# An Enhanced RF Energy Harvesting System for Low-Power Wireless Sensors in 900 MHz Band

Mohammed M. Bait-Suwailam, Zia Nadir

***Abstract*****—**This paper describes a technique to enhance energy conversion module for Radio Frequency (RF) energy harvesting system at 900 MHz band. The function of the energy conversion module is to convert the RF signals into direct-current voltage at the given frequency band. The proposed design is capable of charging small power consumption sensors by capturing ambient RF waves. The technique comprises the use of high-profile monopole antenna array with a reflector at the front-end of the harvesting circuitry in order to maximize the RF energy received by the antenna system. Furthermore, a prototype of the proposed RF energy harvesting system was simulated, built and tested in laboratory. The proposed design is compared with a reference case that uses only a single monopole antenna element at both transmitter and receiver sides. The achieved results show better performance. The designed system is useful in many wireless applications and can easily be integrated with other high-gain antenna systems to further maximize the harvested energy.

***Keywords*****—** Electromagnetics, energy harvesting, energy scavenging, radio-frequency harvesting, and rectenna.

## I. INTRODUCTION

Nowadays, wireless devices are growing in many applications like mobile phones or sensor networks. Such wireless devices provide efficient and practical solutions to consumer, industrial, and military needs. This dramatic growth in wireless applications produces a large usage of batteries that gives alternative solutions for empowering most wireless devices. However, such batteries pose constraints due to packaging size, operational time, and their deposition cause environmental issues. Furthermore, many applications, like wireless sensor nodes are located in difficult or inaccessible places so their battery maintenance becomes a crucial issue. This problem motivated lots of researchers to think of infinite power supply resources or enhanced power over a period of time. Fig.1 depicts several potential sources of power harvesting around us, including ambient electromagnetic waves. It is indeed possible to capture sufficient energy by harvesting the energy from, for example, vibration from people walking or even automobile heat, wind or broadcasting waves, etc..., to power very small devices such as wearable electronic devices and wireless sensor networks. Although the amount of energy harvested from Radio Frequency (RF) waves is relatively low, nevertheless, in many instances only a few milliwatts of power is needed to power wireless sensors.

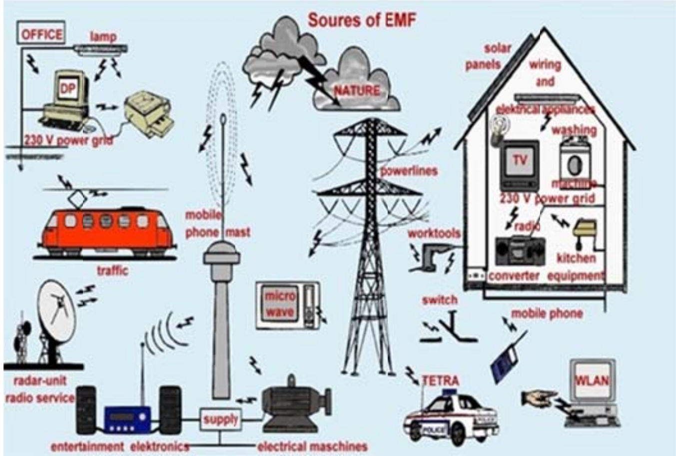

Fig. 1: Potential radio-frequency (RF) sources.

The concept of RF energy harvesting system is shown in Fig.2, which consists of a radiating system, a matching network, RF-DC conversion and load circuits.

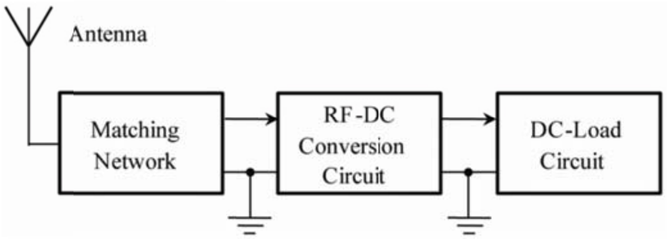

Fig. 2: RF harvesting system block diagram.

Currently, many technologies have been developed that attempt to overcome the limitations imposed on wireless devices. For instance, recent advancements in rechargeable batteries and use of double-layer capacitors, as well as technologies that harvest solar, wind, or even kinetic energy to name a few have been effective at satisfying a large portion of the established market need. Moreover, in some deployments, owing to the sensor location, battery replacement may be both practically and economically infeasible, or may involve significant risks to human life [1]. Another alternative is to get an advantage of the electromagnetic RF waves that exist around us. Such waves can propagate through the surrounding

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space and hence can be captured by an antenna. This kind of energy harvesting is still a new research direction and is of great interest to engineers and researchers worldwide. Several sources for RF energy harvesting exist, which can be classified into three categories: intentional sources, anticipated ambient sources, and unknown ambient sources. The intentional sources are in fact dedicated power transmitters that provide controlled amount of power. Unknown ambient RF sources can still provide minimal amount of power, however, with no control and no knowledge of the sources of such transmitted energy. The levels of power RF available in the ambient environment are low, which requires a matching circuit to minimize the losses by reflection and to maximize the transmission of power towards the electronic device [2].

The main objective of an RF energy harvesting system is to convert the RF power from the space into usable electrical energy source. When harvesting energy in the GSM or WLAN band, one has to deal with very low power density levels. Therefore, neither GSM nor WLAN are likely to produce enough ambient RF energy for wirelessly powering miniature sensors, unless a large area is used for harvesting. Alternatively, the total antenna surface can be minimized if one uses a dedicated RF source, which can be positioned close (a few meters) to the sensor node, thereby limiting the transmission power to levels accepted by international regulations [3].

In order to achieve that, a system with several stages is required. The RF power is generated from a transmitting antenna (i.e., the ambient RF waves), which are then captured by a receiving antenna as an input feeder to the harvesting circuitry. In this work, we propose the use of linearly polarized antenna system for ease of impedance matching. Second step is to transfer the power received by the antenna to the circuit with minimal losses. Therefore a matching circuit, if needed, is placed at the input stage of the harvesting circuit to minimize the mismatch between the antenna and the next component of the circuit. Furthermore, a voltage booster circuit is added to the device as an amplifying unit for the voltage input in order to increase the output voltage of the system. Since most of the consumer devices require a DC supply unit to charge, a rectifier circuit takes its function to convert the AC voltage into DC and stores it in a storage unit. Significant amount of research work have been conducted in this exciting field ranging from antenna design to high-efficiency rectifying devices. The RF-DC conversion efficiency of the rectenna with a diode depends on the microwave power input intensity and the connected load. We need to get the optimum microwave power input intensity and the optimum load to maximize the efficiency. When the power or load is not well matched, the transferred power is not the optimal power and the efficiency becomes quite low. The efficiency is also determined by the characteristic of the diode; the diode has its own junction voltage and breakdown voltage. If the input voltage to the diode is lower than the junction voltage or is higher than the breakdown voltage, the diode does not show a rectifying characteristic. As a result, the RF-DC conversion efficiency drops with a lower or higher input than the optimum [4].

It is instructive to mention here that tremendous amount of work have been allocated to antenna design of such harvesting systems [5]-[9]. Many of such research attempts have adopted commercially available antennas or even designed ones that are electrically-large. As such, this imposes constraints on the usability of such systems. In [10], a conceptual view of enhancement mechanism of RF energy harvesting was briefly introduced. In this paper, we provide a thorough analysis of a cost effective and efficient antenna design to maximize the amount of power that is captured by the antenna system of the harvesting circuitry. An appropriate receiving antenna design is imperative since the antenna characteristics, such as gain, radiation pattern, and impedance bandwidth, can affect the amount of harvestable energy [11]. The enhancement is achieved here through incorporating a monopole antenna array designed at 900 MHz band with a reflector to maximize the amount of captured energy by the antenna system. Several sensitivity analysis and experiments were carried out in laboratory and results are comprehensively presented in this paper. For comparison purposes, single antenna elements at both transmitter side and receiver end of the harvesting circuit were adopted. In this work, an enhanced RF energy harvesting circuitry is designed and tuned to work at the 900 MHz frequency band. However, for broadband applications it is necessary to have a broadband antenna and a broadband matching unit for the diode [12], which is currently under investigation.

This paper is organized as follows. Section two explores the proposed energy harvesting system. Both the circuit layout and fabricated prototypes are further discussed. Section three describes procedure of the experimental work that was conducted in controlled laboratory environment. The results are also discussed and several case studies quantifying the performance of the energy harvesting circuitry are explored. Finally, section four concludes this research work with a brief summary of the findings.

## II. RF ENERGY HARVESTING SYSTEM

Based on the block diagram of the harvesting system described in section I (see Fig.2), Fig.3 shows the schematic layout of an energy harvesting system. It is worth noting that by increasing number of voltage multiplier stages, a substantial increase of the output voltage of the harvesting circuit can be developed depending on the type of choice of diodes and capacitors. In this work, 3- and 7-stage voltage booster circuits are considered. Prototypes of such harvesting devices with the 3- and 7-stage booster circuits were modeled and manufactured in-house. The harvesting circuits were tuned to operate at a frequency of 868 MHz. An anticipated RF source was used at transmitter side to provide a sufficient RF energy in order to quantify the performance and efficiency of the proposed harvesting circuit. To increase the DC power harvested and the efficiency of conversion RF/DC, a special RF source can be used to feed certain devices [2]. Below are the details of blocks of the RF harvesting circuitry adopted in this work.

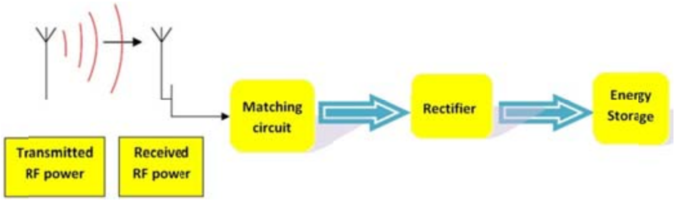

Fig. 3: System diagram of RF harvester.

### A. Voltage booster circuit

The multiplier acts as a charge pump to effectively boost as well as rectify the input voltage. The adopted circuit is a half wave version of the circuit and depends heavily upon impedance matching for maximum wireless power transfer. The design hence is a non-linear system where the input voltage at each stage of the booster circuit has an exponential relationship with output power [13]. Fig.4 depicts the schematic layout of the 7-stage voltage booster circuit.

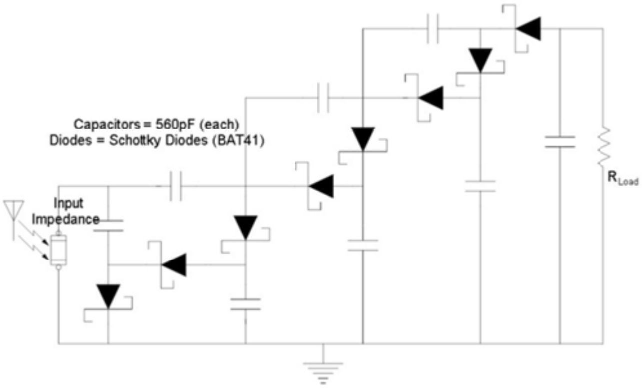

Fig. 4: Schematic of the 7-stage voltage booster circuit.

### B. Effect of choice of diode on harvested energy

As the voltage booster circuitry in this work constitutes the use of diodes, it is instructive to study the effect of the choice of diode on the amount of harvested energy. For this study, a 7-stage voltage booster circuit was used. An experimental study based on the use of the 7-stage booster circuit had been conducted in laboratory in order to investigate the effect of diodes on performance.

Several observations were noted. First of all, a big improvement on the amount of harvested output voltage was achieved when using silicon carbide (SiC) schottky diodes as compared to the normal schottky diodes. In fact, the output voltage can reach a value of 1.6 V from an input of just 32 mV within couple of minutes. The employed SiC schottky diodes were tremendously able to resolve the problem of having small amount of AC voltage at the front-end of the harvesting circuitry. The power lost within the circuit is due to the dissipation of power in the internal resistance of the diodes of the circuits. The findings of achieved gain from the circuit based on choice of diode are discussed next. For an input voltage of 32 mV, the achieved gain from the circuit that is based on normal schottky diode was nearly 14 dB and the power lost was 8 $\mu$W. However, this result was more than double when SiC schottky diodes are used and the loss-in power decreased to 0.08 $\mu$W.

In summary, the above discussion shows that SiC schottky diodes are most suitable for very high frequency switching applications. This is because of the fact that the switching losses in SiC schottky diodes are negligible and such diodes have low resistivity. The power loss in boosting diodes is due to both conduction and switching losses. The conduction loss is mainly caused by the diode forward voltage drop, whereas the switching power loss is due to the reverse recovery energy loss. Overall in SiC schottky diodes, the switching loss is negligible, because the reverse recovery current is nearly zero.

### C. Proposed antenna design

In order to enhance the captured energy, we propose to use a conducting reflector along with a monopole antenna array. Fig.5 shows the circuit prototype after incorporating the proposed enhancement technique. A 3-stage voltage booster circuit was used for proof of concept, although higher-order booster circuits would result in dramatic increase on the harvested energy. In this work, only two monopole antenna elements are adopted. In addition to that, we propose the use of a reflector along with the antenna array. This should substantially focus more the ambient RF energy into the antenna system, and hence fed into the circuit. The reflector used here is an aluminum foil sheet placed at the back side of a parabolic-shaped thick paper. In brief, this should collectively increase the directivity of the monopole antenna system in one direction instead of being omni-directional along the azimuthal plane.

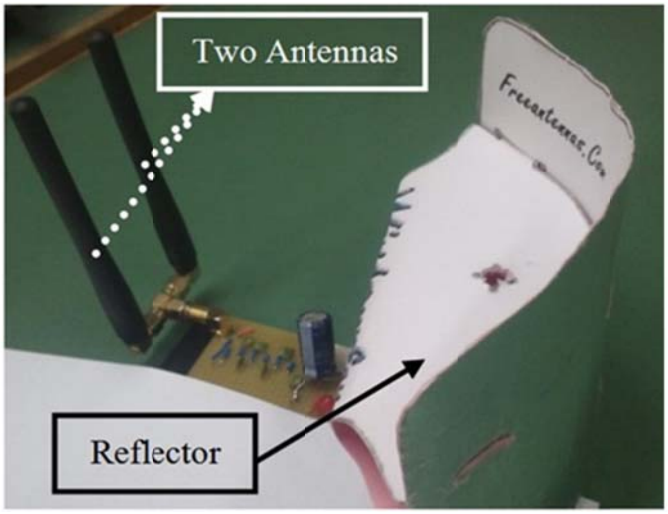

Fig. 5: A snapshot of the designed antenna array along with the conducting reflector.

Fig.6 shows the simulated radiation pattern (both E-plane (Fig.6) and H-plane (Fig.7)) of a single antenna with and without the reflector. For this purpose, open source simulator was used to generate the radiation pattern mimicking the deployed antenna system in one of the scenarios considered in this study. As can be seen from the two figures, the reflector will guide the pattern to be more directive and collectively focus received power towards the harvesting circuitry.

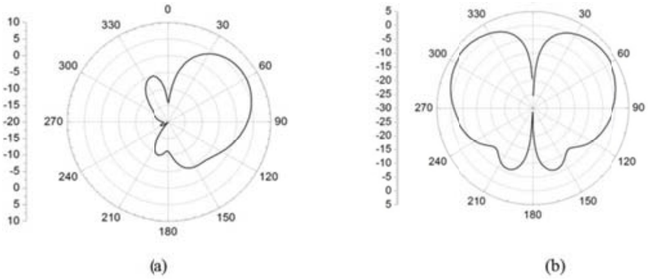

Fig. 6: Simulated E-plane radiation pattern of a single monopole antenna element (a) with and (b) without a reflector.

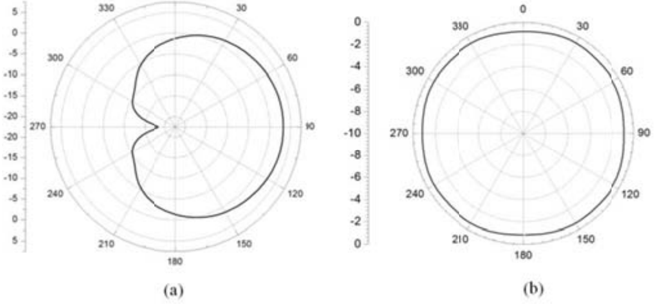

Fig. 7: Simulated H-plane radiation pattern of a single monopole antenna element (a) with and (b) without a reflector.

An image of the built-in prototype with a 3-stage voltage booster circuit is shown in Fig.8. Notice that each two diodes and two capacitors form a single boosting stage. Along the edge of the printed circuit board, an SMA connector was soldered to connect the antenna system with the remaining parts of the circuit. In the three stage voltage multiplier, schottky BAT41 diode and 560 pF ceramic capacitors were used. As discussed before, schottky diode offers low forward voltage and high switching speed and is considered as an ideal component for RF energy harvesting [14].

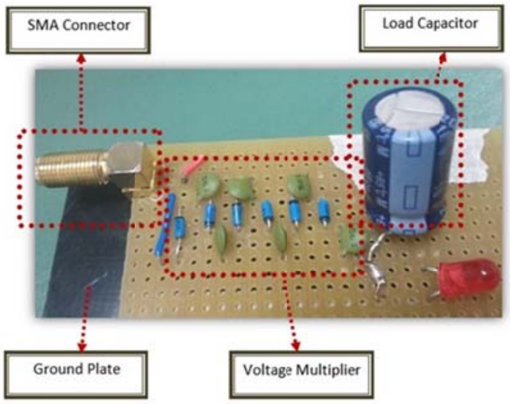

Fig. 8: A built-in prototype of an RF energy harvester. Note that the antenna system is not shown.

Upon boosting the output voltage, a load capacitor with a value equal to 2.2 mF is used to store the output power. That capacitance has been chosen after several trial-and-error stages performed to achieve an optimized capacitance value. The ground plate is important here to shield the circuit from any external electromagnetic interference and to provide better performance for the monopole antenna array. In practical cases, the amplitude of the AC signal will be divided by coupling capacitors and the junction capacitance of the diode. Also the reverse leakage current of the diode and the resistance of the diode will limit the feasible DC output voltage. Therefore, to obtain an optimal output voltage, large coupling and charge-storage capacitance is preferred [15].

## III. EXPERIMENTAL SETUP AND RESULTS

In the experimental setup, an RF source Agilent, N9310A was used to supply RF signal from a monopole antenna at the transmitting side. A frequency of 868 MHz was used so that no interference can result from licensed frequency bands used by other agents. At the receiver front-end side, another monopole antenna had been used in order to capture the radiated emissions. For optimal signal strength, the sending and receiving antennas have been chosen identical in shape, size and with same polarization. Furthermore, it is important to place the receiving antenna at the far field region to make sure that the captured energy is only due to the radiated electromagnetic waves (i.e., no reactive field). The receiving antenna is connected to the harvesting circuitry. Fig.9 shows the schematic of the measurement setup as conducted in the laboratory. A Spectrum Analyzer, Agilent N9320B, was used at the receiver side in order to display the captured energy or power.

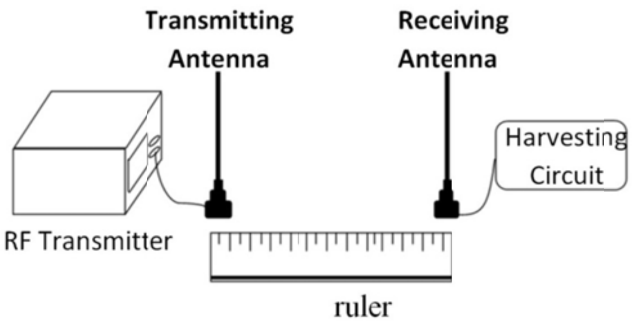

Fig. 9: Measurement setup with distance controlled using measuring ruler.

In this experiment, the output power of the RF signal generator was considered at a frequency of 868 MHz with power amplitude strength equal to 20 dBm. 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 amplitude of 0.1 W. As the peak voltage of the AC signal obtained at the antenna is generally much smaller than the diode threshold, diodes with lowest possible turn on voltage are preferable [1]. The expected receiving signals should be less than the transmitted signals due to propagation losses. One of these losses is the path loss. In this study, this loss was calculated using Friis equation, which is solely used to study RF communication links [16]. This transmission formula is expressed as:

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi d}\right)^2, \qquad (1)$$

where $P_r$ is the received power at the receiver side (in watts), $P_t$ is the transmitted power (in watts), $\lambda$ is the wavelength of the transmitted signal (in meter), $G_t$ and $G_r$ are transmitting/receiving antenna gains, and d is the separation distance between the transmitting/receiving antennas (in meter). It is clear that the received signal strength is inversely proportional to the square of the distance between the transmitting and the receiving antennas. Furthermore, the Federal Communications Commission (FCC) regulations have set limits on the allowable transmitted signal power on specific frequencies. For calibration purposes, several measurements were conducted in a non-anechoic laboratory environment to validate this relationship for the proposed harvesting circuit.

In the first measurement setup, one antenna was used as a transmitter and another was used as a receiver. The captured energy was measured directly after the receiving antenna using the spectrum analyzer (see Fig.10). Then, measured received power data were converted to RMS voltages using Ohm's Law Power equation:

$$P_r = \frac{V_{in}^2}{Z_0}, \qquad (2)$$

where $P_r$ is the received power, $Z_0$ is equal to 50 Ω, and $V_{\text{in}}$ is the RMS input voltage at the front end of harvesting circuit.

At the end, the output voltage was measured at the end of the harvesting circuit. The input RMS voltage and the output DC voltage were recorded and the results are as shown in Fig.11.

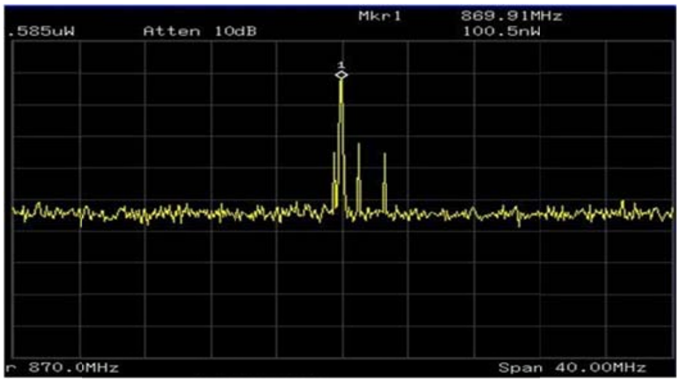

Fig. 10: Spectrum view of the captured antenna resonance frequency.

Different measurements were taken in order to study the effectiveness of the proposed enhancement method. This can be done by measuring the output DC voltage for different cases. The results were taken for one antenna without any enhancement, one antenna with the reflectors, two antennas only and two antennas with the reflectors. Fig.12 summarizes and compares the results between the four cases.

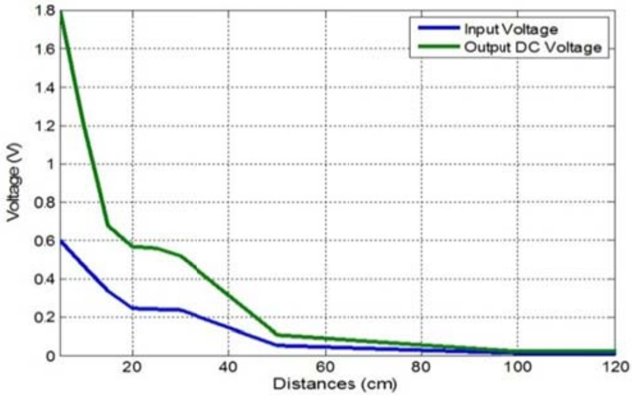

Fig. 11: Input AC voltage $V_{in}$ and output DC voltage $V_{out}$ of the RF harvesting circuit as a function of separation distance.

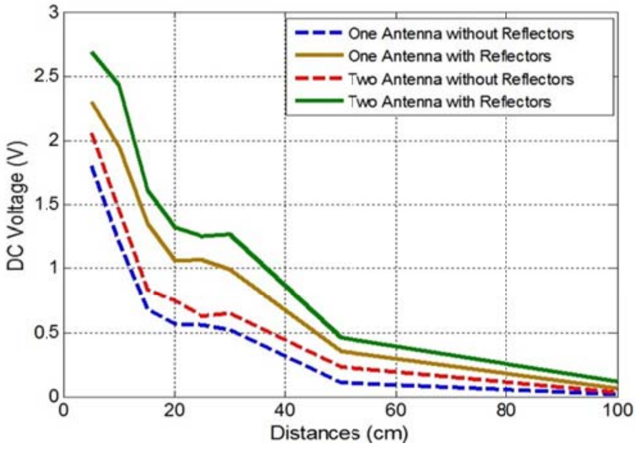

Fig. 12: Measured output voltage as a function of separation distance between transmitting and receiving antenna system without a load capacitor.

As can be seen from Fig.12, the recorded DC output voltage at a separation distance of 25 cm between single antenna elements located at both transmitter/receiver (Tx/Rx) sides is approximately equal to 570 mV. This result is without any enhancement but when reflectors were incorporated at both Tx/Rx sides, the output voltage was increased to reach 1.06 V in couple of seconds. Moreover, adding another antenna will increase the output voltage more. The use of two monopole antennas has increased the output voltage to 630 mV (without reflectors) and to reach 1.27 V with the use of two reflectors with both transmitting/receiving antennas. It is clear from results above that enhancement of energy harvesting is attainable from the proposed technique.

Other measurements had also been carried out with a capacitive load at output of the harvesting circuit. The output voltage without the loading capacitor is instantaneous. However, adding a capacitor at the output stage of the harvesting circuit makes the reading more stable. Hence, it provides more reliable readings, however, at the cost of time as it does take some time to stabilize the measured output voltage due to the uncontrollable charging delay at each individual distance. Nevertheless, capacitors with minimal charging delay will overcome this issue. In fact, the issue of controlling the charging delay of load capacitors in the context of this study is an important parameter, and is the subject of future work.

Fig.13 depicts the measured results obtained when using a load capacitor. Data were taken for several separation distances between transmitting antenna and receiving antenna system. Comparison is made with a reference circuit when adopting single antenna elements at both Tx/Rx sides. As can be seen, capacitors require large amount of time to reach stabilized output DC voltage when comparing these results with those obtained in Fig.12 without using the load capacitor. However, results obtained when using the load capacitor confirm the proposed technique that is adding the reflectors and adopting a high-gain antenna array increase the received input (AC) and output (DC) voltage of the harvesting circuit.

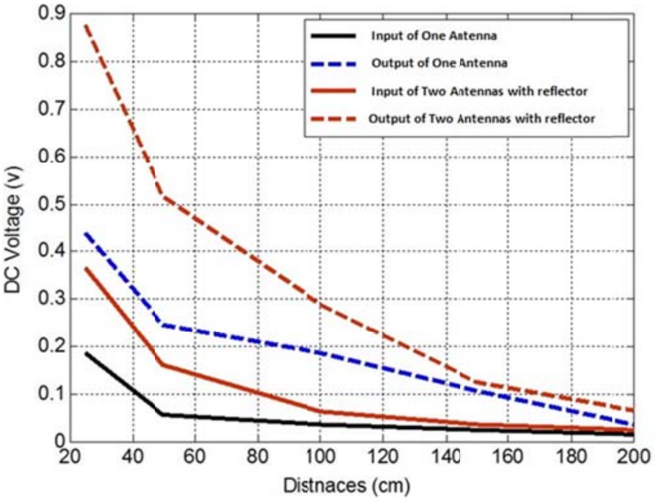

Fig. 13: Measured output DC voltage for the antenna array and single antenna at both Tx/Rx sides using a load capacitor.

The electrical energy stored in the load capacitor is studied next. The stored energy is given by the well-known expression,

$$W_E = \frac{1}{2} C V^2, \tag{3}$$

where $W_E$, $C$ and $V$ are the stored energy by the load (in Joule), the capacitance of the load capacitor (in Farad) and the DC output voltage (in Volt), respectively. As expected, the strength of stored energy decreases as far as the output voltage decreases (see Fig.14). For instance, at a separation distance of 25 cm between the transmitter and the RF harvester circuit, the energy stored from one antenna without any enhancement reached to about 213 $\mu$J. As the received power increases, the output voltage starts to gradually increase, which in turn increases the stored energy in the capacitor. On the other side, the energy stored, when using two monopole antenna elements with the reflectors reached to 850 $\mu$J, which is about four folds higher than the previous case. At a separation distance of 2 meters, the energy is dropped to 1.85 $\mu$J, due to the drop in the received power density. Fig.14 also depicts the energy stored as a function of separation distance between the transmitter and receiver for both cases, namely: proposed prototype and reference case without any reflectors. The normalized stored energy as a ratio between the two cases is in the range of 1:4. That ratio starts to decrease as far as separation distance is increased. This is attributed to effectiveness of the reflectors as well as the decay of the received power strength.

It is worth highlighting here that more enhancements in terms of captured power density at the front-end of the RF harvesting system and captured energy is conceivable when using a high-gain antenna array system.

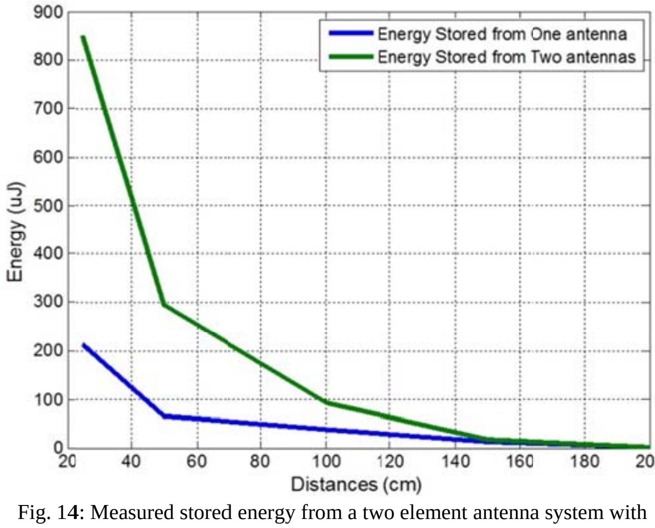

Fig. 14: Measured stored energy from a two element antenna system with reflector compared with an antenna without a reflector

## IV. CONCLUSION

In this paper, a technique for enhancing RF energy harvesting systems was proposed. The proposed system consists of monopole antenna array, a 3-stage voltage booster, rectifying circuit and a unit storage device. To further enhance the captured energy, an in-house made conducting reflector was used. Moreover, the performance of 7-stage voltage multiplier circuit on the overall captured output voltage was emphasized. Several design constraints related to manufacturability of such systems were also discussed with more emphasis given to the choice of diodes.

The experimental results, based on this study, show that the power harvested by one antenna decreases when separation distance between transmitting antenna and receiving circuitry increases. Furthermore, the use of high-gain antenna array as well as RF reflector at the input of the harvesting system has resulted in a substantial increase in the harvested power. Currently, more work is being carried out to investigate the effect of load capacitors delay on performance as well as the use of high-gain planar antennas in order to maximize the captured energy by the harvesting circuitry.

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