Commercial of the Shelf (COTS) (commercially available discrete circuitry) Components the system was crudely tested for the functionality and performance. RF power detector IC (LTC5505) was used with both the antennas. C_{tune} of Matching Circuit was manually tuned in response to the *RF Power Detector* and output power. Antenna was matched using trial and error ("annealing") empirical approach. Three-Stage voltage multiplier, consisting of schottky diodes is explained in section–V. The charging controller or Power Management circuit acts as a switch. Using the battery power level as a reference it charges the device battery or run the device terminal functions if battery is fully charged or only running the terminal functions is required as in battery less devices. The switch can easily be designed using a low power MOSFETs as comparator.

IV. Schottky Diode Based RF Energy Harvesting System

Schottky diode offer low forward voltage and high switching speed, and consider as an ideal component for RF energy harvesting.

A. Antenna and Matching Circuit

The RF signals can be captured using Multiband antenna as shown in Fig. 3. Antennas such as quad band are easily available in market and usually work at 900MHz/1800MHz/1900MHz/2.4GHz. These are of usually whip type, but small size such as printed, patch, spiral antennas are also testable.

For a 50Ω antenna, matching circuit (C_{tune}) is used as shown in Fig. 3, to capture the maximum power at required frequency range. Using only C in antenna matching circuit we can tune the antenna at its resonant frequency. The tuning Capacitor (C_{tune}) can be verified using following formula to resonate with antenna inductance ($L_{antenna}$), where f is the frequency of operation.

$$2\pi f = \frac{1}{\sqrt{L_{antenna} \times C_{tune}}}$$

At higher frequencies such as 800 or 1900MHz the low values of inductors are difficult to construct especially at board level circuit design. But using the inductor along with capacitor at integrated circuit level design greatly improves the performance. Resonant frequency is also influenced by diode capacitance as it is related with reverse diode voltage and input voltage.

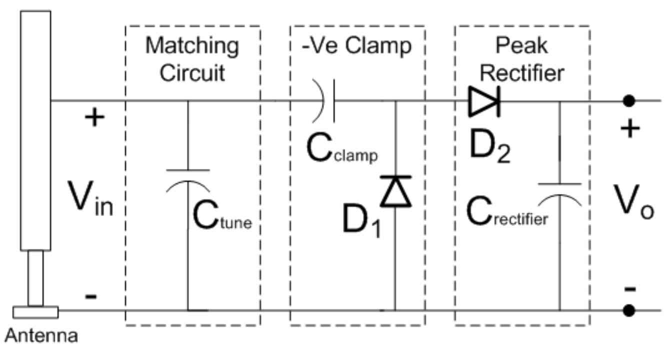

Figure 3: Single stage Voltage Doubler Circuit for converting ambient RF waves to DC

B. *Voltage Doubler Rectifier*

The Radio Frequency is AC signal, to get a DC signal out of the AC signal, a rectifier circuit is employed.

The charge pump circuits, such as voltage doubler (Villard voltage multiplier in this paper) are used to rectify the input voltage (V_{in}), by employing multiple stages the required output voltage (V_o) can be obtained. The voltage output is twice the input peak voltage, minus twice the diode threshold voltage. Under load, output voltage drops due to capacitor charge drain. Charge drained (Δq) by the load current (I_{load}) per period, where f is input signal frequency, is

$$\Delta q = I_{load}/f$$

The circuit can be extended to n stages, producing theoretical $2nV_{in}$ for output voltage. Under ideal condition the output of an n- stage charge pump circuit, with stage capacitance (C) will be

$$V_o = nV_{in} - \frac{n-1}{fC} I_{load}$$

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 high operating frequency. We tested a Schottky diode for rectifier as a safe operation.

C_{clamp} and D_1 form the negative clamp, while $C_{rectifier}$ and D_2 form peak rectifier. $C_{rectifier}$ also smooth the output.

Other forms of voltage multiplier or charge pumps circuits schemes can be used like Cockcroft-Walton (and Resonant-Villard) voltage multiplier and Dickson (and Resonant-Dickson) rectifiers [9].

A modified Villard Voltage doubler as an RF power harvesting circuit is presented by [21] for improving the efficiency.

C. *Villard Voltage Doubler Rectifier simulation results*

The Villard voltage multiplier was simulated using the circuit level simulator. The simulation employed the device level model of HSMS-2850 parameters to achieve the results presented in Figures 4.

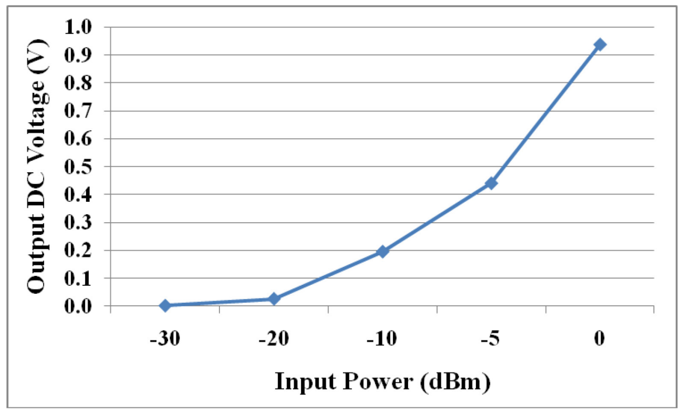

Figure 4: Output voltage and Input Power relation of schottky diode based single stage Villard voltage doubler circuit

From the simulation, it can be concluded that the output of voltage doublers circuit is:

$$V_{out} \approx 0.95\,(n)\,(2V_{in})$$

The output voltage V_o of an n stage Villard voltage multiplier can be calculated using the expression

$$V_{out} = \frac{nV_o . R_L}{nR_o + R_L} = \frac{V_o}{\frac{R_o}{R_L} + \frac{1}{n}}$$

where, V_o is the open circuit voltage, R_o is the internal resistance, R_L is the load resistance and n is the number.

V. Experimental Performance of 3-stage Schottky diode based Villard Voltage doubler circuit

The number of voltage doubler stages can boost the input AC voltages to a higher level and convert it to the DC. After studying different combinations of the Villard voltage multiplier, by following the techniques and simulation presented in [9] [12] [15] and [22], a 3-stage voltage multiplier was constructed with each stage using two HSMS2820 Schottky diodes and 2.2nF capacitors as shown in Figure-5.

Output capacitor was chosen to be 200nF. A 1MΩ resistive load was used at the output for measurement of the output power. Different experiments were conducted to measure the circuit's parameters and influence of the RF Power Source (Anritsu MG3700A). The output power around the resistive load was measured using Keithley 6485 Picometer and 2182A Nano-Voltmeter. Experimental setup for testing two parallel schottky diode based circuits is shown in Figure 6.

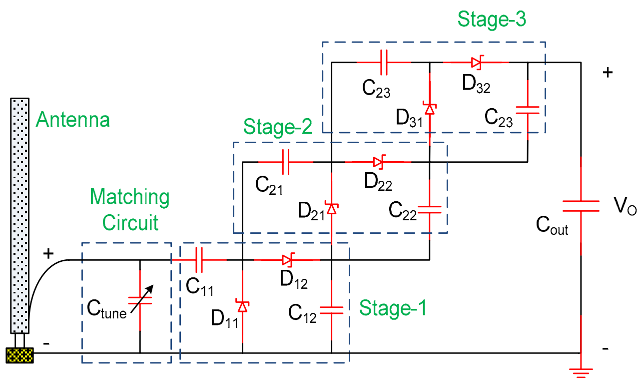

Figure 5: A 3-Stage Villard Voltage Multiplier Circuit

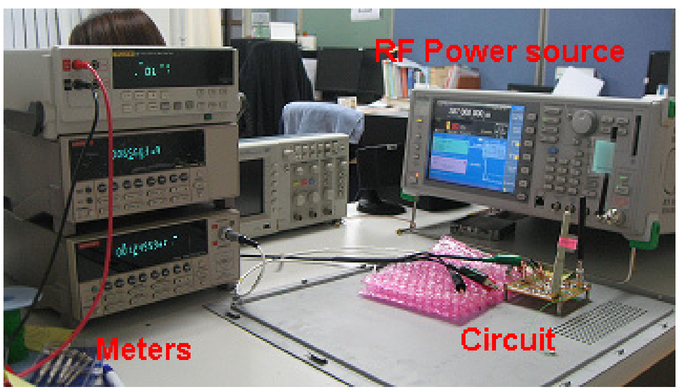

Figure 6: Experimental setup for testing of schottky diode based voltage doubler circuit

Proposed RF energy harvester circuit performance was tested with different helical antennas that pick up 400MHz, 315MHz, 868MHz, 915MHz and 2.4GHz frequencies. The impedance of each antenna is 50 ohm. Two circuits are constructed each having a 3-stage Villard voltage multiplier.

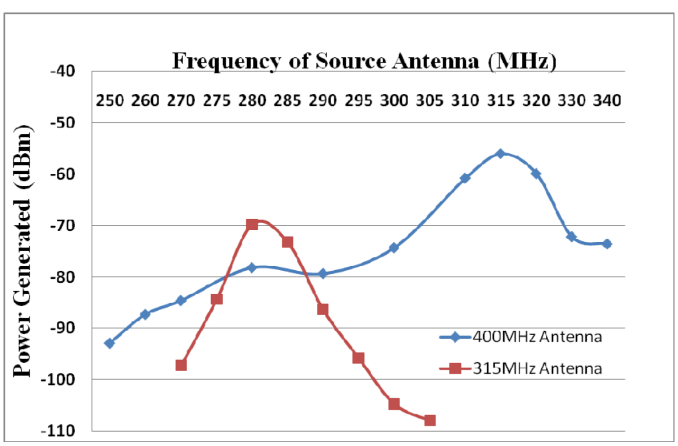

Figure 7: Output power at 2cm from 13dBm RF source

Figure-7 shows the result when source power was constant 13dBm from 400MHz antenna. The distance between circuit and source antennas, 400MHz and 315MHz, was 2 cm. C_{tune} was varied and tuned with respect to each antenna to get the maximum output power. The frequency of the source was varied to observe the maximum output power obtained at different frequencies, which shows that even with a single frequency source, different antennas can be tuned, output power from the best match antenna will be high, but still some power can be earned from other antenna as well.

Figure-8 shows the results when source power is variable and each circuit (400MHz and 2.4GHz) was tuned and tested separately. Distance between circuit and source antennas is 2 cm.

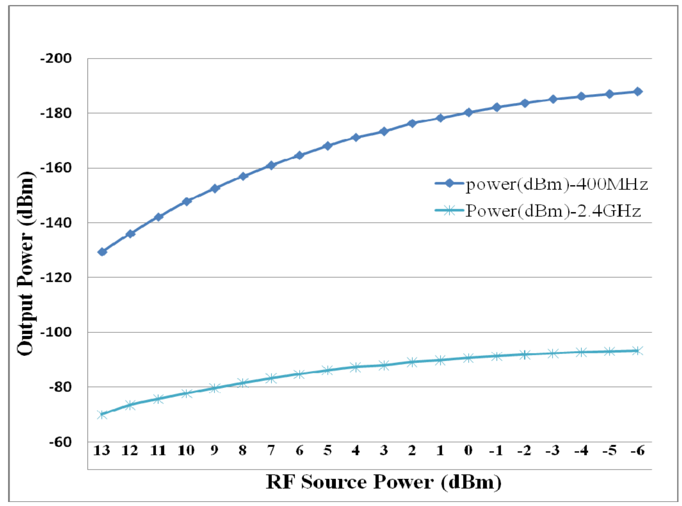

Figure 8: Power generated at 2cm from variable RF source power level

The RF power harvester is a strong function of the distance of the harvester from the power source. In free space, the path loss (L_p) of the RF signal is given by Friis' equation

$$L_P = \left(\frac{4\pi R}{\lambda}\right)^2$$

R= distance between the power source and power harvester,
λ = wavelength of the RF signal transmitted from the power source

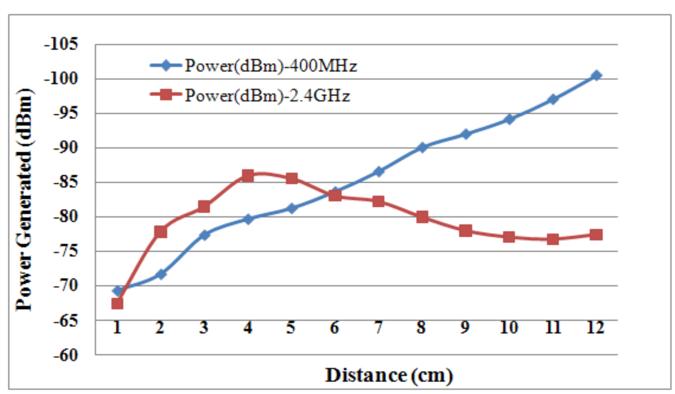

Figure 9: Power generated at variable distance from 13dBm RF source

Figure-9 shows the result when Source power is constant 13dBm and distance between the source and circuit is varied. Each circuit (400MHz and 2.4GHz) was tuned and tested separately. The 2.4 GHz circuit response was not in a straight line due to the presence of wireless Access Points in the building.

The output voltage is independent on the charge storage capacitance. Larger capacitance stores more energy, and only takes longer charging time. The rise time decreases as the output capacitor size increases.

VI. CMOS Transistor based Voltage Multiplier Circuit Design

As the schottky diode cannot be implemented in normal CMOS processes, a transistor based circuit is required for ambient RF energy harvesting. A traditional Villard voltage multiplier (shown in figure 10), also known as Cockroft-walton multiplier is simulated using the transistors as diodes to implement the circuit in CMOS based Integrated circuits [21].

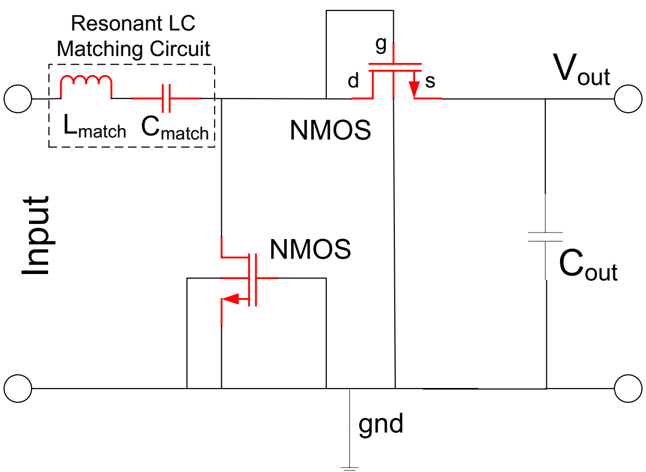

Figure 10: Traditional Villard voltage multiplier circuit using the NMOS transistors

For a typical 50Ω antenna, the -20dBm received RF signal power means an amplitude of 32mV. The peak voltage of the AC signal is much smaller than the diode threshold. A CMOS circuit is needed which can be switched by this low level signal and having the minimum power loss.

Previous studies have shown the use of resonant tank based matching circuit produces a larger voltage swing and improve efficiency [21].

In the ideal case, the highest output voltage is achieved at the resonant frequency of antenna having inductance L,

$$f = \frac{1}{2\pi \cdot \sqrt{LC}}$$

In [21] a Villard voltage multiplier is presented, which improves upon the traditional design through the implementation of a matching network resistant to parasitic losses, through a form of self-biasing to reduce the threshold voltage inherent in diode connected CMOS, and by floating the body of a PMOS to reduce body effect losses. The efficiency of the circuit is 22.97% at 66μW input.

In order for this design to work, it is critical that there is sufficient isolation that the body of the PMOS can be connected to V_{out} without any current flowing from the PMOS body to the bulk substrate. The body of a diode connected PMOS can be connected to V_{out} due to the fact that PMOS FETs are placed in an n-type doped well inside of the p-type substrate.

The improvement is the above mentioned circuit was desired to improve the efficiency to utilize the maximum part of available minimum power in this energy harvesting process.

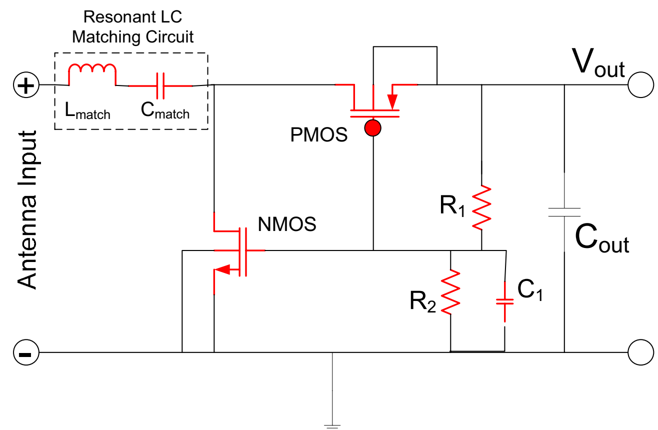

Figure 11: Villard voltage multiplier circuit for and energy harvesting simulated in this research work

As shown in Figure-11 the circuit simulated in this research work uses only one self-biasing circuit, consisting of R_1, R2 and C_1 for both the transistors as compared to two in [21]. As the self-biasing uses the self generated output voltage, using only one self biasing circuit reduces the load seen by the output voltage. This technique also reduced the circuit size as resistors are of larger values.

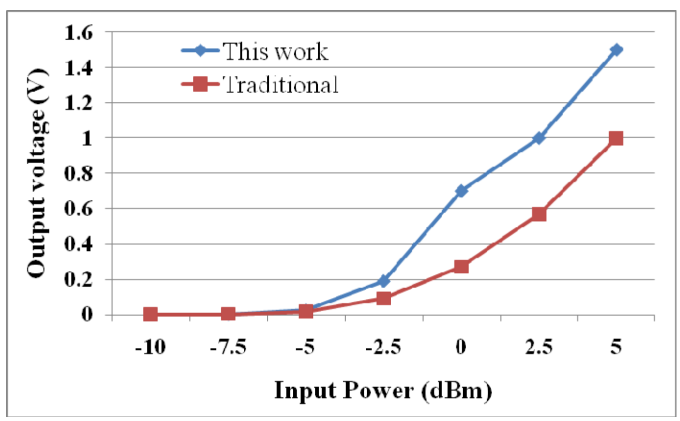

Figure 12: Simulation Results Showing the Input and output Voltage of the traditional and the circuit of this research work

Simulation results, input and output voltage, using the TSMC 0.25 μm technology is presented in Figure-12 showing the output voltage at different input power compared with the traditional Voltage multiplier circuit output voltage at 5MΩ resistive load. Table-1 shows the output power as compared with the output power of traditional CMOS based voltage multiplier (shown in Figure-10). The percentage increase in power using circuit in Figure-11 over the traditional circuit of Figure-10 is shown in last column of Table 1. We are interested in low input power considering a scenario the circuit is placed close to the RF source to harvest power.

TABLE 1
OUTPUT VOLATGE COMPARISON OF TRADITIONAL AND CIRCUIT SIMULATED IN THIS RESRACHJ WORK

Input Power (µW)	Output power (µW)		% Increase over Traditional
	Traditional	This Work	
316.23	8.43	12.39	47.06%
562.34	45.12	94.19	108.79%
1000	133.85	347.03	159.26%
1778.28	282.58	495.75	75.44%
3162.28	495.75	743.63	50%

VII. CONCLUSION

Low series resistance Schottky diodes are most suitable for implementing the RF energy harvesting circuit due to its high forward bias current for a given voltage. This paper presents the CMOS based Villard voltage multiplier circuit to be compatible with CMOS processes. The circuit can be used in RF energy harvesting and RF power transmission systems.

The circuit parameters are set according to design and input power range from -10dBm to 5dBm. The circuit shows improved output power than the traditional CMOS circuit. Higher performance can be achieved by implemented the circuit in low sub micron manufacturing processes. Output voltage level can be increased using multiple stages of the multiplier circuit.

The circuit can be used to capture the RF energy from a RF sources by placing it adjacent to RF source (wireless routers, mobile handset etc.). The circuit can be implemented in mobile handsets, wireless sensor nodes etc.

This technique can be helpful in charging of mobile handset (primary device) by placing to be charged mobile handset (secondary device) very close to fully charged mobile handset and draining primary device energy for charging the secondary device.

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BIOGRAPHIES

Hamid Jabbar received his Bachelor of Mechatronics Eng. degree from National University of Sciences and Technology, Pakistan in 2002 and MS in Electronics and Communications Eng. from Myongji Univ., Korea on Higher Education Commission of Pakistan scholarship. He started his career in NESCOM, Islamabad, Pakistan as Assistant Manager in 2003. Hamid Jabbar is award holder of Asia-Pacific Broadcasting Union Robot Competition, Japan in 2002. His research interests include circuit designing, mechatronics systems.

Young S. Song received his bachelor, master, and doctoral degrees from the Department of Materials Science and Engineering at the Seoul National University, Korea. Currently, he is affiliated with the Department of Fiber System Engineering at Dankook University, Korea. His research interests include advanced material processing and system engineering

Taikyeong Ted. Jeong received the M.S. and Ph.D. degree from the Dept. of Electrical and Computer Eng., the University of Texas at Austin in 2000 and 2004, respectively. He performed research in the area of high-performance circuit and low-power circuit design. Prof. Jeong currently an Assistant Professor at Myongji University, working on high-performance circuits for next-generation space robotics devices and analog circuits design. His research interests include low-power analog circuit design and biomedical application. He is a member of IEEE, IEICE, and IEE.