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Design and measurement of the receiving antenna for electromagnetic field energy harvesting in UHF band

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ABSTRACT

This paper aims to design a receiving antenna for harvesting energy using the wireless energy transfer (WET) method based on the ultra-high frequency (UHF) band. The study was conducted by comparing four types of receiving antenna design. A mathematical and experimental analysis has been done to evaluate the performance of the designed antennas. A Yagi-Uda antenna is utilized as the transmitter. The results show that the zig-zag type antenna has the best performance. It can receive electromagnetic energy from a transmitter with maximum efficiency is 0.1% for the receiving antenna volume of 0.34 cm^3. The proposed method can meet the energy necessity of an implant device with a charging time of approximately 21.61 hours for the 700 mAh rechargeable battery capacity. As our preliminary conclusion, based on our results, this proposed method can be used as a reference for the practice in the WET field and the medical and restricted areas in the electromagnetic energy harvesting case.

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1. INTRODUCTION

Electromagnetic waves can be used as a medium to transfer energy from a transmitter to a receiver [1]–[3]. There are abundant electromagnetic waves available in our spaces, for example, electromagnetic waves for televisions, mobile phones, wireless networking, and amateur radio [4], [5]. Based on this issue, wireless technology is a potential method for energy transfer [6], [7]. In addition, energy harvesting is also a potential technology based on radio frequency using the generation of electromagnetic waves [8]–[10]. This resource can be utilized to support human activity that requires energy [11].

Wireless energy transfer (WET) experiments have been conducted widely by some researchers. Various applications for this technology have been implemented, such as for energy harvesting [12]–[16] communication [17], charging devices [18], [19], medical [20]–[24], and off-body radio link [25]. Those applications adopted one of the five techniques of WET technology, namely coupling inductive, coupling capacitive, coupling magnetic, coupling magnetic resonant, and microwave radiation [26]. Commonly, two-coils coupling is used for a near-field applications such as charging electric vehicles [27]. Using two, three, or four couplings will occur weak coupling and crosstalk. This will result in a poor delivery system and will reduce the efficiency of the wireless energy transfer system [28]. Additionally, it also has a large size, therefore it cannot be implanted in human body.

Sunarno developed WET technology for energy harvesting in order to charge rechargeable lithium batteries [15]. The method for transferring energy was using ultra-high frequency (UHF) transmitter and the parabolic metal reflector as a receiver system. The result of the experiment using the electromagnetic wave was a success in charging the rechargeable lithium battery with an efficiency of 1%. The author also conducted the energy transfer using Yagi-Uda directional antenna based on a UHF transmitter. The range of frequency in the experiment was about 400 to 489 MHz, and the standing wave ratio (SWR) was 1.2. The best efficiency occurred when the rotation angle of the directional antenna was 60° at 0.36% [12]. The following research used the same method to cover 10 cm in distances, with an efficiency of 0.00116% and a size of 1.44 cm^3 [14]. The efficiency is low, and the size is still unable to be planted in the human body.

This research investigated the receiving antenna design for energy harvesting using WET technology. The receiving antenna size needs to be applicable as an implant device. We design four types of receiving antenna patterns. The receiving antenna consists of a copper plate on the printed circuit board (PCB), called a printed antenna. A Yagi-Uda antenna is utilized as the transmitter and the process is carried out in the UHF band. Thus, we compare the receiving antennas by placing the receiving antenna in front of the transmitter. The voltage and current measurements were conducted to determine the best antenna performance. A mathematical analysis is also conducted to indicate the efficiency and charging time. The next session discusses the research method, mathematical analysis, and design process. Then, testing was conducted to verify the performance of the designed antenna. At last, we discuss and analyze the results before coming to a conclusion.

2. METHOD

In this research, the receiving antenna will be designed to be as small as possible for getting the energy in the UHF band. Additionally, the receiving antenna must be able to arrest and store the energy in the rechargeable battery. The antenna can be used for electromagnetic energy harvesting based on its function.

2.1. Wireless energy transfer (WET) system

Wireless energy transfer is the technology with contactless when charging devices [29]. In this study, the system was designed to transfer energy from the transmitting antenna to the receiving antenna for electromagnetic harvesting. The block diagram for this system is shown in Figure 1. It consists of an electrical energy source (RTVC PV-4310 DC power supply), the UHF transmitter (UHF transmitter: Firstcom FR-488), a wattmeter (Dummy Load-Wattmeter), a coaxial cable RG-58, the transmitting antenna (Yagi-Uda antenna), the receiving antenna design, the energy receiver circuit, a rechargeable battery, a voltmeter, and an ammeter.

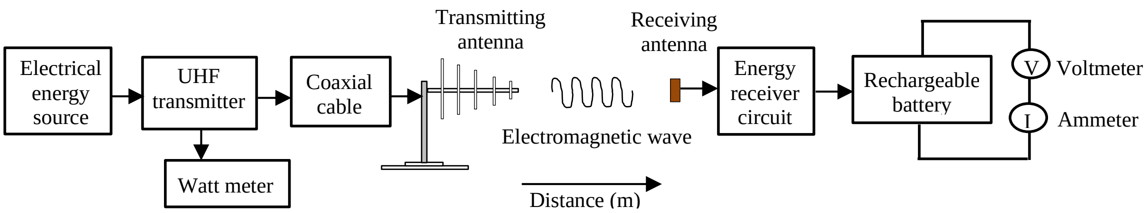


Figure 1. The wireless energy transfer system for electromagnetic energy harvesting

As an electrical energy source, the RTVC PV-4310 DC power supply will give the UHF transmitter electrical power to generate the frequency signal. The electrical current in the UHF band will be changed to an electromagnetic wave and transmitted by the transmitting antenna to the receiving antenna. A wattmeter can measure the power transmitted by the radio wave [30]. Then, the UHF transmitter will be connected to the Yagi-Uda antenna by the coaxial cable. Electromagnetic waves will be generated from the Yagi-Uda antenna as the transmitting antenna to the receiving antenna [31]. The receiving antenna will be designed in this research. After that, there is an energy receiver circuit that consists of a coil, diode, and resistor. The function of the circuit is to convert the received energy to direct voltage and current. This direct current will be stored in the rechargeable battery. The current and voltage can be obtained using an ammeter and voltmeter.

2.2. Research steps

The research steps consist of conducting the experiment for designing the receiving antenna, testing the receiving antenna design, and retrieving the data from the WET system. Before creating the receiving antenna, the first step is to describe the design requirements. Then, the receiving antenna can be designed based on it. In the testing, three power levels and some distances will be given until the signal is lost. Lastly, the data will be obtained utilizing the WET method.

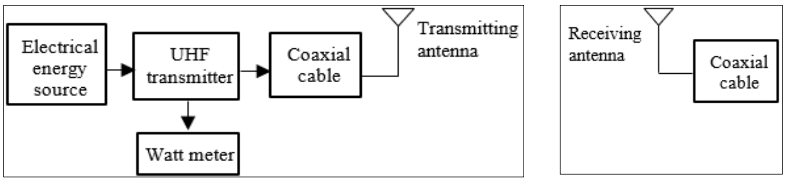
2.2.1. Design requirements

The design requirements for receiving antenna are mentioned as follows:

- The receiving antenna works in UHF band, especially at 430 MHz with ¼ lambda and the SWR is 1.48.
- The receiving antenna consists of a copper plate on the PCB, called a printed antenna.
- The receiving antenna must have no more than 1 cm^3 of dimension.
- The receiving antenna designed in the research must be able to harvest the electromagnetic energy with the WET method from the transmitter system that will be set up in the experiment according to the UHF 430 MHz band.

2.2.2. Testing of the receiving antenna design

The function of testing is to find the best performance of the receiving antenna design in the system that has been set up. In the research, a WET system was chosen. The excuse is because of the flexibility and capability of harvesting energy from the environment. The WET system has a transmitter and receiver system. The block diagram of the WET system is shown in Figure 2. The block diagram of the transmitter system in Figure 2(a) consists of a Yagi-Uda antenna as a transmitting antenna, coaxial cable, UHF transmitter, and direct current power supply. The receiving antenna design and energy receiver circuit are the receiver system shown in Figure 2(b). The energy receiver is an electronic circuit. It consists of a coil, diode, and resistor. The function of the circuit is to convert the received energy to direct voltage and current. This direct current will be stored in the rechargeable battery. The power received will be held in the rechargeable battery. In this research, the specification of the rechargeable battery is 700 mAh in capacity and 1.2 volts in voltage. Nickel-Metal Hydride (NiMH) is the chemical system of the battery [32]. The energy receiver circuit is shown in Figure 3.



(a) (b)

Figure 2. Block diagram of the system: (a) the transmitter system and (b) the receiver system

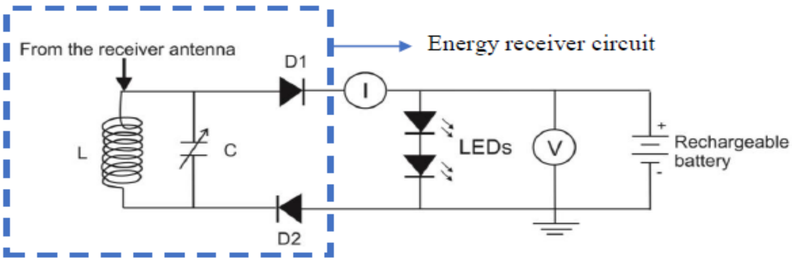


Figure 3. Experimental energy receiver circuit for data retrieval

The transmitting antenna in the transmitter system converts the electron kinetic energy to photonic energy, also called electromagnetic energy. Electromagnetic energy will be captured by receiving antenna. Then, the energy receiver circuit converts the electromagnetic energy to direct voltage and current. For testing, the researchers used the power from the transmitter system. The power is categorized into three types: high, mid, and low power. These powers are classified according to UHF transmitter specifications. The distance between transmitter (Tx) antenna and the receiver (Rx) antenna varies with an increment of 10 cm until the signal is lost.

2.2.3. Data retrieval

Based on the wireless transfer of electromagnetic energy, the voltage and current will be measured in the UHF band with the variation of the transmitter power. Varying the distance between the transmitting and receiving antenna is also conducted for data retrieval. The data retrieval with an increment of 10 cm until the signal is lost.

2.2.4. Experiment set up

The experiment set up for the research is as follows:

- Selecting the specific UHF band for designing the receiving antenna.
- Designing the antenna, lambda (λ), and light speed variable are needed.
- The pattern variation of the receiving antenna design will be determined based on the best performance for electromagnetic energy receiving.
- The variation of frequency will find the best pattern of the receiving antennas.
- The receiving antenna needs inductor L and capacitor C to receive electromagnetic energy. The specification of L and C is appropriated with the specific UHF band.
- The selected receiving antenna is used for the electromagnetic energy transfer experiment. It is done by getting the measured voltage and current.
- From the measured voltage and current, it can be proven that an electromagnetic wave carries the energy.
- With the three levels of power, high, mid, and low, and the distance variation between the Tx and Rx antenna, it will obtain the difference of measured voltage and current.
- The voltage and current will be measured ten times.

3. RESULTS AND DISCUSSION

3.1. Frequency transmission

The scope of the research is using the Yagi-Uda antenna as the transmitter in the UHF band. The specific frequency used in this research is 430 MHz. Selecting the UHF was done due to several reasons, as follows:

- UHF has a wavelength of λ 10 to 100 cm that is suitable for antennas designed for electromagnetic energy harvesting, especially for human implant device recharging.
- UHF is allowed by the government for the experiment.
- It is easy to obtain a transmitter that operates in the UHF frequency for the experiment.
- The amateur radio frequency band plan is for the experiment.
- For testing in the research, the frequency was set up in the range of 428 MHz to 434 MHz.

3.2. Design of a receiving antenna

The UHF band was selected as the basis for designing the receiving antenna. The UHF is used for television, and satellite communication. Therefore, it is abundant in the environment and can be harvested. The specific frequency that is used in this research is 430 MHz. The wavelength of the design is ¼ lambda (λ). The frequency and the wavelength are used for calculating the length of the antenna. The total length of the printed antenna is calculated as follows:

$$\lambda = \frac{c}{f} \tag{1}$$

$$\lambda = \frac{300\times10^6\ m/s}{430\times10^6\ Hz} \tag{2}$$

$$\lambda = 0.7\ m \tag{3}$$

where c is the speed of light, 300×10^6 m/s. Because the selected lambda λ is ¼, so the length of the antenna is,

$$\lambda = \frac{1}{4}\times 0.7m \tag{4}$$

$$\lambda = 0.17\ m = 17\ cm \tag{5}$$

the result shows that the receiving antenna design length is 17 cm. Therefore the shape of this antenna is shown in Figure 4. There are four receiving antennas designed, namely spiral antenna in Figure 4(a), square spiral antenna in Figure 4(b), zig-zag antenna in Figure 4(c), and square zig-zag antenna in Figure 4(d). The antennas are the same size. The 17 cm in length refers to the square strip on the PCB, called the printed antenna. The printed antenna consists of conductor copper designed as small as possible. It is 1.3 cm in length, 1.3 cm in width, and 0.2 cm in thickness with total volume of 0.34 cm^3.

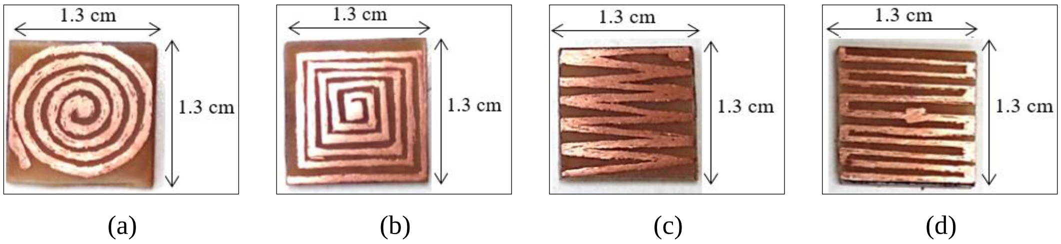


Figure 4. Designs of the receiving antenna with various patterns: (a) spiral antenna, (b) square spiral antenna, (c) zig-zag antenna, and (d) square zig-zag antenna

3.3. Pattern of the antenna

In this research, four receiving antennas have been designed. They have different patterns with the same length. They should be tested for testing the performance of each antenna. The testing was conducted based on the type of transmitted power and the frequency at the same distance, 10 cm. There are three types of transmitted power; high, mid, and low. The value of the high, mid, and low power sequentially is 54.05, 35.14, and 15.54 watts. These transmitted power values are according to the UHF transmitter specification. The various frequencies for testing the performance of the antenna were 428 MHz, 430 MHz, 432 MHz, and 434 MHz. The results of the testing are shown in Tables 1-4.

Table 1. The received power at 428 MHz

The pattern of the receiving antenna	Transmitted power		
	15.54 watt	35.14 watt	54.05 watt
	Received power (mW)		
Spiral antenna	6.02	35.2	62.92
Square spiral antenna	8.7	36.94	62.3
Zig-zag antenna	15.48	52.65	71.2
Square zig-zag antenna	10.32	41.36	70.2

Table 2. The received power at 430 MHz

The pattern of the receiving antenna	Transmitted power		
	15.54 watt	35.14 watt	54.05 watt
	Received power (mW)		
Spiral antenna	5.59	34.32	61.6
Square spiral antenna	9.68	34.71	57.85
Zig-zag antenna	15.91	47.52	72
Square zig-zag antenna	9.68	38.28	66.15

Table 3. The received power at 432 MHz

The pattern of the receiving antenna	Transmitted power		
	15.54 watt	35.14 watt	54.05 watt
	Received power (mW)		
Spiral antenna	4.25	32.12	58.08
Square spiral antenna	7.395	31.15	52.955
Zig-zag antenna	13.985	45.32	69.3
Square zig-zag antenna	8.6	33.88	58.5

Table 4. The received power at 434 MHz

The pattern of the receiving antenna	Transmitted power		
	15.54 watt	35.14 watt	54.05 watt
	Received power (mW)		
Spiral antenna	2.975	31.68	53.24
Square spiral antenna	5.16	23.14	47.17
Zig-zag antenna	11.61	41.36	62.325
Square zig-zag antenna	5.59	27.5	50.4

According to Tables 1-4, the zig-zag antenna has the best performance compared to the others in every frequency that was used for testing. The best frequency for the zig-zag antenna is 430 MHz. Based on Table 2, the zig-zag antenna has the largest value of received power at 15.54 watts and 54.05 watts of transmitted power. The value is 15.91 mW and 72 mW. There isn't phase cancellation in the zig-zag antenna, but the spiral, square spiral, and square zig-zag antenna patterns cause a phase cancellation signal from the transmitting antenna. Phase cancellation occurs when two sine waves are out of phase, which results in the reduction of the summed signal strength. Figure 5 shows the phase cancellation process in the receiving antenna.

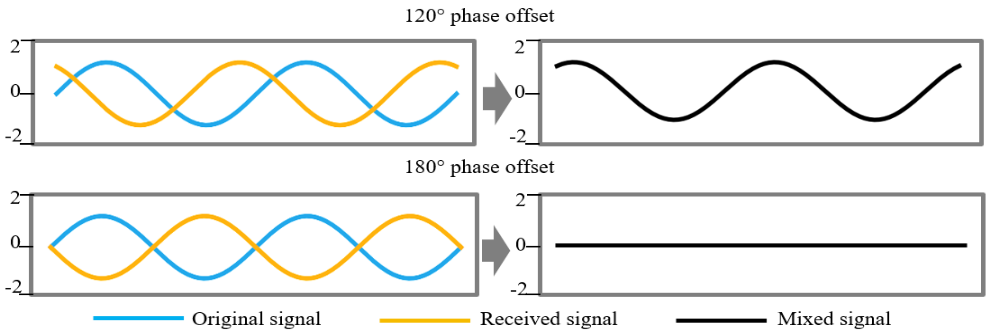


Figure 5. Phase cancellation

3.4. Energy receiver circuit

The function of the energy receiver circuit is to convert the received energy to direct voltage and current. It consists of two diodes, an inductor, and a capacitor. The research selected a germanium 1N60 diode because of its sensitivity. The sensitivity of a diode to radio waves depends upon its forward bias voltage, which is across the diode terminal. When it falls below the threshold value, the diode will stop conducting. The sensitivity of the diode to the radio signal will be greater if the threshold value is lower. The 1N60 germanium diode has a forward bias voltage of 0.32 V, providing better radio signal sensitivity [31]. The inductor and capacitor could be varied based on the specific frequency. If the frequency and inductor were 430 MHz and 5×10^{-5} H, the capacitor value was calculated as follows:

$$f = \frac{1}{2\pi\sqrt{LC}} \quad (6)$$

$$C = \frac{\left(\frac{1}{2\pi f}\right)^2}{L} \quad (7)$$

$$C = \frac{\left(\frac{1}{2\times3.14\times(430\times10^6 Hz)}\right)^2}{5\times10^{-5}H} \quad (8)$$

$$C = 2.74\times10^{-12} mF \quad (9)$$

the variable L is the inductor value, C is the capacitor value, f is frequency, and π is 3.14.

The frequency was set up at 428 MHz to 434 MHz with the following energy receiver circuit spelling: 5×10^{-5} H inductor value, 2.74×10^{-12} mF capacitor value, and two 1N60 diodes. The energy receiver circuit is given in Figure 6.

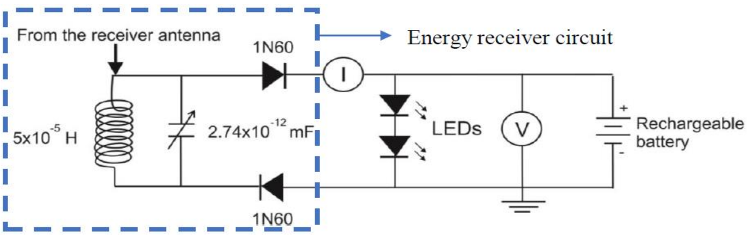


Figure 6. Energy receiver circuit

3.5. Electromagnetic energy transfer analysis

The printed receiving antenna that has been designed will be tested to determine its performance in energy capture. The testing was conducted based on the type of transmitted power and the frequency at the same distance, 10 cm. There are three types of transmitted power: high, mid, and low. The value of the high, mid, and low power sequentially is 54.05, 35.14, and 15.54 watts. These transmitted power values are according to the UHF transmitter specification. Then, the distance between Tx antenna and Rx antenna varies with space every 10 cm until signal loss. The loss of signal occurs at 120 cm. Based on the power and distance variation; the receiving antenna's energy-capturing ability is tested. The method for this test is to use the WET system. Printed antenna data retrieval in the research is done to the voltage and current.

Figure 7 shows the graphs of the current average that were calculated based on the voltage measured in the distance variation between the transmitting and the receiving antenna. The maximum voltage average exists when the Rx antenna is placed 10 cm in front of the Tx antenna and the power transmitter is set to 54.05 watts. Based on the result, the distance and the transmitted power affect the measured voltage.

On the other hand, Figure 8 shows the graphs of the current average that were calculated according to the measured current. The current average is higher along with the closer distance and the higher power transmitter. The maximum current average also exists when the power transmitter is 54.05 watts, and the distance between Tx and Rx antenna is 10 cm. It can be concluded that the measured current depends on the space and the power transmitter. In addition, the voltage and current data show that the energy can be captured from the electromagnetic wave, especially at 340 MHz of frequency.

The average voltage and current received that has been calculated will be used to find out the average power received. The graph of the received power is shown in Figure 9. When the spacing of the Tx and Rx antenna is 10 cm, the average power received has the highest value. In this position, the WET system can work optimally in transferring energy. Because of it, the selected distance for recharging the battery is in the 10 cm position. The efficiency will be obtained after the power is transmitted and received. The efficiency is calculated by comparing the power transmitted and the average power received. The three efficiency graphs shown in Figure 10 are based on the transmitted power. Between the three transmitter powers, the highest efficiency is 0.1 % at the 10 cm distance and 15.54 watts of the power transmitter.

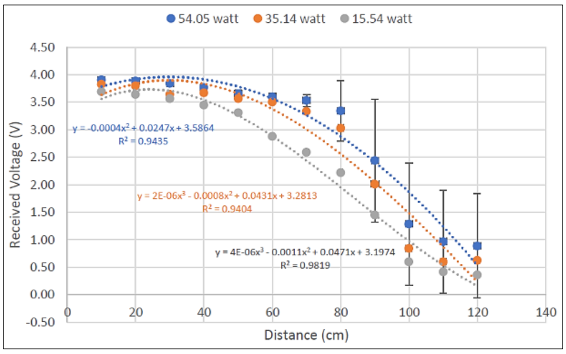


Figure 7. The received voltage based on the distance for zig-zag pattern

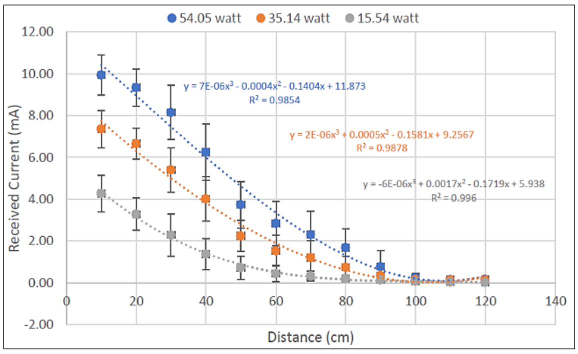


Figure 8. The received current based on the distance for zig-zag pattern

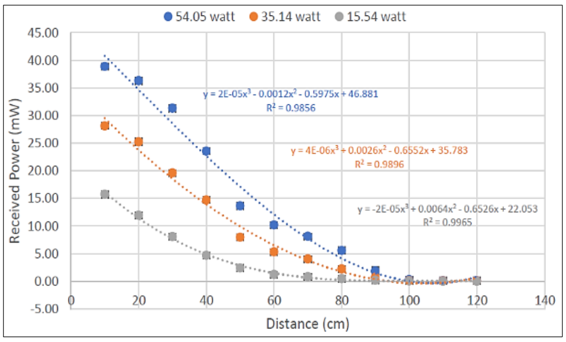


Figure 9. The received power based on the distance for zig-zag pattern

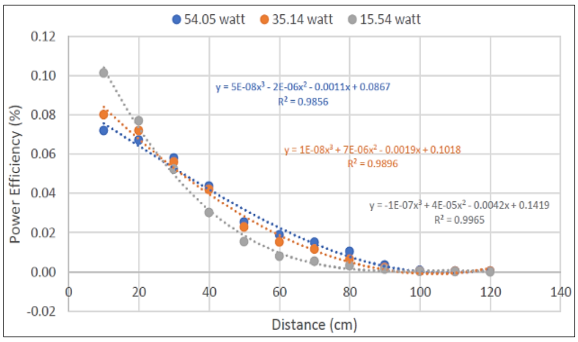
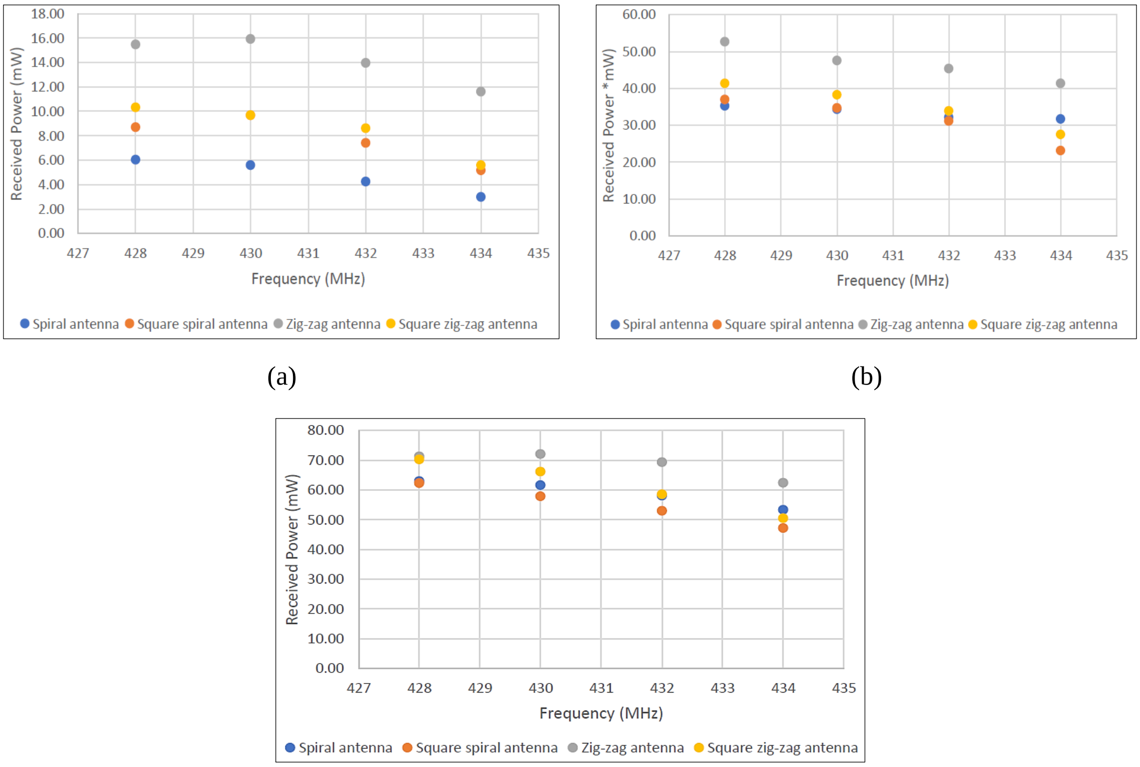


Figure 10. Power efficiency for zig-zag pattern

Although the highest efficiency occurs when the power transmitter is set to 15.54 watts, domination of the high efficiency occurs when the power transmitter is set to 54.05 watts. So, it will be used for the analysis of battery charging. Furthermore, Figure 11 shows the performance of the receiving antennas in graphs. Figures 11(a), 11(b), and 11(c) show the receiving antenna performance at 10 cm of distance and 15.54, 35.14, and 54.05 watts of power transmitter, respectively. At 15.54 and 54.05 watts of power transmitter, the best performance of the antenna to receive power is at the 430 MHz frequency. On the other hand, 428 MHz is the best frequency for the antenna to acquire power. Finally, the 430 MHz frequency with 54.05 watts is selected for data and analysis charging.



(a) (b)

(c)

Figure 11. The performance of the receiving antenna: (a) at 15.54 watts of the power transmitter (b) at 35.14 watts of the power transmitter, and (c) at 54.05 watts of the power transmitter

3.6. Charging analysis

The charging was held with a rechargeable battery with 700 mAh. The charging uses the WET method in the UHF band. The voltage of the battery is evaluated every 5 minutes of charging. The distance between Tx and Rx antenna is 10 cm with a high-power transmitter or 54.05 watts. The power and position were selected because they have the highest average voltage and received current. Table 5 contains the result of the experiment for charging the battery every 5 minutes. It proves that the WET system could charge the rechargeable battery.

Table 5. The recharging time

Data	Time of charging (minute)	Voltage changing ΔV (mV)
1	5	6
2	5	5
3	5	6
4	5	4
5	5	4
6	5	5
7	5	5
8	5	4
9	5	6
10	5	6

According to Table 5, the average voltage change is 5.2 mV per 5 minutes. Furthermore, for estimating the charging time, it could be held by calculation. The distance between Tx and Rx antenna and the power transmitter was set to 10 cm and 54.05 watts, respectively. If the capacity of the rechargeable battery is 700 mAh; 1.2 V and the electric circuit is shown in Figure 12, so the charging current based on the received voltage and current in Figure 12 is as (10)-(13).

$$P_{received} = P_{battery} \tag{10}$$

$$V_{received} \times I_{received} = V_{battery} \times I_{charging} \tag{11}$$

$$3.91\,V \times 9.94\,mA = 1.2\,V \times I_{charging} \tag{12}$$

$$I_{charging} = 32.39\,mA \tag{13}$$

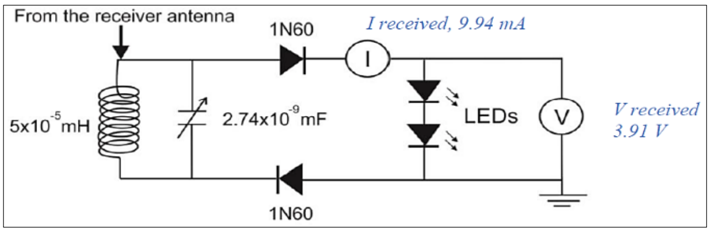


Figure 12. Electric circuit for the received power

Then to fully charge the rechargeable battery, the time needed is as follows:

$$Battery\ capacity = Charging\ capacity \times t \tag{14}$$

$$700\,mAh = 32.39\,mA \times t \tag{15}$$

$$\frac{700\,mAh}{32.39\,mA} = 21.61\ hours \tag{16}$$

based on the calculation, to fully charge the rechargeable battery with the 700 mAh of capacity by the WET system that has been designed, the time of charging is 21.61 hours. According to this result of the calculated prediction and Table 5, the WET system's receiver design based on UHF can transfer electromagnetic energy. Moreover, this system can be applied for electromagnetic energy harvesting because the power can be stored in a rechargeable battery.

3.7. The comparison

This research has been conducted with the size of the receiving antenna design is 0.34 cm^3 and 0.1% for efficiency. On the other hand, the previous results from the other research have 1.44 cm^3 for the size of the receiving antenna and the efficiency is 0.00116%. Based on this data, we have larger efficiency and the receiving antenna design also has a smaller size than previous research. Then details of the comparison are the size of the receiving antenna design and the efficiency of previous results, and our result is shown in Table 6.

Table 6. The comparison of size and efficiency

	Size of the receiving antenna	Efficiency
Previous study	1.44 cm^3	0.00116%
This study	0.34 cm^3	0.1%

4. CONCLUSION

According to this research, the findings are that electromagnetic energy could be transferred from the UHF transmitting antenna and could be received by the receiving unit design. The maximum efficiency was 0.1% using the WET system at a 10 cm distance with a transmitter power of 15.54 watts. The receiving antenna design has a volume of 0.34 cm^3. The electromagnetic energy harvested was successfully stored in the 700 mAh rechargeable battery with a charging time of 21.61 hours. The experiment method should be developed for future works to get a receiver system design that improves the WET efficiency and minimizes the receiver unit size to be applied as an implant device.

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