



## An IOT Based Wireless Energy Harvesting System Using Hybrid Voltage Multiplier Stages in an RF to DC Converter

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### ABSTRACT

The Internet of Things (IoT) is a technology that enables machines to communicate and exchange data with each other without much human intervention, with the aim of enhancing the quality of life. To achieve efficient data transmission, low-cost sensor nodes, actuators, and similar devices generate, exchange, and process data autonomously. However, energy consumption is a significant challenge for IoT nodes due to limited battery power. Energy harvesting, which involves capturing transmitted RF energy from the environment and using it to power low-power devices or store it for future use, is a promising solution to improve energy efficiency. However, one of the major challenges in energy harvesting is receiving extremely low-level signals from captured RF energy. To address this issue, this study developed a Hybrid Voltage Multiplier (HVM) stage that improves the output voltage of the existing Villard Voltage Multiplier stages. By using a Greinacher Voltage Multiplier circuit and a buck-boost converter, the HVM modifies the VVM circuit. Simulation results showed that the HVM modified with a Greinacher Voltage Multiplier circuit improved the output voltage by 4.76% when compared to other existing works. The simulation tool used in this study was Multisim 13.0."

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### INTRODUCTION

The Internet of Things (IoT) is a technology that connects uniquely identifiable devices wirelessly through the internet, allowing them to communicate globally. Its applications are not limited to household devices or smartphones, but include smart transportation systems, smart homes, surveillance, smart hospitals, and others. To function effectively in a complex network, IoT devices require energy-aware electronic circuits that can harvest power from the environment (Misra *et al.*, (2018). These devices are equipped with sensors, processors, transceivers, and an energy source to transmit and receive data. The major challenge of IoT communication is to provide sufficient power to run the network without affecting its Quality of Service (QoS). To achieve better energy efficiency and longer device life, energy harvesting is a promising technique that

traps transmitted RF energy from the environment and converts it into usable power (Ercan *et al.*, 2018). This idea requires a powerful antenna and a circuit that can change RF signals into DC voltage. Sources for RF energy harvesting include cellular base stations, television, Wi-Fi access points, and radio stations. However, the power harvested from RF sources (with frequency bands of 10 kHz to 30 GHz) is generally low and must be converted and enhanced for efficient load application. Voltage converters and multipliers, such as the Villard Voltage Multiplier (VVM), Dickson voltage multiplier, and Greinacher voltage multiplier, are commonly used to enhance the harvested voltages. This study proposes the development of an IoT-based wireless energy harvesting system that uses improved voltage doubler stages in an RF-to-DC converter to enhance the harvested voltages from RF sources.

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The proposed Hybrid Voltage Multiplier (HVM) stage modifies the existing VVM circuit by using a Greinacher Voltage Multiplier circuit (Filiz & Yunus, 2019).

The major contributions of the paper are summarized as follows:

1. Result from the simulation showed that the HVM had a 4.76% improvement in output voltage when compared with the existing works.
2. An improvement of 9.39%, 6.23%, 3.84%, 3.72%, 5.87%, and 4.26% was achieved at stages 2, 3, 4, 5, 6, and 7 respectively when compared with the existing works.

### REVIEW OF FUNDAMENTAL CONCEPTS

This subsection presents some of the fundamental concepts of energy transfer for spectrum sharing in cellular IoT communication and the systems model for RF and IoT energy harvesting amongst other concepts are also discussed. The review of fundamental concept will aid the easy understanding of some concepts that will be used during the course of this research.

#### IoT Communication

In the past, human-to-human and human-to-machine communication have been the standard methods of network communication. However, in recent years, machines have been communicating with each other in an impressive manner with minimal or no intervention from humans. This is achieved through the use of low-cost sensors, actuators, and other similar devices that generate, exchange, and process data

automatically, leading to efficient performance (Ercan *et al.*, 2018). With the world's population increasing, IoT is expected to play a significant role in addressing related challenges such as high energy consumption, limited resources, and interference. In IoT-enabled smart cities, common devices such as household machines, vehicles, and industrial equipment are expected to engage in machine-to-machine communication, displaying enough intelligence to sense and process information ubiquitously and in real-time. Fifth Generation (5G) networks are anticipated to play a significant role in IoT systems by ensuring good quality of service for a large number of network users as planned by 5G network.

IoT devices in smart cities will primarily use wireless communication technologies, particularly 5G. Therefore, it is essential to explore IoT in 5G networks, which are expected to provide massive connectivity and high data rates. The current wireless spectrum will not be able to meet the needs of all IoT devices with the significant increase in the number of users, making it challenging to address the limited spectrum. This can be resolved by the use of intelligent frequency spectrum allocation schemes (Osseiran *et al.*, 2016). IoT network employs a cluster form of communication for efficient communication processes. The use of clusters facilitates proper coordination and aggregation of information for effective transmission. Based on the available bandwidth and application. Figure 1 shows the architecture of cluster-based IoT Network (Alzahrani *et al.*, 2018)

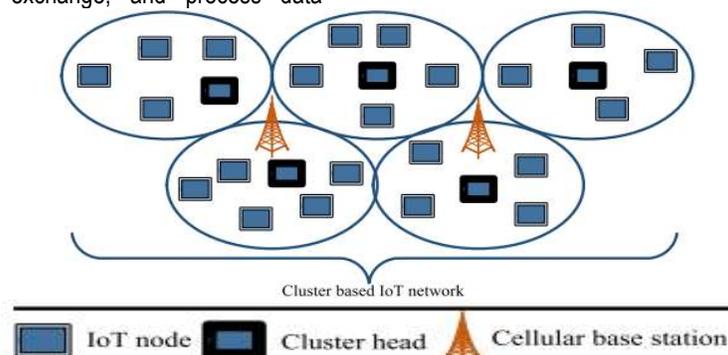


Figure 1: Architecture of Cluster-based IoT Network (Alzahrani *et al.*, 2018)

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### **Cellular Technology for IoT Network**

The coexistence of cellular networks with IoT networks requires the effective allocation and use of resources. LTE networks use OFDM and SC-FDM schemes in the downlink and uplink, respectively, and allocate resources through time-frequency slots called cellular resource blocks. The IoT network operates in synchronous time slots with cellular network TTIs, but SNs have different communication technology due to limited energy (Ercanet *et al.*, 2018). To reduce complexity and energy consumption, SNs' radios are tuned to a fixed bandwidth to communicate with CH using a simplified physical layer. Energy harvesting is a promising approach to recharge IoT devices and is used to harvest energy from ambient sources such as thermal, mechanical, solar, and RF. Dedicated RF sources have high power density and are used to power wireless nodes that require high energy. RF power extraction is achieved by receiving an RF signal using an antenna, rectifying it to produce the desired direct current, and matching the impedance to prevent reflection of RF energy into free space (Gozalvez, 2016). The average power that can be harvested from each energy source during energy harvesting is in the order of 1 mw for human movement, 10 mw for solar, 10  $\mu$ w for RF, and 1  $\mu$ w for vibrations. The concept of wireless RF power transmission increases the lifetime of the IoT network by allowing SNs to harvest energy from cellular networks.

### **ENERGY HARVESTING**

Energy Harvesting refers to the process of scavenging energy from various sources to power communication devices, such as network sensor nodes, for the Internet of Things (IoT). Research has been dedicated to developing energy harvester circuits for IoT devices. Energy can be harvested from different sources, such as dedicated and ambient sources (Gomez, 2016).

#### **Ambient and RF Energy**

Ambient and RF Energy is crucial to IoTs, as they face limited node energy for carrying out operations. Energy harvesting is a promising approach to ensuring that sensing and

communication devices remain charged and self-energized. Ambient energy can be harvested from various physical phenomena, including thermal, mechanical, solar, and RF. In IoTs, sensor nodes primarily harvest energy from RF sources (Gomez, 2016). The ambient source typically covers a transmission frequency range of 0.2 – 2.4 GHz and is available from the environment, such as television (TV), GSM, Wireless Local Area Networks (WLAN), and Wireless Fidelity (Wi-Fi) (Gomez, 2016). Dedicated RF sources are available on-demand for supply and usually have a high power density due to directional transmission. They are used to power wireless nodes that require a high amount of energy (Nechibvute *et al.*, 2017).

To extract RF power in standard RF energy harvesting systems, an antenna receives the RF signal, which is then rectified to produce the desired direct current that powers external devices. Impedance matching circuits are necessary to manage the RF energy received by the antenna, prevent the reflection of RF energy into free space, and increase the RF signal power of the rectifier circuit (Nechibvute *et al.*, 2017). It is essential to note that the power that a sensor node can harvest depends on the nature of the source, availability of energy/power, and dimensions of the energy harvester. Solar, human movement, vibrations, or RF waves already have implementable transducers for sensors (Gomez, 2016). During the energy harvesting process, the average power that can be harvested from each energy source is approximately 1 mw for human movement, 10 mw for solar, 10  $\mu$ w for RF, and 1  $\mu$ w for vibrations (Sudevalayam and Kulkarni, 2011).

The concept of wireless RF power transmission is a significant breakthrough for sensor nodes with the ability to harvest RF energy from cellular networks. The harvested energy increases the lifetime of the general IoT network, allowing SN to last longer for efficient communication (Ajayi *et al.*, 2022).

#### **Principles of Energy Harvesting**

The process of energy harvesting involves trapping transmitted RF energy from the

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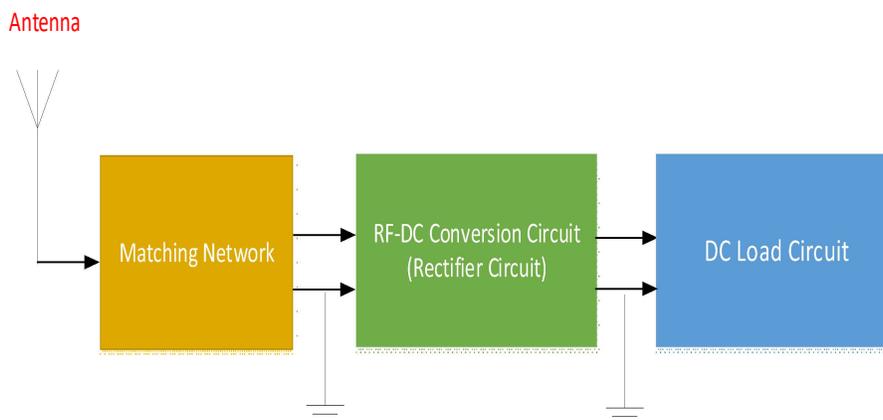
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environment and using it to power low-power IoT devices or storing it for future use. To achieve this, an efficient antenna and an RF to DC converter circuit are required to transform the RF energy to DC voltage. The efficiency of the antenna during the harvesting process largely depends on the impedance matching between the antenna and the energy transformative circuit. This work aims to enhance the collection of ambient energy from free space at a frequency of 900MHz by ensuring appropriate impedance matching between the two impedances. Various ambient RF sources, such

as FM (88-108 MHz) and AM (<1 MHz) radio systems, can provide power in the kilowatt range at specific MHz frequency ranges. Television broadcasts occur in the milliwatt range at a frequency range of 150-450 MHz, while cellular base stations provide power in watts at a frequency band of 900/1800 MHz. After impedance matching, the circuit's impedance in the electronic circuit becomes equal to the complex conjugate of the antenna's impedance. The basic principle of the RF to DC harvesting scheme is represented in Figure 2.



**Figure 2:** Schematic of an RF Energy Harvesting System (Nechibvute *et al.*, 2017)

### Voltage Multipliers for RF Energy Harvesting System

In energy harvesting, voltage multipliers are commonly used in the RF to DC conversion stage to increase the harvested voltage. The voltage multiplier circuit is made up of capacitors and diodes, which play a crucial role in energy harvesting. This stage boosts the harvested signal and converts it to DC voltage with minimal losses (Nechibvute *et al.*, 2017). Voltage multiplier components, also known as diode rectifier circuits, can provide an output voltage greater than their input voltage. Figure 3 illustrates the RF energy harvesting structure, with more emphasis on the multiplier level of the network (Feliz and Yunus, 2019). The three types of voltage multipliers are Villard voltage multiplier, Dickson voltage multiplier, and Greinacher Voltage Multiplier (Filiz and Yunus, 2019).

The Villard voltage multiplier circuit consists of two parts connected in series. The first part, which utilizes C1 and D1, forms a clamped capacitor circuit. Assuming perfect diodes, this circuit produces a voltage waveform similar to the input but increased by  $V_p$  across diode D1 when activated by a sinusoid of amplitude  $V_p$ . The positive peaks reach  $2V_p$ , whereas the negative peaks are clamped at 0 V. The second part uses D2 and C2 to create a peak rectifier circuit. In response to the voltage across the first diode, this circuit delivers a DC voltage of magnitude  $2V_p$  across capacitor C2. This circuit is called a voltage doubler because the output voltage is always twice as large as the input voltage (Shahshahan, 2012).

The Villard circuit comprises two capacitors and two diodes for each stage. Its principle of operation depends on the polarity of

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the input voltage, which determines the behavior of the diodes. Specifically, if the RF voltage is negative, D1 is active and D2 is not active,

whereas if the RF voltage is positive, the two diodes will reverse their configuration.

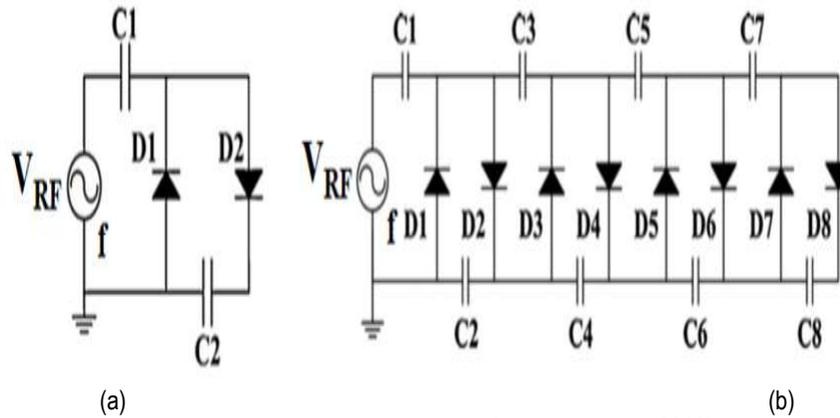


Figure 3: Villard Voltage Multiplier (Filiz and Yunus, 2019)

The model equation for output voltage of n-stage Villard voltage multiplier is given as Misra *et al.*, (2018):

$$V_{DC} = \frac{nV_o}{nR_o + R_L} \quad (1)$$

where:

n is the number of stages.

$V_o$  denotes the open circuit output voltage.

voltage.

$R_o$  represents the internal resistance of the circuit.

$R_L$  is the load resistance of the circuit.

The application of the Villard voltage multiplier is simpler to actualize when compared to other types of voltage multiplier circuits (Misra *et al.*, 2018). The application of Villard voltage multiplier in the work of Misra *et al.*, (2018) during energy harvesting process is given in Figure 4.

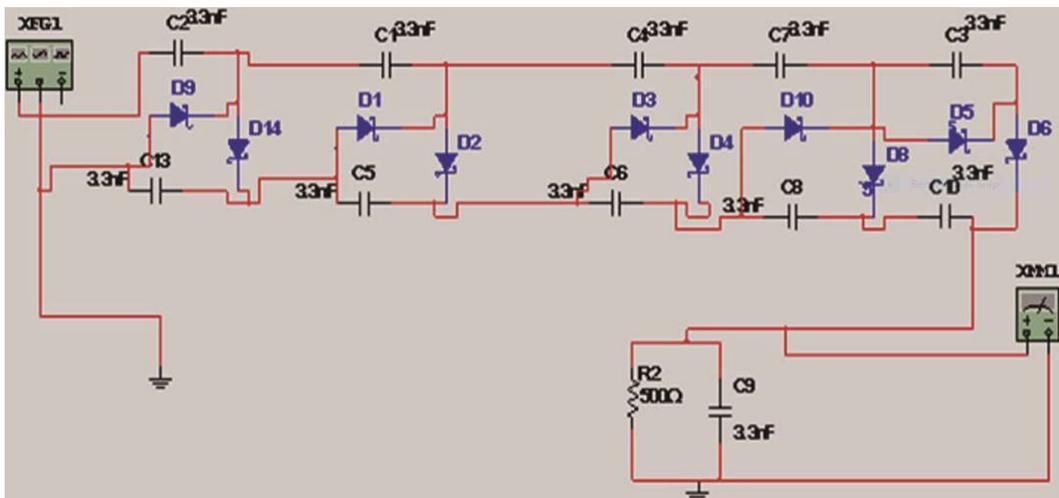


Figure 4: Application of Villard Voltage Multiplier Circuit (Misra *et al.*, 2018)

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### Greinacher Voltage Multiplier

The Greinacher voltage doubler is one of the earliest examples of voltage doubling circuits in the literature, and when used in a cascaded structure, it forms the Greinacher voltage multiplier. Figure 5 depicts the typical architecture of a half-wave Greinacher voltage multiplier, which is also known as the Cockcroft-Walton multiplier. Although the Greinacher doubler has better output ripple characteristics compared to the Villard rectifier (Guler & Ghovanloo, 2017), modifications are still required to improve its power conversion efficiency (PCE). Curty et al.

(2017) proposed several improvements to increase the PCE of the Greinacher voltage doubler, with the most important being the reduction of input impedance by better matching the receiver coil and rectifier. This reduction is achieved by rearranging and placing capacitors symmetrically, ensuring that every diode in the voltage doubler is excited with the same input signal amplitude. Additionally, the symmetric placement of the capacitors also reduces reflected harmonics.

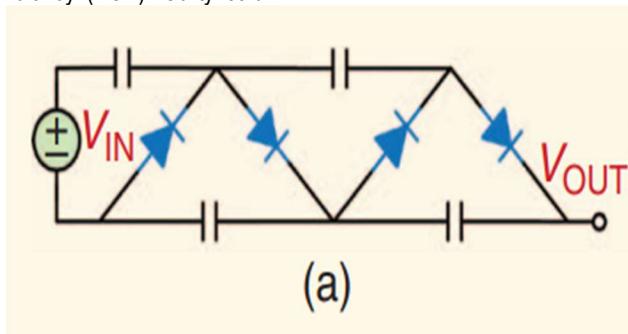


Figure 5: The Greinacher Voltage Multiplier (Guler & Ghovanloo, 2017)

Dickson utilized a modified Greinacher voltage doubler as a DC-DC converter by proposing a charge pump circuit that converts DC supply voltage to a higher one. The output of the Villard circuit is higher than that of a simple rectifier, but it does not much resemble DC. The Greinacher doubler improves significantly on the Villard by following it with another diode and a capacitor to form a peak detector and smooth the extreme fluctuations of the Villard into something more resembling the output of a simple rectifier. However, the voltage is still much higher (Joseph, 2019; Ansari et al., 2015).

### REVIEW OF SIMILAR WORKS

For RF energy harvesting applications, Ozturk and Coshun (2019) developed a unique power divider/combiner design with a stacked conic line. Three alternative designs were completed with a central frequency of 2 GHz.

According to the number of transmission layers in each design, the bandwidth and S parameter characteristics were compared, and it was found that as the number of transmission layers rises, so does the bandwidth. The triple layer Wilkinson power divider was chosen to link to the Villard voltage doubler circuit based on the design results. The Wilkinson power combiner circuit inputs received input powers ranging from 10 dBm to 5 dBm. As a result, efficiency was seen to be around 70% when minimal input power was used. Although, the output of the Villard circuit is higher than the output of a simple rectifier, it doesn't much resemble DC, which could reduce the efficiency of the output power.

For RF energy harvesting systems, Tafekirt et al. (2020) presented a revolutionary sensitive triple-band power rectifier. At relatively low and medium ambient power densities, the suggested rectifier can simultaneously harvest RF energy from the GSM-900, GSM-1800, and Wi-Fi-

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2450 bands. Due to the nonlinearity and distinctive input impedance of the rectifying circuit at these frequencies, a few multi-band antennas have previously achieved a steady conversion efficiency overall frequency range of interest. The improved impedance matching technique that improves the rectifier's effectiveness and performance is what makes this article unique. Three parallel branches make up the high-efficiency triple-band rectifier that is being proposed. A single voltage doubler using the Schottky diode HSMS-2852, a DC-pass filter to smooth the DC output voltage, and an input matching circuit for optimal RF power transfer to rectifying diodes are included in each branch. To compare its performance to the simulation results, a prototype of the suggested rectifier circuit is built and tested. The measured RF to DC conversion efficiency reaches 33.7%, 21.8%, and 20% at 0.9, 1.8, and 2.45 GHz, respectively, with an ideal load resistance of 3.8 k at -10 dBm input power level. Under 0 dBm input power, the overall efficiency is more than 46.5%. Although, the output of the Villard circuit is higher than the output of a simple rectifier, it does not much resemble DC, which could reduce the efficiency of the output power.

Li *et al.*, (2021) developed a novel dual-band multi-port compact rectenna design for RF energy harvesting. The authors made use of an E-shaped coaxial fed microstrip antenna combined with an inverted L shaped structure to achieve 2.4 GHz (WiFi) and 0.9GHz dual band operating frequency with gains of 0.8 dBi and 4.4 dBi respectively. In order to restrict the antenna size to 50mm x 47mm, a shortened post was incorporated in the system design. Also, to ensure adequate conversion of frequency of about 50%, a compact rectifier circuit covering both the frequency bands was designed for an input power of -20dBm. The design also incorporated matching circuits in order to ensure that the nonlinear impedance of the rectifier matched with that of the antenna under varying operating conditions. Additionally, the rectennas designed were combined and arranged together to form a cubical structure to produce an output voltage of 0.5 V for an input power of -20 dBm. With 360° coverage and orthogonal polarization reception,

the cubical antenna arrangement ensured that an improved harvesting efficiency was achieved. However, the matching network made use of the conventional circuit design which involves lots of ripple losses thus reducing the targeted harvesting efficiency of the study.

The described rectifier circuit in this work of Doan *et al.*, (2016) was created in the same 2.4 GHz Industrial, Scientific, and Medical (ISM) band as a result of the rising popularity of Internet of Things (IoT) devices using that frequency range. The voltage doubler circuit is initially selected as the primary rectifier circuit, and then it is cascaded into additional stages until the best possible outcome is attained. By adjusting the value of the capacitor and resistor at a single stage, the optimization is studied across -30 dBm to 0 dBm of RF input power. According to the simulated results, the Dickson topology produces somewhat more voltage than Villard topology. The optimal number of stages is therefore 6, as more stages led to lower output power. However, the output of the Villard circuit is higher than the output of a simple rectifier, it doesn't much resemble DC, which could reduce the efficiency of the output power.

Based on the 7-stage Villard rectifier voltage multiplier circuit, which was examined and simulated using Agilent Design Systems, Pinto *et al.* (2021) developed a framework for a Wi-Fi Energy Harvesting system (ADS). Input power of -18 dBm and design parameters are used to set the circuit parameters. It was discovered that the 7-stage Villard cascade circuit's final simulated output was around 204 mV. The simulated output showed that a higher output voltage was created by feeding the power management circuit the output of the multiplier circuit. The drawback is that the output of the Villard circuit is higher than the output of a simple rectifier, it doesn't much resemble DC, which could reduce the efficiency of the output power.

## METHODOLOGY

The following methodology will be used in carrying out the stated objectives:

- i. Development of an IoTs based wireless energy harvesting circuit using seven stage

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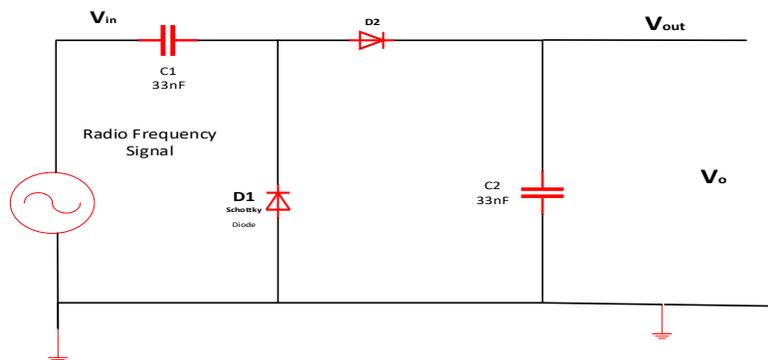
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- Villard voltage multiplier stages in a RF to DC converter is carried out using the following steps:
- a) Designing of the energy harvesting system
  - b) Assembling of the circuit components of the work of Misra *et al.*, (2018) which include HSMS 2850 Schottky diodes, electrolytic capacitors, XEG1 RF harvester module operating at 900MHz and a reactive load.
  - c) Connecting the circuit components based on single stage Villard Voltage Multiplier (VVM) configuration.
  - d) Connecting the circuit components for seven stage VVM.
- ii. Connecting electronic device for Hybrid Voltage Multiplier (HVM) stages involves the following:
- a) Connect the Circuit Components for a Single Stage VVM and Greinacher Voltage Multiplier (GVM)
    - b) Connecting the HVM for seven Stage Phase
    - c) Connect the reactive load
    - d) Read and record the output voltage of HVM
  - iii. Comparing the performance of the developed system in items 1 and 2 with that of Misra *et al.*, (2018) using simulated output voltage as performance metrics.

### Connect the Circuit Components for a Single Stage VVM and GVM

In order to develop a hybrid circuit, the single stage VVM circuit designed is adopted. Also, the GVM single stage circuit is designed. The circuit components for simulating the GVM circuit is selected which include the diodes and the capacitors. The diodes are the Schottky diode and the capacitor has a value of 33nF. The circuit diagram for the designed GVM is given in Figure 6. The output of the VVM is connected to the input of the GVM thus forming the first phase of the Hybrid Voltage Multiplier (HVM).



**Figure 6:** Designed Single Stage Greinacher Circuit

Noting the fact that the Greinacher circuit has the advantage of having peak to peak voltage at every stage. The HVM takes the advantage both VVM and GVM in ensuring that a circuit with better performance is developed. The model equation for a single stage Greinacher output voltage is given as:

$$V_o = 2V_m$$

(2)

where:

$V_{DC}$  is the DC voltage

$V_m$  represents the peak amplitude of

the input voltage

In order to implement the HVM, the single stage Villard voltage is connected to the Greinacher voltage. The Lumped capacitors in the Greinachers circuit are classed as shunt

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capacitors and series capacitors. Shunt capacitors are omitted by the I-V characteristics of the Schottky diode. In general, for the rectifier that rectifies only a single tone signal, the power series expansion method is used to obtain the output current. The output current  $y(t)$  can be expressed as equation (3). The constants  $c_1$ ,  $c_2$ , can be obtained by equation (4) for a specific forward bias voltage.

$$y(t) = c_1 \cos \omega t + c_2 \cos^2 \omega t + \dots \quad (3)$$

$$c_1 = \frac{1}{1!} \frac{\partial y(x)}{\partial x_{x=V_d}} \quad (4)$$

$$c_2 = \frac{1}{2!} \frac{\partial^2 y(x)}{\partial x^2_{x=V_d}} \quad (5)$$

The role of the shunt capacitor of the rectifier that uses a PN junction diode at a low

frequency is charging, and for the mixer, the role of the shunt capacitor is as an envelope detector or Low Pass Filter (LPF). For the rectifier using the Schottky diode, the charging mechanism is not needed due to its linear I-V characteristic in the operating region. The series capacitor used in the Greinacher voltage multiplier circuit acts as both an High Pass Filter (HPF) and also a DC Block (DCB) for DC bias. That is, unlike the shunt capacitor, which acts as a simple LPF, the series capacitor acts as a charging capacitor. Moreover, for the series capacitor at the input network, the operating frequency surpasses this and thus blocked higher order harmonics as well as the DC at the same time. Therefore, the series capacitor should act as a Band Pass Filter (BPF) and a DCB. The first phase of HVM involves connecting the output of the single stage Villard voltage circuit to the input of the Greinacher voltage circuit as shown in Figure 7.

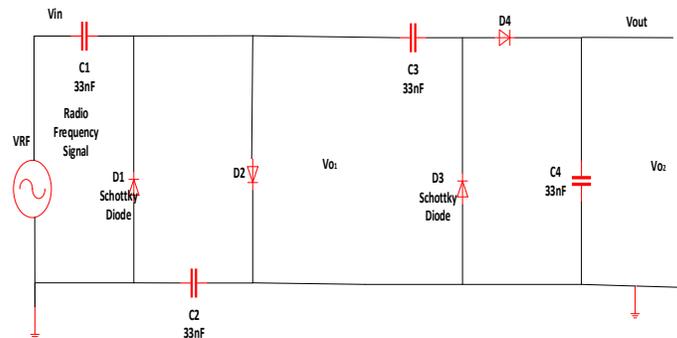


Figure 7: First Phase Designed Single Stage HVM

#### Connecting the HVM for seven Stage Phase

The major aim of the design of this circuit is to efficiently multiply the output voltage. Increasing the stages of the circuit has the ability of increasing the expected output voltage of the entire circuit. Thus, the seven-stage design of HVM involves interconnection of single stage HVM. This was carried out using the multisim 13.0 software. Here, the output of a single stage HVM is connected to another phase of single phase HVM. This is shown in Figure 8.

The important characteristics of the developed circuit is that as the number of stages

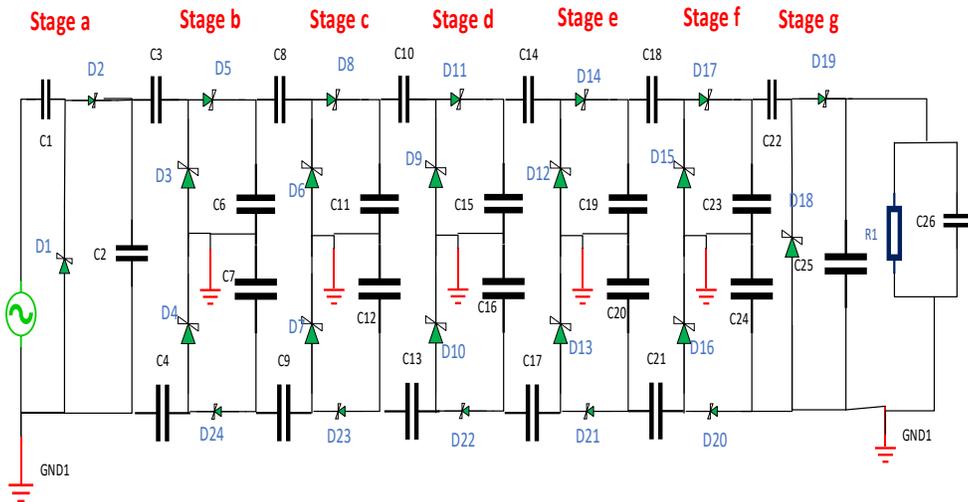
increases, the voltage also added proportionally. For instance, the DC voltage that is obtained at 1st stage is not only accurate DC voltage, but it is having ripple content. Thus, the use of GVM and the buck-boost converter, makes up for the ripple voltage. It's good to note that for this typical characteristic of the circuit, successive stages can produce more voltage than the previous stages. When the second stage appears after the first stage multiplier, the input that the second stage accepts is the voltage of the first stage. The voltage gets doubled and is summed to the DC voltage that receives from first stage.

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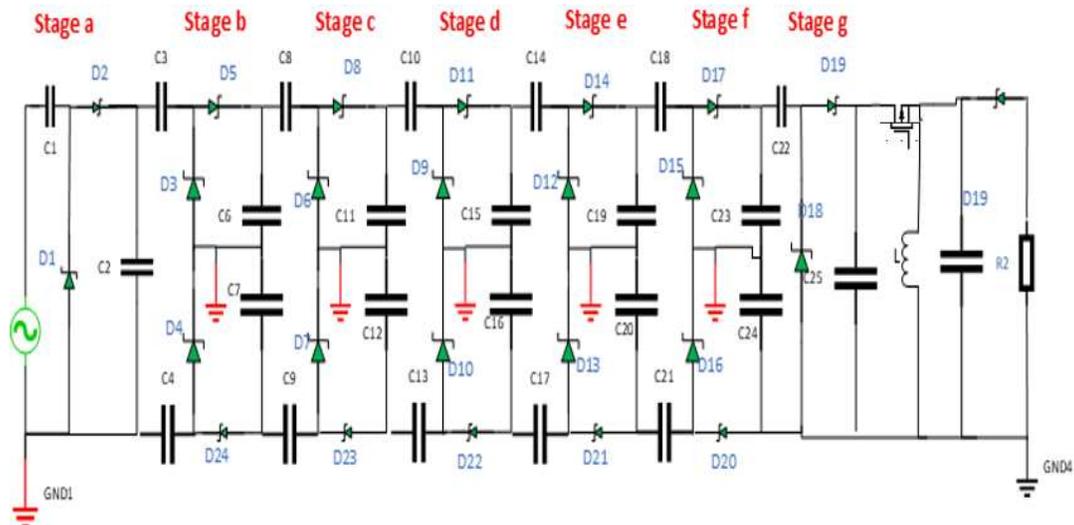


**Figure 8:** HVM Seven Stage Circuit with a Greinacher Voltage Multiplier circuit

From Figure 9, stage “a” is a single stage VVM which implies that the output voltage of this stage is given by equation (5). Stage “b” to “f” is a five stage GVM circuit, while stage “g” is a single stage VVM circuit. With respect to these stages, the output DC voltage of HVM is the stage-by-stage summation of DC output voltages of

individual stage running from stage “a” to “g”. Hence, the HVM model equation for output DC voltage is given as:

$$V_{DC} = \left[ \frac{V_o}{R_o + R_L} \right]_a + [2nV_m]_{b-f} + \left[ \frac{V_o}{R_o + R_L} \right]_g \quad (5)$$



**Figure 9:** HVM Seven Stage Circuit using a Buck-boost converter

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### Testing of the Developed Circuit by Reading and Recording the Output Voltage

The complete developed circuit diagram made use of radio frequency signal of the environment as input to the circuit. The circuit consists of 14 Schottky diodes (HSMS-2850). The unique characteristics of the diode is that it gives a small forward potential difference, small amount of substrate leakage and it also provides a one-way flow of current under best condition. Here, RF source is used as the input to the circuit. The input RF voltage determines the output DC voltage. Mobile phone's RF signal acts as a RF source. RF to DC conversion starts if the input voltage is more than the Schottky forward voltage.

### PERFORMANCE EVALUATION

The performance analysis for this work is implemented using the equation (6) and (7). Equation (6) is utilized to compute the individual percentage improvement of the HVM model over the VVM. While equation (7) is used to compute the mean percentage improvement over the seven stages considered:

$$\% \text{ Improvement} = \frac{\text{HVM} - \text{VVM}}{\text{VVM}} \times 100\% \quad (6)$$

$$\text{Average \% Improvement} = \frac{\sum_1^7 \left( \frac{\text{HVM} - \text{VVM}}{\text{VVM}} \times 100\% \right)}{7} \quad (7)$$

### RESULTS AND DISCUSSION

In this section, the detailed procedures for the implementation of the proposed work are considered. These procedures will highlight the

steps taken for the actualization of the proposed work.

### Comparison of Simulated HVM and VVM Output Voltage at Different Stages

Figure 10 is a graph of the simulated outputs of DC voltage of HVM circuit and the VVM circuit from the work of Misra *et al.*, (2018). It can be observed that an increase in the number of stages increases the recorded output voltage. It can be observed that when the number of stages was increased from four (4) to Seven (7), there was a significant increase in voltage as compared to the other earlier stages. This is because, a cumulative increase in the number of stages gives better voltage multiplication. From the graph, simulations were carried out for both HVM and VVM circuits. It can also be observed that the output voltage of the HVM at all stages outperformed that of VVM from the work of Misra *et al.*, (2018). Notice that at the second stage the HVM showed a sudden shoot up in voltage.

This is because, the second stage in the HVM represents where the Griener circuit configuration was introduced in the HVM circuit. However, at the third stage and beyond, there was a stable increase in the output voltage. Here, the circuit simulated output voltage when  $V_{in}$  is 1000mV and  $R_{Internal}$  and  $R_{Load}$  ratio is 0.25 was simulated. The output voltage for VVM and GVM stages was estimated using equations (5) and (6) respectively. From the Figure, it can be observed that the developed HVM as an output voltage improvement of 4.76% when compared with work of Misra *et al.*, (2018). Percentage improvement is shown in Table 1.

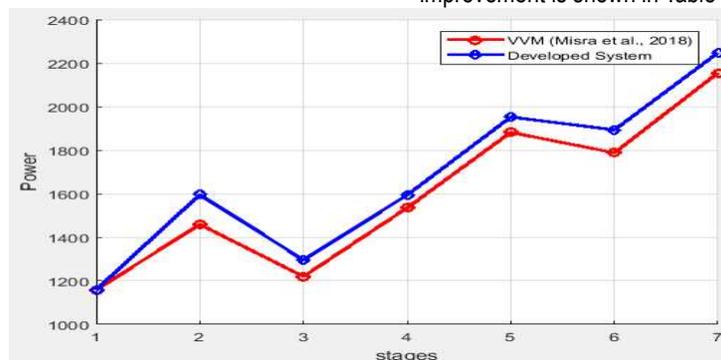


Figure 10: HVM and VVM Output Voltage

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**Table 1: Mean Percentage Improvement of HVM against VVM**

Variable	VVM (Vm) Misra <i>et al.</i> , (2018)	HVM (Vm)	Percentage Improvement
Circuit Average Output voltage	1599.71	1676.71	4.76%

The voltage improvement at each stage is analyzed in Table 2. It can be observed from the table that the HVM showed better output voltage for stages of the network. Thus, the use of any  $n$

stages of HVM will improve the output voltage of energy multiplying circuit when compared with VVM energy multiplying circuit.

**Table 2: Percentage Improvement of HVM against VVM**

Stages	VVM (Vm) (Misra <i>et al.</i> , 2018)	HVM (Vm)	Percentage Improvement
Stage 1	1159	1159	-
Stage 2	1459	1596	9.39%
Stage 3	1220	1296	6.23%
Stage 4	1535	1594	3.84%
Stage 5	1882	1952	3.72%
Stage 6	1788	1893	5.87%
Stage 7	2155	2247	4.26%

## CONCLUSION

This research has developed an IoTs based wireless energy harvesting Hybrid Voltage Multiplier (HVM) circuit using the Villard voltage multiplier circuit and the Greinacher voltage multiplier circuit. Results from simulation showed that the developed HVM circuit improve the output voltage of the energy harvesting circuit when compared with the VVM circuit from the work of Misra *et al.*, (2018). Also, the output power of the developed HVM was analyzed at various output voltages. The developed HVM showed increased power that is suitable for most electronic load networks, which further enhances the efficiency of wireless energy harvesting systems.

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