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RF-DC conversion for RF energy harvesting from digital TV signals using voltage multiplier circuits

Piyapat Panmuang[1], Amornthep Sonsilphong[2], Chaiyong Soemphol[3]
[1]Faculty of Technical Educationg, Rajamangala University of Technology Isan Khonkaen Campus, Khonkaen, Thailand
[2]Department of Electrical Engineering, Faculty of Engineering, Rajamangala University of Technology Isan Khonkaen Campus, Khonkaen, Thailand
[3]Research Unit for Computational Electromagnetics and Optical Systems (CEMOS), Department of Electrical Engineering, Faculty of Engineering, Mahasarakham University, Maha Sarakham, Thailand

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ABSTRACT

Due to the development of wireless communications, there has been a growth in the use of IoT devices and sensor nodes. A potential power source for powering equipment in remote or inaccessible locations is necessary. This research investigates the feasibility of employing digital television (DTV) signals as an energy harvesting system, with a focus on RF-DC conversion using a voltage multiplier circuit. Commercial 5 and 9 element yagi-uda antennas are used as receiver for ambient DTV signal. The device's performance is initially evaluated within the laboratory setting, it has been shown that when the RF signal generator is at 660 MHz, the proposed energy harvesting device can generate a maximum DC voltage of 781.3 mV and 1056.4 mV for 5 and 9 element antenna, respectively. This is based on measurement of voltage output when using the input signal from DTV base stations in Thailand. It was found that the voltage output levels decreased gradually with increasing distance ranging from 153.4 V at 0.1 km to 4.5 mV at 10 km for 5 element yagi-uda antenna. In contrast, the 9-element yagi-uda antenna consistently exhibited higher voltage levels, ranging from 354.7 mV at 0.1 km to 12.6 mV at 10 km.

Corresponding Author:

Chaiyong Soemphol
Research Unit for Computational Electromagnetics and Optical Systems (CEMOS)
Department of Electrical Engineering, Faculty of Engineering, Mahasarakham University
Kantarawichai, Maha Sarakham, 44150, Thailand
Email: chaiyong.s@msu.ac.th

1. INTRODUCTION

The advancement of wireless communication technology has led to new technological innovations. There are now more and more low power devices such as internet of thing (IoT) devices and sensor nodes. These devices find extensive usage, particularly in the fields of measurement, data recording, transfer for the aplications in the fields of IoT, autonomous driving, smart farming, smart city, and many more [1]–[4]. However, uninterrupted wired power in remote locations will limit the potential of wired ultra-low power devices [5], [6]. Therefore, a primary obstacle in the development of ultra-low power devices is the constraint of energy storage. This makes it necessary to find alternative energy sources. As a result of these factors, energy harvesting technology is experiencing rapid growth across various scientific and engineering disciplines [7]. This technology can offer advantages including extended battery life, decreased maintenance requirements, and the ability to power devices in distant or inaccessible areas.

The opportunity to power low-power devices arises through energy harvesting from sources like solar, thermal, microwave, or radio frequency (RF). However, recent reports indicate a significant surge in the adoption of RF energy harvesting due to its continuous viability throughout both day and night hours, in rural and urban area for both indoor and outdoor environments. Furthermore, there have been reports that highlight the capability of RF energy harvesting to enable the powering of low-power devices without the need for wires, batteries, or dedicated energy sources [8]. The RF frequency bands encompass a range of frequencies stretching from 10 kHz to 30 GHz, spanning from very-low frequency (VLF) to super-high frequency (SHF) [9]. There are several ranges of frequencies that can be used to harvest energy such as Wi-Fi access points [10], [11], cellular base station [12], radio broadcast stations (FM/AM radio) [13] as well as television/digital television (TV/DTV) [14]–[18].

However, there are some problems with RF energy harvesting systems such as the signal is uncertain and it takes a long time to accumulate energy. The power achievable from RF sources is exceedingly low. Hence, it is of utmost importance to convert the obtained power into a usable form with minimal loss [19]. For this process, certain auxiliary circuits are employed. Various types of rectifier circuits have been proposed. These circuits are not only rectifying the RF signal but also possess amplification characteristics, enabling them to generate higher output voltages from low-power input signals [20]. According to previous research, various rectification techniques for improving the efficiency of havesting system include single state voltage doubler [21], [22], multistate voltage double [23]–[27], villard voltage doubler [28], dickson voltage double [29], and greinacher voltage multiplier [30]. It has been discovered that by employing circuit multiplication techniques, the output voltage can be significantly enhanced for low-power RF inputs.

The emergence of IoT for smart farming has revolutionized global agricultural landscape including in Thailand. It is offering farmers the means to optimize operations, boost productivity, and contribute to sustainable development. The IoT sensors and devices can be deployed across the farmland to collect data on soil moisture, temperature, humidity, and nutrient levels. This information can be analyzed to create precise irrigation and fertilization schedules, minimizing water and chemical wastage while maximizing crop health. However, the implementation of IoT devices in remote areas is hampered by limited power supply. To address this, RF energy harvesting technology shows promise, capturing ambient RF energy to power IoT devices in off-grid locations. Additionally, Thailand’s transition to digital television since 2014 has led to extensive coverage of digital TV signals, which researchers have identified as potential energy harvesting sources [31]. There has been research using Thailand’s digital TV signals for energy harvesting [18], but the name of few. In our research, we investigate the feasibility of using digital TV signals for energy harvesting, focusing on the multiplier circuit that is used as a RF-direct current (DC) conversion for ambient RF energy havesting.

The paper is divided as follows. Section 2 provides an overview of the theoretical background of the voltage multiplier circuit. Section 3 showcases the device’s performance, beginning with laboratory experiments and followed by an evaluation in an ambient environment. Finally, section 4 presents the conclusions.

2. RF ENERGY HARVESTING CIRCUIT

The primary goal of the RF energy harvesting system is to transform RF power into usable electrical energy. Figure 1 demonstates a block diagram of RF of an energy harvesting system. It concists of antenna, matching network, RF-DC conversion, and load circuit. The antenna serves the purpose of capturing the incident electromagnetic wave and converting it into electrical signals. The matching network is employed to minimize losses and establish an optimal matching environment between the antenna and the RF-DC conversion section. Then the sin wave of electrical with high frequency is fed to the RF-DC converting rectifier for transforming the signal into DC voltage for driving the DC load.

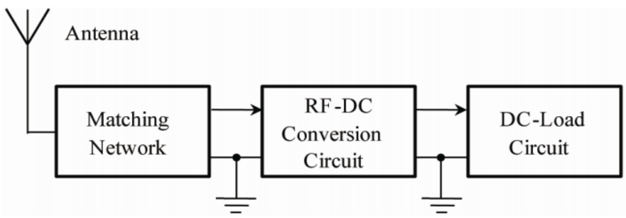


Figure 1. RF energy harvesting system block diagram [30]

This study focuses on the frequency ranges of DTV signals in Thailand, specifically ranging from (490) 510 MHz to 790 MHz. To receive these signals, a commercial yagi-uda antenna was utilized. Two variations of the yagi-uda antenna were tested, consisting of 5 elements (5E) and 9 elements (9E). The gain of these antennae was 6 dB and 20 dB for 5 and 9 elements, respectively. The impedance of both antennae was 75 ohms, covering the receiving frequency range of 470–860 MHz, which aligns with the DTV band in Thailand. To ensure impedance matching between the antenna and the load, an L-matching network was employed. In this particular study, the matching network was specifically designed for an input impedance of 75 ohms.

In order to convert the low AC voltage output from the energy harvester into a higher DC voltage, a voltage multiplier circuit was employed as part of the RF-DC conversion process. By increasing the number of voltage multiplier stages, the small input AC voltage could be amplified to a higher level and transformed into DC voltage. Figure 2(a) and Figure 2(b) illustrate the schematic diagrams of a single-stage and n-stage villard voltage multiplier circuit, respectively. Each stage of the circuit comprises two diodes and two capacitors.

The villard voltage multiplier circuit operates by utilizing the properties of diodes and capacitors to produce an amplified output voltage. During each stage, the capacitors accumulate charge when the input AC voltage is at its positive peak, and subsequently discharges this stored energy through the diodes when the input AC voltage is at its negative peak. This cyclical process results in an increase in voltage magnitude at each subsequent stage.

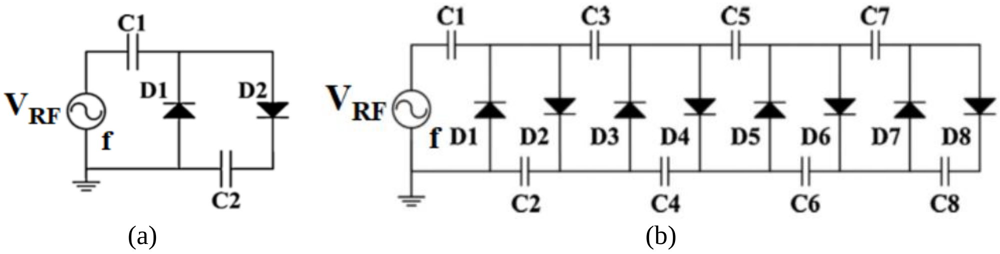


Figure 2. Voltage multiplier topology: (a) single stage and (b) n-stage villard voltage multiplier circuit [32]

The fourth stages villard voltage multiplier was chosen to convert RF to DC. The use of villard voltage multiplier circuit was implemented with Schottky diodes HSMS-2580. The characteristics of this Schottky diode is demonstrated in Table 1. This diode can exhibit a low forward voltage and substrate leakage, while also leveraging its non-symmetric properties to enable unidirectional current flow under ideal conditions.

Table 1. The characteristics of Schottky diodes HSMS-2580

Parameters	Unit	Value
B_V	V	3.8
C_{J0}	pF	0.18
E_G	eV	0.68
I_{BV}	A	3E-4
I_S	A	3E-6
N	-	1.06
R_S	Ω	25
$P_B(V_J)$	V	0.35
$P_T(XTI)$	-	2
M	-	0.5

The fabricated proposed voltage multiplier circuit on printed circuit board (PCB) is shown in Figure 3. This device concists of three parts; RF input, matching circuit, and fourth stage villard voltage multipler circuit. The bayonet neill-concelman (BNC) and radio grade 6 (RG6) connector was used at the input of PCB to receive RF signal from antenna and RG6 cable was used to connect between antenna and BNC connector. Following the RF input stage, the device included a matching network. The winding inductance and capacitor worked in conjunction to match the impedance, thus maximizing power transfer efficiency and enhancing the overall performance of the energy harvesting system. The heart of the energy harvesting device lies in the fourth stage villard voltage multiplier circuit. This circuit utilizes diodes and capacitors in a cascaded configuration to efficiently convert the RF signal into a higher amplitude direct current (DC) output voltage. The diodes and capacitors work collaboratively to multiply the voltage, resulting in an increased DC output voltage compared to the original RF signal.

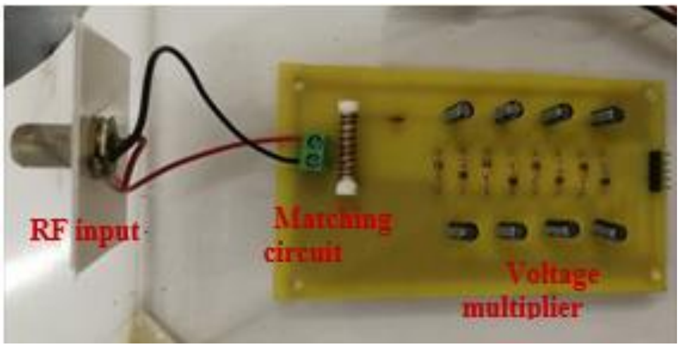


Figure 3. The fabricated of the proposed RF energy harvesting device

3. RESULTS AND DISCUSSION
3.1. Laboratory characterization

The performance of the device is first assessed through experimental characterization conducted in a controlled laboratory environment. The experimental setup is depicted in Figure 4. It involved the utilization of the KEYSIGHT N9310A RF signal generator as the source of the RF signal. This signal generator was capable of generating signals spanning a frequency range of 9 kHz to 3.0 GHz. To transmit the signal into the air, a horn antenna was employed. In the laboratory testing setup, a receiving antenna consisting of a yagi-uda antenna with 5 and 9 elements was incorporated.

Figure 4. Experimental setup for laboratory characterization

In the initial experiment, the RF signal generator was set to an output of 20 dBm, with a frequency range sweeping from 500 MHz to 800 MHz. The distance between the transmitter and the receiving antenna was varied from 0.10 m to 2.0 m. To measure the open-circuit voltages of the prototype device, a digital multimeter was employed. Figure 5 displays the voltage generated by the the proposed device when connected to a yagi-uda antenna with 5 and 9 elements, respectively. The findings indicate that, at the same distance, the use of a 9-element antenna yields a higher output voltage compared to a 5-element antenna. Specifically, the proposed RF energy harvesting device achieved a maximum DC voltage of 764.5 mV when the RF generator operates at 660 MHz with a 5-element yagi-uda antenna. In contrast, when employing a 9-element yagi-uda antenna at the same frequency of 660 MHz, a maximum DC voltage of 1021.6 mV was achieved. Therefore, based on these results, a frequency of 660 MHz was selected for further testing in subsequent experiments.

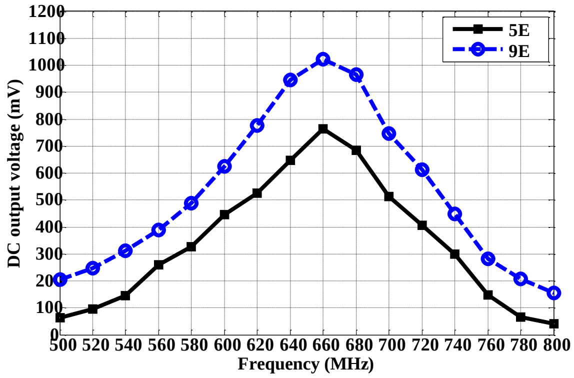
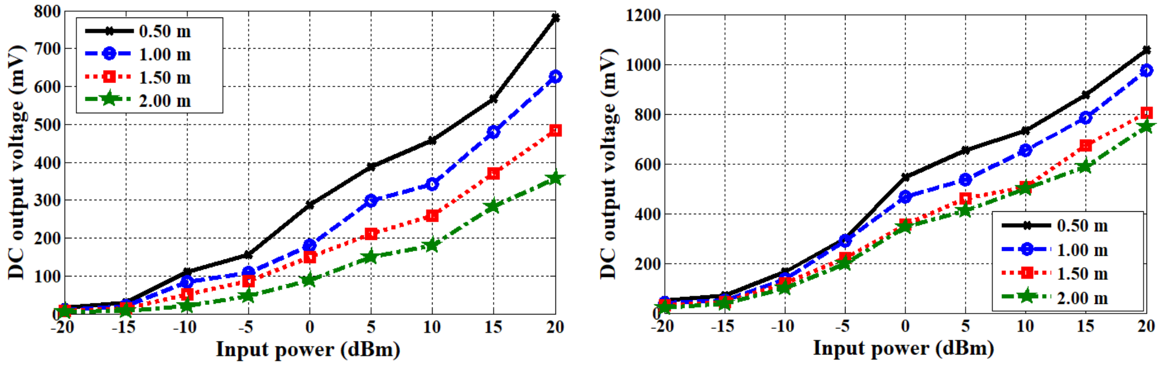


Figure 5. A plot of DC output voltage as function of frequency

In this study, we evaluated the performance of an energy harvesting system using a multiplier circuit and both 5-element and 9-element yagi-uda antennas. The experiments were conducted at a fixed frequency of 660 MHz, while varying the output power of the RF signal generator from -20 dBm to 20 dBm and the distance between the transmitter and the receiving antenna was varied from 0.5 m to 2.0 m. The measured results at the output voltage of the multiplier circuit are displayed in Figures 6(a) and 6(b). The results showed that higher output power levels led to increased harvested energy, while greater distances resulted in diminished energy harvesting capability. The 5-element yagi-uda can generate a maximum DC voltage of 781.3 mV as shown in Figure 6(a). While using a 9-element yagi-uda antenna at the same frequency and same distance, a maximum DC voltage of 1056.4 mV was generated. From the results it can be concluded that the 9-element antenna consistently outperformed the 5-element antenna in terms of output voltage, indicating its superior energy harvesting efficiency.

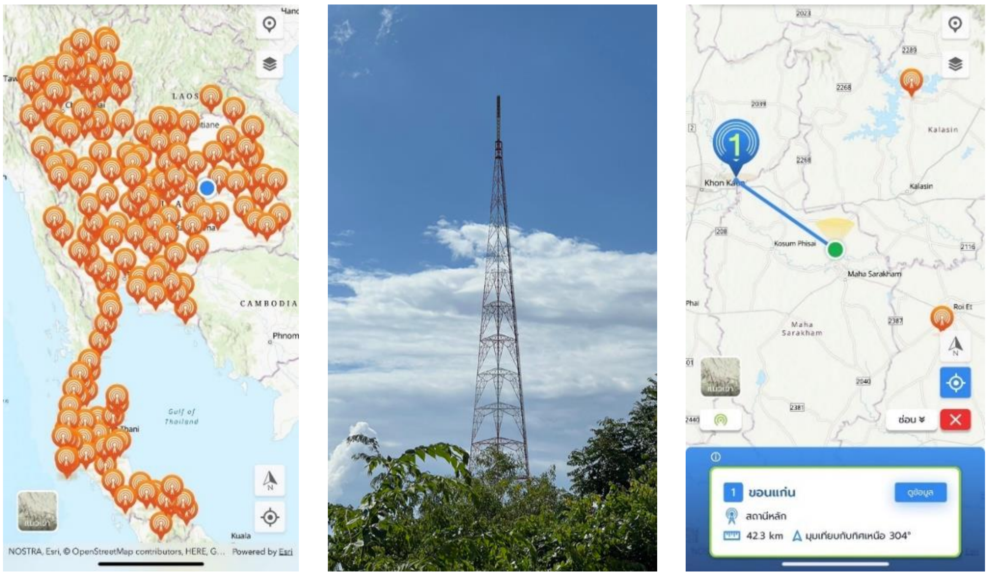


(a) (b)

Figure 6. A plot of DC output voltage with different input power levels and distance: (a) 5-element antenna and (b) 9-element antenna

3.2. Energy harvesting from ambient DTV signals

Following the characterization of the proposed device in a laboratory setup, its performance was assessed in an ambient environment where it is intended to harvest energy from the DTV ambient frequency. Nowadays, there many DTV towers in Thailand as shown in Figure 7(a). The proposed device was tested with signals from a DTV station. This DTV tower is located at Khonkaen Province with latitude 16.463686° and longitude 102.946222°. The transmission tower had a height of 156 meters as shown in Figure 7(b). Table 2 illustrates the effective radiated power (ERP) across various frequency ranges. We tested it by measuring the voltage level generated at distances from 0.1 to 10 kilometers from the transmission tower. The measurement location and distance from the transmission tower were determined using the DTT servicearea application, developed by the national broadcasting and telecommunications commission (NBTC) of Thailand as demonstrated in Figure7(c).



(a) (b) (c)

Figure 7. DTT service area application: (a) location of DTV base station in Thailand, (b) DTV tower at Khonkaen Province, and (c) an example of displaying distance measurement from a transmission tower

Table 2. The effective radiated power (ERP) of DTV base station

Network service provider	Frequency channel	Center frequency (MHz)	ERP (kW)
MUX#1	43	650	50
MUX#2	45	666	50
MUX#3	29	538	50
MUX#4	25	506	50
MUX#5	48	690	50

In this part of the experiment, the voltage measurements were conducted at distances ranging from 0.1 km to 10 km from transmission towers using 5-element and 9-element yagi-uda antennas. During measurements, the antennas were directed towards the digital TV antenna based on the specified angle in the DTT servicearea application. Figure 8 shows the measurement results. The voltage levels obtained from the 5-element yagi-uda antenna decreased gradually with increasing distance, ranging from 153.4 mV at 0.1 km to 4.5 mV at 10 km. In contrast, the 9-element yagi-uda antenna consistently exhibited higher voltage levels, ranging from 354.7 mV at 0.1 km to 12.6 mV at 10 km. From the measurement results, it can be concluded that the measured voltage value gradually decreased with increasing distance between proposed device and radiating source.

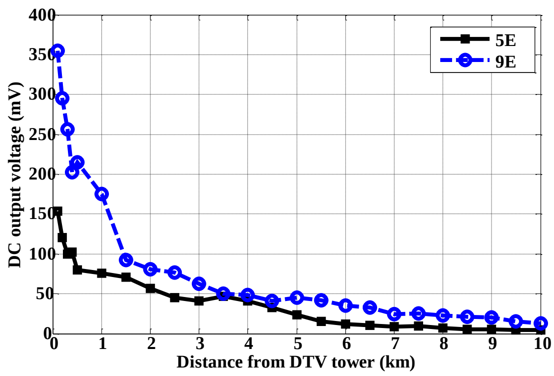


Figure 8. A plot of output voltage as a function of distance from digital TV tower

4. CONCLUSION

This work demonstrates the feasibility of RF energy havesting from DTV band using the villard voltage multiplier circuit topology. Through laboratory characterization, the performance of the system was evaluated using 5-element and 9-element yagi-uda antennas, revealing the superiority of the latter in terms of output voltage. The 9-element yagi-uda antenna consistently outperformed the 5-element counterpart, achieving a maximum DC voltage of 1056.4 mV at 660 MHz, compared to 781.3 mV. Moreover, in the ambient environment tests, the 9-element antenna exhibited higher voltage levels, ranging from 354.7 mV at 0.1 km to 12.6 mV at 10 km, while the 5-element antenna ranged from 153.4 mV at 0.1 km to 4.5 mV at 10 km. These results highlight the potential of DTV signals as a reliable and sustainable energy source for the proposed RF-DC conversion system, fostering advancements in energy harvesting technology for wireless sensor networks and IoT devices. Future research in this area will undoubtedly lead to greener and more sustainable technological solutions.

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BIOGRAPHIES OF AUTHORS

Piyapat Panmuang was born in Khonkaen Province, Thailand. He received his bachelor degree in Electrical Engineering from Khon Kaen University, Thailand and his master degree and Ph.D. in Electrical and Computer Engineering from Mahasarakham University, Thailand. He is currently a lecturer at the Faculty of Industrial Education, Rajamangala University of Technology Isan Khonkaen Campus, Khonkaen, Thailand. His research interest includes thermoelectric, solar energy, renewable energy conversion, and power electronics. He can be contacted at email: piyapat.pa@rmuti.ac.th.

Amornthep Sonsilphong was born in Khonkaen Province, Thailand. He received his bachelor degree in Electrical Engineering with first-class honors from Khon Kaen University, Thailand in 2010. He also received his master degree and Ph.D. in Electrical Engineering from Khon Kaen University, Thailand. He is currently a lecturer at the Department of Electrical Engineering, Faculty of Engineering, Rajamangala University of Technology Isan Khonkaen Campus, Khonkaen, Thailand. His research interest includes metamaterials, chirality, micro nano-fabrications and nanocircuits, automation control systems, 3D printing, and design and biomedical engineering. He can be contacted at email: a.sonsilphong@gmail.com.

Chaiyong Soemphol was born in Surin Province, Thailand. He received his B.Eng. in Electrical Engineering with second-class honors from Khon Kaen University, Thailand in 2011. He also received his Ph.D. in Electrical Engineering from Khon Kaen University, Thailand in 2017. Since 2018, he has been with the Department of Electrical Engineering, Faculty of Engineering, Mahasarakham University, Maha Sarakham, Thailand as a lecturer. His research interests include compact microstrip devices, metamaterial applications for RF, microwave sensor, wireless power transfer systems, reneable energy, and electromechanical energy conversion. He can be contacted at email: chaiyong.s@msu.ac.th.