OPTIMIZATION OF WIRELESS POWER TRANSMISSION

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OPTIMIZATION OF WIRELESS POWER TRANSMISSION

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A project report submitted in partial fulfilment of the requirements for the award of Bachelor of Engineering (Hons.) Electronic Engineering

Faculty of Engineering and Green Technology
University Tunku Abdul Rahman

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DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

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APPROVAL OF SUBMISSION

I certify that this project report entitled **"OPTIMIZATION OF WIRELESS POWER TRANSMISSION"** was prepared by **LIM CHEN LOONG** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Engineering (Hons) Electronic Engineering at Universiti Tunku Abdul Rahman.

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OPTIMIZATION OF WIRELESS POWER TRANSMISSION

ABSTRACT

In this final year project, wireless power transmission (WPT) system is investigated. A WPT system is normally made up of one transmitter and one receiver. This type of conventional WPT system will be referred as CWPT system. In this project, however, parasitic element is inserted into the system. The WPT system integrated with parasitic element will be referred as PWPT system.

There are different methods of inserting parasitic element into WPT system such as different shape, line up, and number. The first idea of PWPT system is created by using a parasitic wire in square shape, rectangular shape, straight lines, and rectangular shape with straight lines. After that, PWPT system is designed by locating parasitic element to different location, such as in front of transmitter or behind of transmitter. The last method is increasing the number of same shape and parameters of the parasitic element from one to maximum eight.

In order to apply all the designs above, FEKO software is used as a platform to conduct the simulation. Method of Moment (MOM) is used by this software to solve the sophisticated mathematical electromagnetism problem. A series of steps are included to obtain the simulation result in FEKO, for example, modelling, declaring variables, meshing and simulating.

The result obtained shows the power transfer efficiency (PTE) of a particular PWPT/CWPT system. In this research, the highest PTE obtained among all the model is PWPT system with eight parasitic rectangular wire which are located in front of

receiver, in front of transmitter, beside of transmitter and behind of transmitter, all the four directions.

However, the design of this PWPT system occupies lot of space which become the disadvantage if utilized it in the real life. A more compact and complex version of PWPT system hope can be designed meanwhile which can either maintain or increase the PTE of the system.

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λ	Lambda, m
η	Efficiency, %
D_{RX1}	Distance between receiver 1 and parasitic wire 1
D_{RX2}	Distance between receiver 2 and parasitic wire 2
D_{PX1}	Distance between parasitic wire 1 and transmitter
D_{PX2}	Distance between parasitic wire 2 and transmitter
D_{total}	Total system distance
D_1	Distance from transmitter to receiver 1
D_2	Distance from transmitter to receiver 2
f	Operating frequency
m	Meter
N	Number of turn
Px	Parasitic wire
PxPx	Distance of parasitic wire to parasitic wire
R_L	Receiver load
Rf	Radio Frequency
Rx	Receiver

S_{21}	Measured of the signal emitted from port 2 relative to signal entering port 1
Tx	Transmitter
TxPx	Distance of transmitter to parasitic wire
TxRx	Distance of transmitter to receiver
X_L	Inductance
ADS	Advance Designed System
CWPT	Conventional Wireless Power Transmission
DE	Differential Evolution
EM	Electromagnetic
GHz	Gigahertz
MHz	Megahertz
MPS	Magnetic Power Source
MoM	Method of Moments
PTE	Power Transfer Efficiency
PWPT	Parasitic Wireless Power Transmission
USB	Universal Serial Bus
WPT	Wireless Power Transmission
Xlp1	Transmission Distance in term of meter

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CHAPTER 1

INTRODUCTION

1.1 Background

In wireless technology, Nikola Tesla is known as 'Father of Wireless Technology'. He is the first scientist who explored into the field of wireless technology. Most of the concepts developed about wireless technology is based on concept created by Tesla. One of the important concepts introduced by him is wireless signal transmission. It allow wave to be transferred via free space. This include wireless power transmission (WPT) system (Agnes, 2017).

1.2 Problem Statement

Wireless power transfer devices or system can already be found in the market and they are safe to be used (Agnes, 2017). However, there are still open issue and challenges yet to be overcome by the producer. The efficiency of the WPT system operating at

9.9 MHz will reduce below 50 % after a distance greater than 2 m. This point of view shows that power transfer efficiency (PTE) is strictly controlled and limited by the distance transfer from transmitter to a target receiver. (Kurs et al., 2007).

1.3 Objective

The aim of this project is to increase the PTE of WPT system by inserting parasitic element into WPT system. This method can further optimize the performance of conventional WPT system which is made up of only one transmitter and one receiver.

CHAPTER 2

LITERATURE REVIEW

2.1 Wireless Power Transmission

Wireless power transfer (WPT) system supplies power from a power source to a load through air gap. This wireless concept has already been around since late 1890s. That time, Nikola Tesla was able to light up his light bulb without using wire at his Colorado Springs Lab using electrodynamic induction (Marie, 2016).

Generally, a WPT system appearance based on Faraday's law of induction. This law states that the change of magnetic field causes an AC current (Magnetics, 2018). Thus AC current is obtained on the other side of the transmitter over an air gap. Theoretically, electrical energy is carried and propagate from transmitter to receiver using the field created by charged particle over the air gap. The air gap is bridged by converting the energy needed into oscillating field, propagating over the air gap, and then converted back to electrical energy by the receiver. The example of oscillating field are electric field, magnetic field or electromagnetic wave.

For common use, a WPT system can be classified into three main types which are based on the technique of transmission. The first type is electromagnetic (EM) radiation technique. This type of WPT system is used for long energy transmission such as satellite. Energy is being propagated as radio wave. The second technique is inductive coupling technique. This type of technique is preferable only in short distance energy transmission. The last technique is called resonant inductive coupling which increasing efficiency of WPT system compare to inductive coupling technique. Two resonators with same resonant frequency are installed to enhance the efficiency of the WPT system (Vijayakumaran Nair and Choi, 2016).

2.2 Application

Wireless electronic appliances have become more and more common as the development of wireless technology advance. There are some examples of electronic devices which apply the concept of wireless power transfer (WPT) system in real life. WiTricity, a system invented by MIT scientists, has enabled electric car charged wirelessly as shown in **Figure 2.1** below. The drivers can direct charge their car battery by positioning the back part of the car above the WPT system at the parking lot.

Figure 2.1 Graphic of a wireless parking charge setup built into a parking space. Image courtesy of Toyota. (Corporation., 2018)

Recently, many companies are trying to make use of the WPT system to enhance or upgrade their products and services. For instance, Starbucks came out with an idea of providing wireless phone charging station at the coffee tables. This idea can ease their customers charging mobile phone when they are eating. A circular Powermat charging spot are built in long bench pattern against the main window. A charging mats which are found on the table top enabled customer enjoy charging phone by putting their smartphone on the top of the mats directly. Phone charging cable becomes unnecessary to be taken out by customers (Andy, 2015). Meanwhile, cordless kitchen appliance are also available in the market. The concept of Cordless Kitchen was first introduced by Qi. In that concept, all the kitchen appliance manufactured by them can be powered up and used by only placing over the magnetic power source (MPS) designed by them. These appliance avoid users annoyed by power cord which are draped across table and plugged into an outlet (Wireless Power Consortium, 2017). For construction field, WPT system can also be applied soon. Cordless power drill is also being developed by Bosch for construction site. IKEA, the furniture company is also trying to create an integrated furniture and lighting for wireless home (Marie, 2016).

From the examples above, there are many benefits which can be obtained from using WPT system. Firstly, the WPT system can secure the safety of the users indirectly. If a person's smartphone runs out of battery when he or she is driving, finding and connecting properly from power bank or charging cord in car is time consuming. If he intended of searching for the charger while driving, he may lose focus of the road condition. Therefore, wireless smartphone charger is needed in order to reduce the risk. All the driver need to do is just put the phone on the armrest. The time consume has significantly reduced compared to phone charging with USB. The second advantage is the WPT system allows the device to be encapsulated completely, so that it becomes waterproof. For a normal smartphone, micro-USB port is needed to plug in the power cord of smartphone. This characteristic increase the difficulty for a smartphone company to design a waterproof product. By using WPT system, no port is needed and hence the entire smartphone can be shielded easily. Another advantage is durability – In our daily life, charging of electronic stuffs is a must. However, matching male with female port using either cable or USB port every day might easily damage the physical contact point between port and connector. Introducing WPT system can totally solve this issue because no more cable is needed (Jacob, 2015).

2.3 Operation of Wireless Power Transmission

There are different methods of operating WPT system and enhancing it in the same time. The first WPT operation studied is WPT system integrated with parasitic element (PWPT). PWPT system with different designs of parasitic wires are introduced to enhance the efficiency of the system. In this system, the energy emitted out from transmitting antenna is propagating through the parasitic wire and is harvested by receiving antenna. This system is formed by inserting a square parasitic wire in between transmitting antenna and receiving antenna. Another idea of PWPT system is created by inserting circular parasitic wire in between transmitting antenna and receiving antenna. This system is known as PWPT system integrated with a circular parasitic wire. The next PWPT system studied is PWPT system with dual receiver system. There are total of two receiving antenna in this system. This system is further enhanced by using inductive parasitic wire instead of original parasitic wire which is non-inductive (Agnes, 2017). All the models geometries are summarized in **Table 2.1.**

Next, multiple coil switching technique is studied which is proposed by Vijayakumaran Nair and Choi (2016). At the beginning, four-coil WPT system are carried out. This model made up of four coils which are source coil, transmitter coil, receiver coil and load coil. The source coil (N1 turns) is transmitted to transmitter coil Tx which is magnetically-coupled (N2 turns). There is another Rx coil before a receiver (N3 turns) which are also magnetically coupled together with transmitter. Lastly, there is the last load coil at receiver side (N4 turns). For maximum power transfer, resonator are designed such that the resonance frequency is identical. The whole model is shown in **Table 2.1**.

Next, WPT System Using Planarized, Capacitor-loaded Coupled Loop is studied. This project is investigated by Li & Ling (2009). This WPT system is installed with capacitor-loaded coupled loop structure at 6.78 MHz for 1 *m* transmission distance. During the project, coplanar shape of coupled loop is realized to be the optimal configuration. This WPT system is using strongly coupled magnetic resonance technique. Firstly, the design's model is standard capacitor-loaded couple loop configuration. The shape of both transmitter and receiver are identical to each other. Each of them consist of one smaller primary loop and one larger capacitor-loaded secondary loop. After modified, the thick wire is then converted into wide strip in order to increase the efficiency of the WPT system. All the model's geometries are shown in **Table 2.1** below.

Another WPT system- Magnetically-coupled Resonance WPT, which similar to resonance inductive coupling method is introduced by Sample, Meyer & Smith (2011). This project introduced is much similar as previous project which is magnetic-coupled resonator. The transmit antenna consists of one single loop and a multi turn spiral coil. When the single loop is powered up, the multi turn spiral coil is excited and hence energy is stored. The same manner is applied to the receiver site. The resonant frequency can also be tuned automatically. The model geometric is shown in **Table 2.1** below.

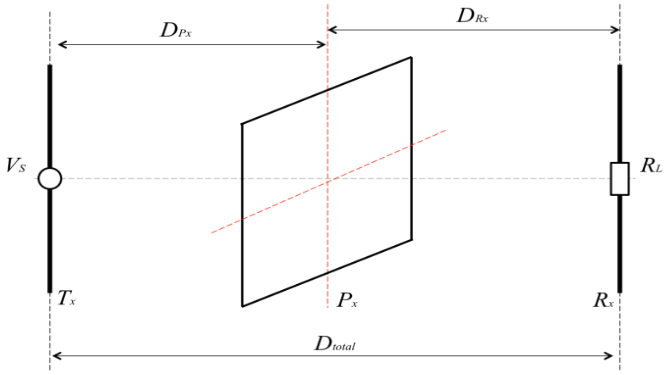
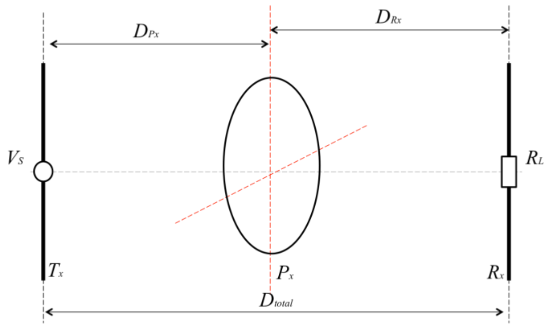
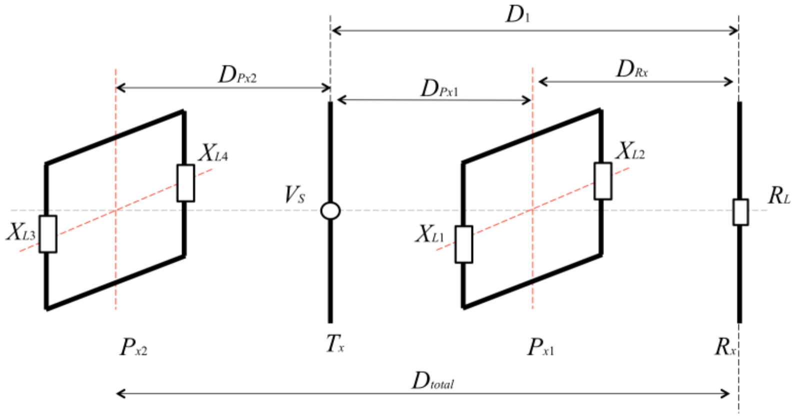
The next system is called WPT system to multiple small receivers. In this system, a large source coil with either one or two coil receiver WPT system is used by Cannon et al (2009). This means that a system with two receivers will be investigated. In this method, a primary coil is driven by a source. Parallel capacitors are added to form a resonant circuit in order to increase the power transfer efficiency. The power from source is transferred to secondary coil at receiver side through the air. There are two LEDs are representing two different receiver loads. The large green coil is served as the large primary transmitter coil. The coils are terminated by lumped capacitances which establishing high Q resonant coupling. The resonant frequency can be determined by adjusting lump capacitances. In order to test the idea, an experiment setup is shown in **Table 2.1** below.

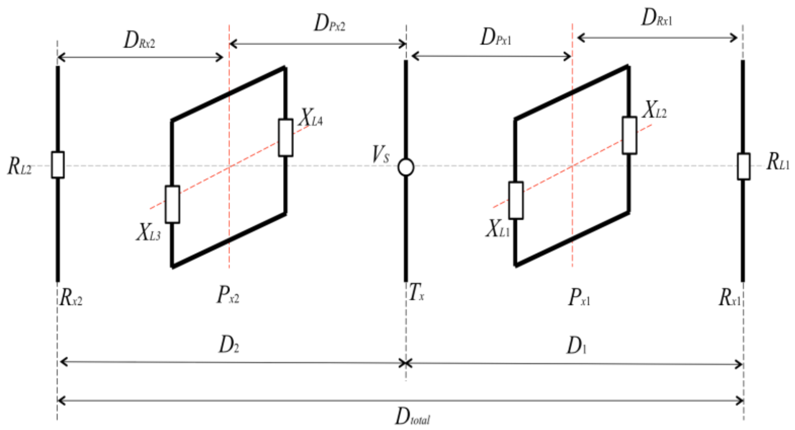
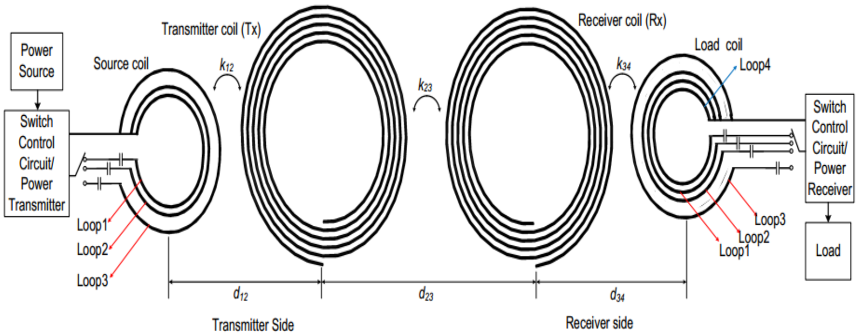
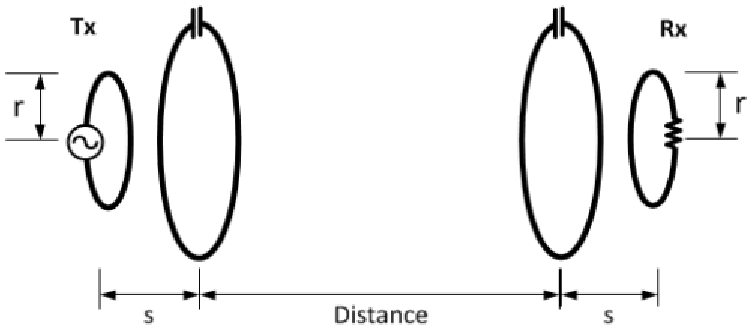
Another type of WPT system is called WPT system with converter circuit. This WPT system is investigating about power source circuit, load circuit and also coil, as an integral system, which is done by Zhang et al (2017). This research focus on the basic WPT system by optimizing the circuit. A circuit which converted DC input into AC excitation as feeding circuit. Two inductors have to be formed by coils, two for transmitter, another one for receiver. The overall feeding circuit and load circuit are shown in **Table 2.1**.

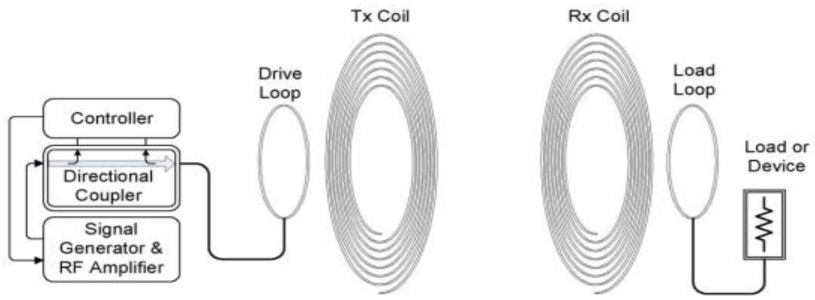
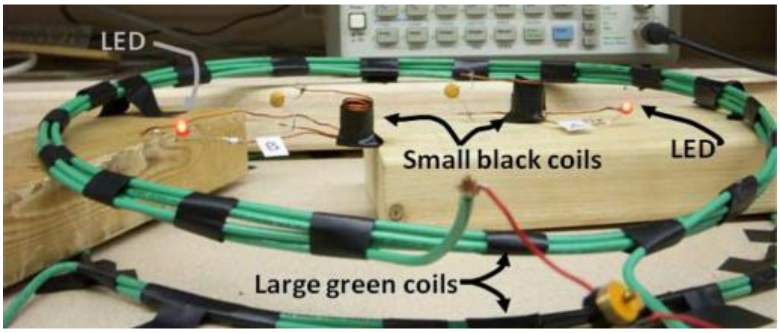
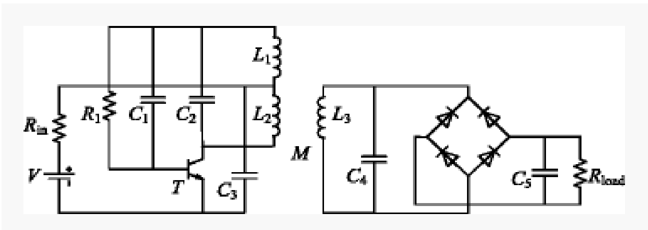
2.4 Enhancement in Efficiency

Most of the models above is simulated using FEKO software or other electromagnetic simulation software such as SPICE and Agilent ADS (Advanced Design System), or some even through experiment. After the results are simulated, most of the efficiency obtained from different methods are enhanced successfully. The results and methods used are summarized in **Table 2.1**.

Table 2.1 Summary of All Models, Methods and Results

Geometric View	Methods and Results
 PWPT System Integrated with a Square Parasitic Wire (Agnes, 2017)	Method: FEKO Peak Efficiency: 10.70 %
 PWPT System Integrated with a Circular Parasitic Wire (Agnes, 2017)	Method: FEKO Peak Efficiency: 8.34 %
 PWPT System Integrated with Dual Square Parasitic Wire (Agnes, 2017)	Method: FEKO Peak Efficiency: 15.57 %

 Dual-Px Dual-Rx Square PWPT System (Agnes, 2017)	Method: FEKO Peak Efficiency: 19.16 %
 Magnetic Resonance-coupled WPT System (Vijayakumaran Nair and Choi,2016)	Method: Agilent ADS tool Peak Efficiency: 93.20% at 0.25 m
 WPT System via Capacitor-loaded Coupled Loop (Li & Ling, 2009)	Method: FEKO Peak Efficiency: 85 % at 0.98 m

 Magnetically Coupled Resonance WPT system (Sample, Meyer & Smith, 2011)	Method: SPICE Peak Efficiency: 70 % at 0.75 m
 Setup of Multiple Receiver WPT system (Cannon et al, 2009)	Method: Experiment Peak Efficiency: None
 Overall Circuit for WPT System (Zhang et al, 2017)	Method: Differential Evolution (DE) Peak Efficiency: 30%

From the result obtained above, there some models which having high efficiency and low efficiency. For models which generate higher efficiency are much more complicated compared to those model which output a lower efficiencies.

In Magnetic Resonance-coupled WPT System, the power transfer efficiency is the highest. However, the intermediate process of the system is very complicated (Vijayakumaran Nair and Choi, 2016). In multiple receivers system, after the result is obtained, the following points can be summarized. Firstly, concept of multiple receivers is workable. Secondly, the key to power up multiple receivers system is coupled mode frequency splitting. This happened when two receiver are close proximity until their magnetic field are strongly coupled. Hence, this type of method is not easy to endure with (Cannon et al, 2009). There is no result of efficiency versus distance showed here, but, the model designed is quite interesting. For WPT system with converter circuit, a curve of efficiency versus frequency is generated after analysed. The result conclude that the power transfer efficiency reaches maximum of 30 % when frequency is 13.56 MHz. However, the result is out of this project’s interest because the result taken is efficiency versus frequency instead of efficiency versus transmission distance. However, this idea is very interesting, we may brainstorm a new idea from this system.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Overall Flow

In this research, the overall methodology flow is shown in **Figure 3.1** below.

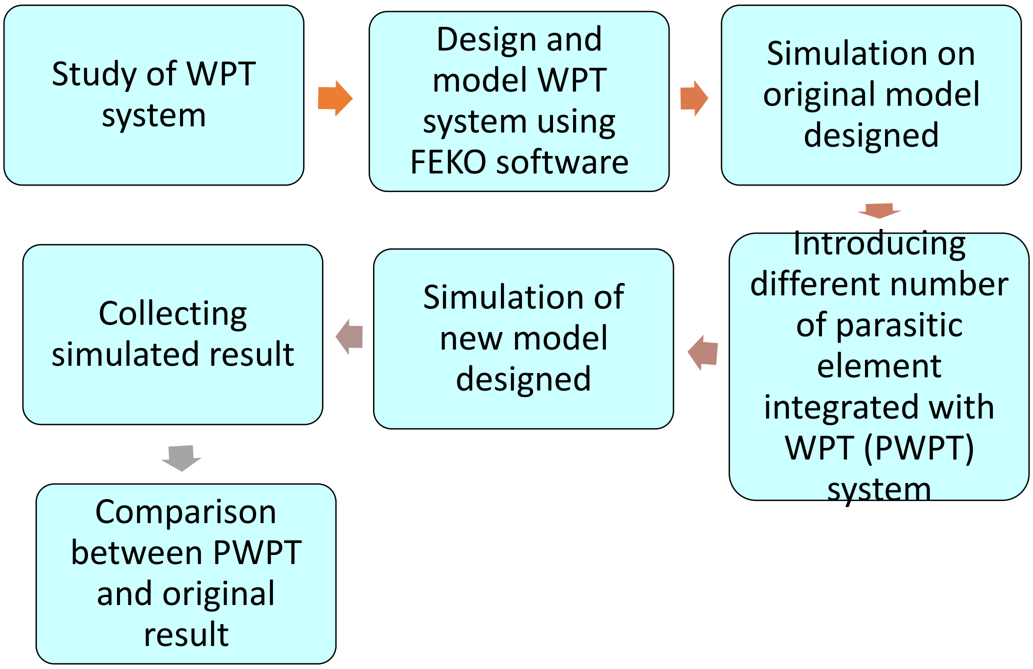


Figure 3.1 Overall Methodology Flow in WPT System.

Basically, investigation and study of WPT system is the first step in this project. After that, modelling of CWPT system using FEKO is carried out. Simulation is then done by using FEKO. Brainstorming of ideas and designed for PWPT system is carried out. The new models designed are simulated using FEKO again. Finally, the results obtained for both CWPT and PWPT system are compared and discussed. The details for each of the section will be discussed in the following section.

3.2 Methodology

3.2.1 Study of WPT System

Before the project is start, several researches and studied are done which basically are described in Chapter 2 (Literature Review). There are books, journals, thesis and online resources are searched, studied and applied. However, the main source of this project is thesis which is written by Agnes. This is because this project is the extension from her project. Besides finding online resource, consultation to my lecturer or supervisor is also done in order to improve my knowledge about WPT system.

3.2.2 Modelling of CWPT System

FEKO software is the main platform in this project. Hence, a brief introduction about the software is needed. In this software, most of the EM problem can be solved. According to user manual in 2017 by Altair, method of moment (MoM) is used in WPT calculation of WPT system. The illustration of FEKO workflow is shown in **Figure 3.2** below.

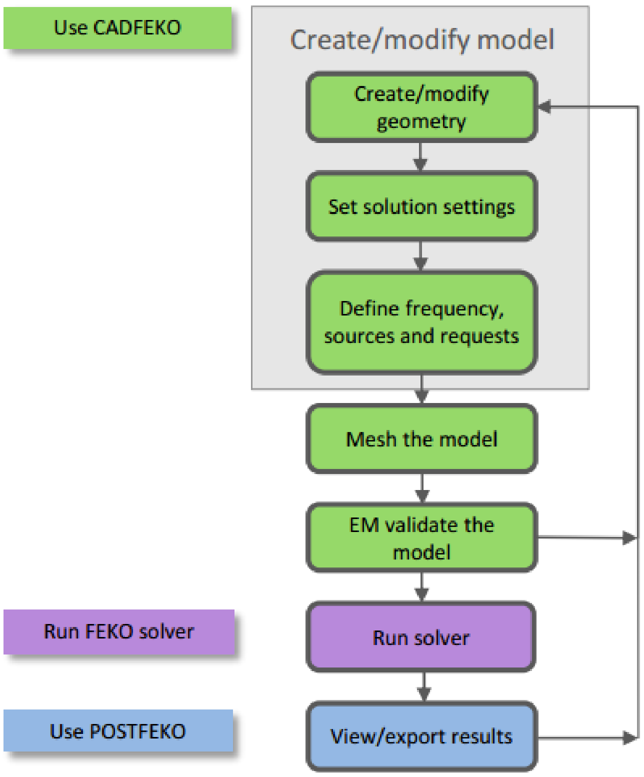


Figure 3.2 Illustration of FEKO Workflow (Altair, 2017)

Generally, FEKO divided into CADFEKO and POSTFKO. CADFEKO is used for setting the model and run. On the other hand, POSTFEKO is used to view the result obtained by CADFEKO after simulation. In CADFEKO, the geometry of the WPT model is assigned and created first. Next, the frequency, s-parameter, line port, source and load are all defined. The next step is model meshing in order to go for calculation. The model is then validated and solved using solver. Finally, the result is obtained using POSTFEKO.

3.2.3 Design of PWPT System

After CWPT system is designed, an advanced version of WPT system, which including parasitic wire inside WPT (PWPT) system is created. In this system, a different shape of parasitic wire is integrated in between the transmitting antenna and receiving antenna. The design is further extended to two or more parasitic wires created. Furthermore, different shape of parasitic wire is created to observe the result. All the above designs are done using FEKO too. The models created and results obtained will be discussed in Chapter 4 in detail.

3.2.4 Simulation of WPT / PWPT System

After modelling, simulation is needed to validate the model. By using FEKO, simulation can be processed in a short period since it is a very powerful EM software. Method of Moment (MoM) algorithm is used by this software for complicated EM calculation. MoM is versatile and having high accuracy when solving open region problems like scattering, planar circuit, and antenna. This type of method have smaller size matrix so it does not suffer from numerical dispersion. This method make use of Green’s function, which consumes quite a lot of computational time when solving three dimensional problem (Agnes, 2017).

3.2.5 Result Collection and Comparison

This is the final phase of the whole project. The results of power transfer efficiency (PTE) from both CWPT and PWPT system are collected by graph. Graph of S-parameter versus distance (in unit meter) will be obtained from FEKO. After that, graph of PTE versus distance (in unit lambda) are plotted using Microsoft Excel after calculation. Note that all the graphs obtained from FEKO are available in Appendix A. In this phase, most of the results obtained are discussed and compared.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 CWPT System Model

CWPT system is the most basic structure of a WPT system. There are a transmitting antenna (transmitter) and a receiving antenna (receiver) in the whole system. The energy radiated out from transmitter is harvested by receiver through the air gap. The model is shown in **Figure 4.1** below.

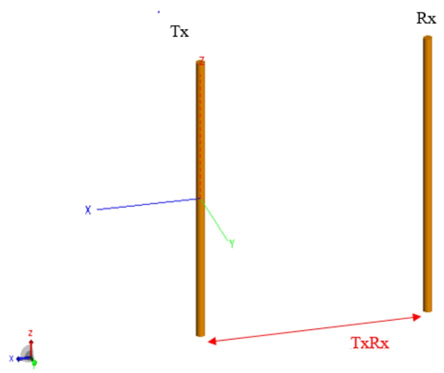


Figure 4.1 Model View of CWPT System

The transmitter and receiver are labelled as Tx and Rx respectively in **Figure 4.1**. The distance between transmitter and receiver is labelled as TxRx in the figure. The parameters of the model are summarized in **Table 4.1** below.

Table 4.1 Parameters of CWPT System.

Parameter	Dimension
Operating frequency (GHz)	1.000
Height of Tx (λ)	0.5
Wire radius of Tx (λ)	0.005
Height of Rx (λ)	0.5
Wire radius of Rx (λ)	0.005
Lambda (m)	0.300

These parameters will be useful in order to design the CWPT system. In order to obtain the PTE, the distance from receiver is increased to a certain fix point. In this project, the distance between transmitter and receiver is increased until 1.5 λ away from each other. Hence, a relationship between PTE over distance between transmitter and receiver is simulated using FEKO software. The PTE obtained from FEKO is expressed in S-parameter. Hence, the PTE can be expressed as follow (Vijith & Rim 2016):

$$n = |{S_{21}}^2| \tag{4.1}$$

where

η = Efficiency, %

S_{21} = Measured of the signal emitted from port 2 relative to signal entering port 1 (Literature.cdn.keysight.com, 2018).

The distance obtained from FEKO (xlp1) is expressed in unit meter (which can be found in Appendix A). Hence, an equation is used to convert distance in unit meter to distance in unit lambda as below:

$$Distance\ (\lambda) = \text{xlp1}\ (m) \div 0.3 \quad (4.2)$$

where

Distance = Distance between transmitter and receiver, λ

xlp1 = Distance between transmitter and receiver generated by FEKO, m

After both S-parameter and distance are converted, the result of PTE against distance is plotted in **Figure 4.2** below. Note that all the graph obtained is available in Appendix A.

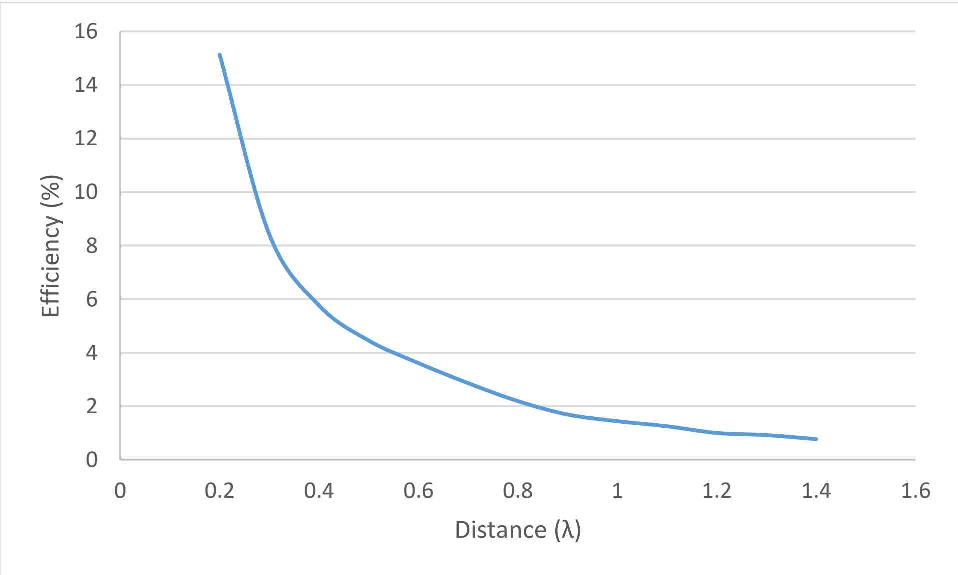


Figure 4.2 Graph of CWPT System.

From the graph obtained above, the peak PTE is 15 % which lies on 0.2 λ. The PTE drops as the distance between the transmitter and receiver increases. Another important result need to be obtained is the effective distance. For this project, the effective distance is defined as the distance where the PTE stay above 10 %. In this CWPT system, the effective distance is 0.28 λ. This means that for a CWPT system with wavelength of 0.3 m, the effective distance is 0.084 *m* or 8.40 cm which very low PTE.

4.2 PWPT System

WPT systems integrated with parasitic wires (PWPT) are introduced to increase the power transfer Efficiency (Masuda et al., 2013). According to Karalis et al. (2008), there is a significant increasing of signal quality and signal attenuation can be reduced when parasitic element is installed into a wireless communication system. In this system, parasitic wires with different geometries are installed. To investigate the efficiency of the system, we first place the parasitic wires at a fixed position, we then change the geometry of the wire to study its effect on the efficiency of the system. We subsequently duplicate the parasitic wires and then place them at various positions. This is to determine the optimal number of parasitic wires and the corresponding positions which will give the best results. **Table 4.2** shows the parameters which will be used in the following section.

Table 4.2 General Parameters Used in PWPT System

Parameter	Dimension
Operating frequency (GHz)	1.000
Height of Tx (λ)	0.500
Wire radius of Tx (λ)	0.005
Height of Rx (λ)	0.500
Wire radius of Rx (λ)	0.005
Lambda (*m*)	0.300

4.2.1 PWPT System Integrated with One Parasitic Square Wire

The first design of PWPT system introduced is by installing one square parasitic wire between transmitter and receiver. This model is first designed by Agnes (2017). The model view is shown in **Figure 4.3** below.

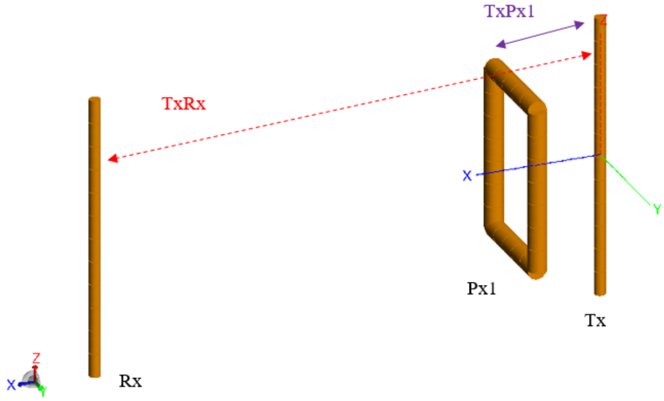


Figure 4.3 Model of PWPT System with One Square Parasitic Wire.

In the figure, the distance between transmitter and receiver is labelled as TxRx, parasitic wire installed is labelled as Px1, and the distance from transmitter to parasitic wire is labelled as TxPx1. The length of TxPx1 is fixed at 0.15 λ. Before the result is simulated, TxRx is fixed with the best value using optimization function in the FEKO software. The result are obtained by moving the receiver away from transmitter gradually. The parameters of this PWPT system is shown in **Table 4.2** in **Section 4.2**.

All the parameters used are the same as CWPT system but only with an extra perimeter of square parasitic wire (Px1) which is 1 λ. The result obtained is shown in **Figure 4.4** below.

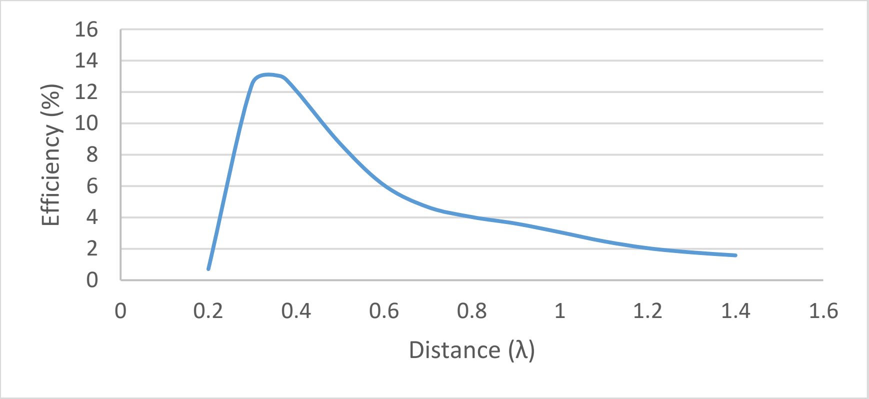


Figure 4.4 Graph of PWPT System with One Square Parasitic Wire.

From the result obtained, the PTE is increasing until reaches distance of 0.35 λ and it start to decay gradually. The peak is 13.32 % and the effective distance is start from the range 0.29 λ to 0.45 λ. The shape of the curve is shifted to the right compared to CWPT model because of the existence of parasitic wire. Hence, the peak efficiency is shift to the right which indicating higher efficiency can be obtained.

4.2.2 PWPT System Integrated with One Rectangular Parasitic Wire

There are two type of rectangular shapes are tested which are tall rectangle and wide rectangle shape. The first model that are going to study is PWPT system integrated with tall rectangular parasitic wire. The model is shown in **Figure 4.5** below.

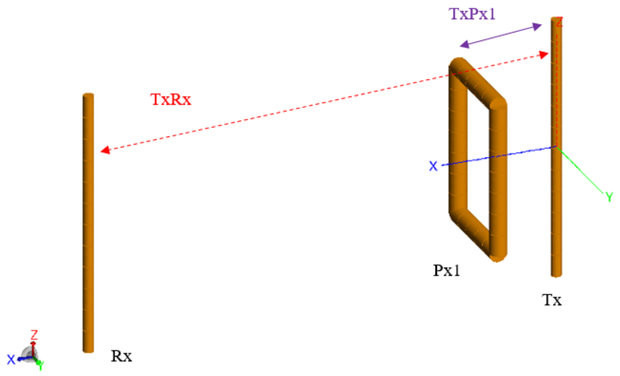


Figure 4.5 Model of PWPT System Integrated with Tall Rectangular Parasitic Wire.

The distance between transmitter and receiver is labelled as TxRx. The distance between tall rectangular parasitic wire and transmitter is labelled as TxPx1. Meanwhile the tall rectangular parasitic wire is labelled as Px1. The height of the Px1 is 0.3 λ, while the width of it is 0.2 λ. The length of TxPx1 is fixed at 0.15 λ. The perimeter of parasitic wire is 1 λ. The other parameters of this PWPT system is shown in **Table 4.2** in **Section 4.2**.

The parameters used in this model are all the same as the model of PWPT system integrated with square parasitic wire. However, tall rectangular parasitic wire is used here instead if square parasitic wire. The result obtained is shown in **Figure 4.6** below.

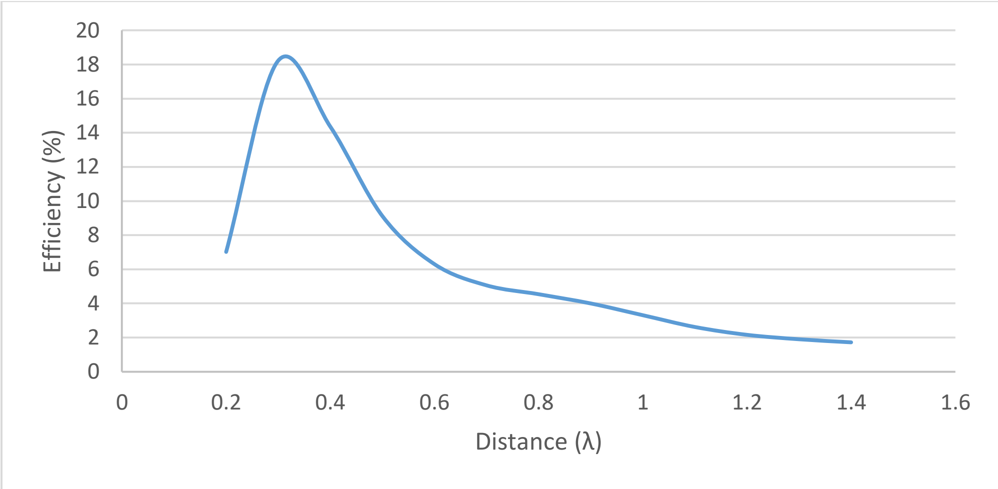


Figure 4.6 Graph of PWPT System Integrated with Tall Rectangular Parasitic Wire.

The result obtained above shows that the PTE increases at first, it then decreases gradually after reaching a peak point. The peak PTE is 18.50 % at distance of 0.3 λ. The effective distance is from 0.23 λ to 0.5 λ. This PWPT system shows a higher peak PTE because a longer length of parasitic wire in z-axis direction is created. The parasitic element in y-axis direction and z-axis direction will have a direct impact on a WPT system which is using electromagnetic wave as energy transfer medium (Yeap, 2017).

Next, PWPT system integrated with wide rectangular parasitic wire is designed. In this model, the setup of the system is the almost similar. The only different is tall rectangular parasitic wire is replaced by wide rectangular parasitic wire. The perimeter of the parasitic wire is 1 λ. The height of the rectangle is 0.2 λ while the width of it is 0.3 λ. The length of TxPx1 is fixed at 0.15 λ. This measurements is totally inverse of the tall rectangular parasitic wire. The model is shown in **Figure 4.7** below.

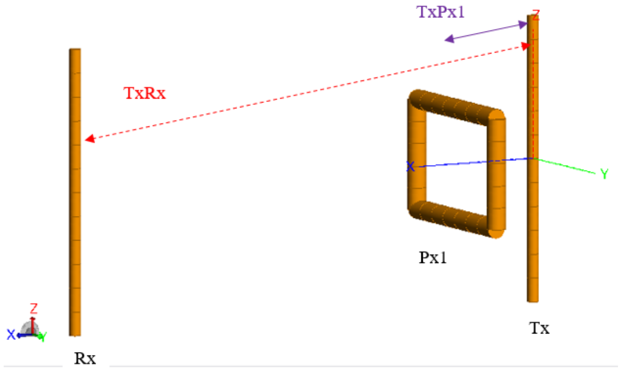


Figure 4.7 Model of PWPT System Integrated with Wide Rectangular Parasitic wire.

All the labels are same as the model above. The only different is the labelling of Px is indicating wide rectangular parasitic wire. The result is obtained as shown in **Figure 4.8** below.

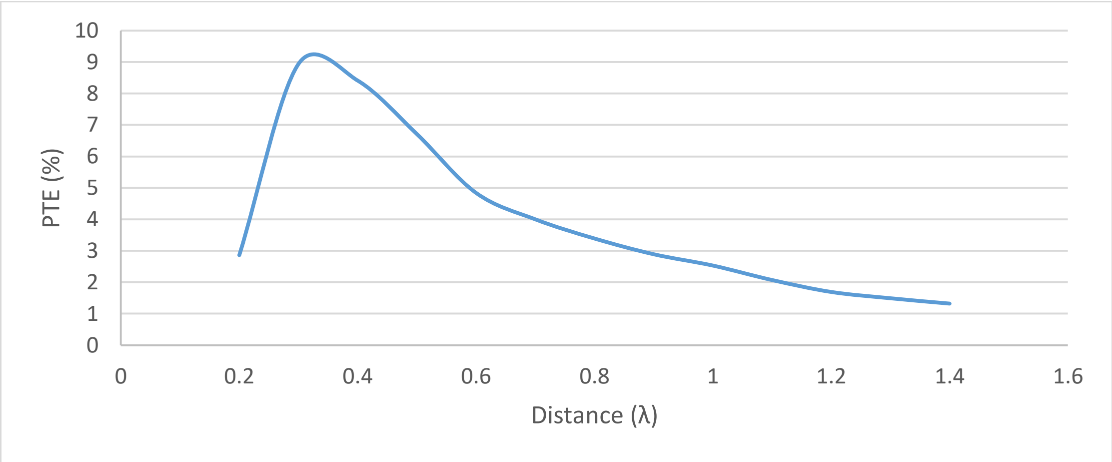


Figure 4.8 Graph of PWPT System Integrated with Wide Rectangular Parasitic Wire.

The shape of the graph is almost same as previous model which is the PTE is increasing at first, then it decreases gradually. The peak PTE is 9.1 % at distance of 0.3 λ. There is no effective distance for this model because the peak PTE is lower than 10 %. The PTE obtained is so low because of the short length of parasitic wire in z-axis direction. Since the model of PWPT system integrated with wide rectangular parasitic wire not so good so the following model will only utilize the model of PWPT system integrated with tall rectangular parasitic wire.

4.2.3 PWPT System Integrated with Four Straight Lines Parasitic Wire

From the model of PWPT system integrated with tall rectangular parasitic wire shape, an idea of removing the top and bottom of the rectangular and including two straight lines in middle of the rectangle is designed and studied. Hence, four identical straight lines which in tall rectangular shape is form. The model is designed as shown in **Figure 4.9** below.

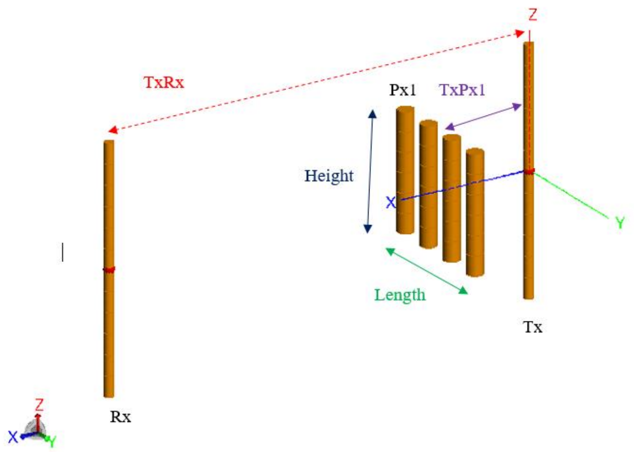


Figure 4.9 Model of PWPT System Integrated with Four Straight Lines Parasitic Wire.

In the figure, four straight line parasitic element is labelled as Px1 and the distance from transmitter is still the same which is TxPx1. The height and the length of the parasitic element is 0.3 λ and 0.2 λ respectively. The length of TxPx1 is fixed at 0.15 λ. The perimeter of all the parasitic wires is 1.2 λ. The other parameters of this PWPT system is shown in **Table 4.2** in **Section 4.2**.The result is obtained as shown in **Figure 4.10** below.

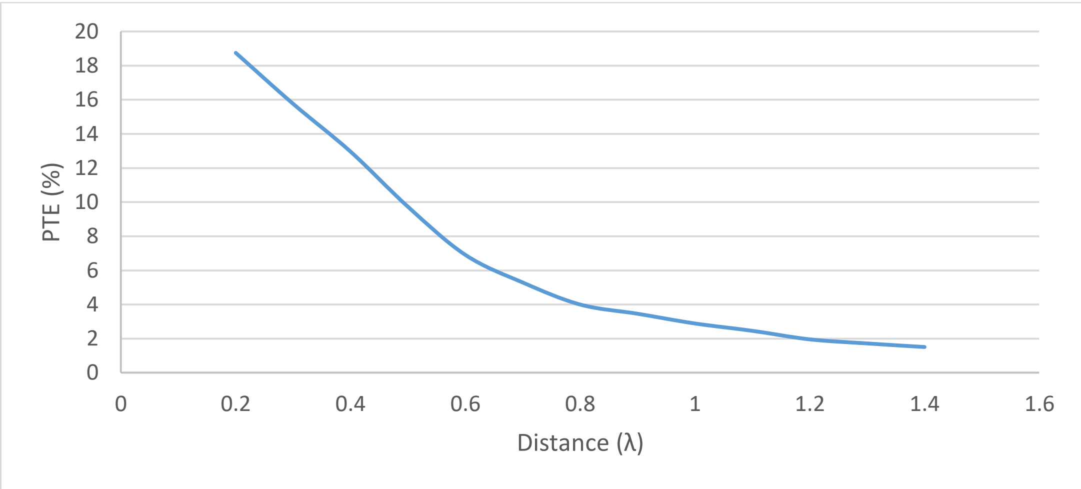


Figure 4.10 Graph of PWPT System Integrated with Four Line Parasitic Wire.

The PTE is decreasing gradually from beginning until the end. The peak PTE is 18.75 % at 0.2 λ while the effective distance is 0.5 λ. From the observation during this research, there is no shifted curve observed in this graph because there is no existence of parasitic wire in y-axis direction. There is only a parasitic element that is made from four parasitic wires in z-axis direction.

4.2.4 PWPT System Integrated with One Line in Rectangular Parasitic Wire

This model is designed in such a way that including one extra straight line in the middle of rectangular parasitic wire. This idea is created because of the hypothesis of longer line in z-axis direction will result in higher PTE obtained. The height of the straight line is 0.3 λ which are same tall as the parasitic rectangle. The model is designed as shown in **Figure 4.11** below.

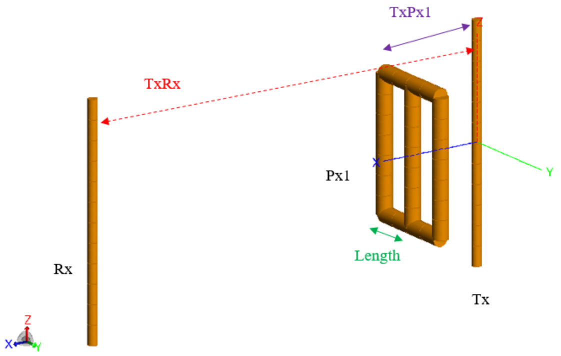


Figure 4.11 Model of PWPT System Integrated with One Line in Rectangular Parasitic Wire.

One line in Rectangular Parasitic Wire is labelled as Px1 and the distance of it from transmitter is labelled as TxPx1. The Length in the figure which labelled in green colour is 0.1 λ. Since the width of the rectangle is 0.2 λ, this denotes that the line is exactly in the middle of rectangle. The length of TxPx1 is fixed at 0.15 λ. The perimeter of parasitic wire is 1.3 λ. The other parameters of this PWPT system is shown in **Table 4.2** in **Section 4.2**.The result obtained is shown in **Figure 4.12** below.

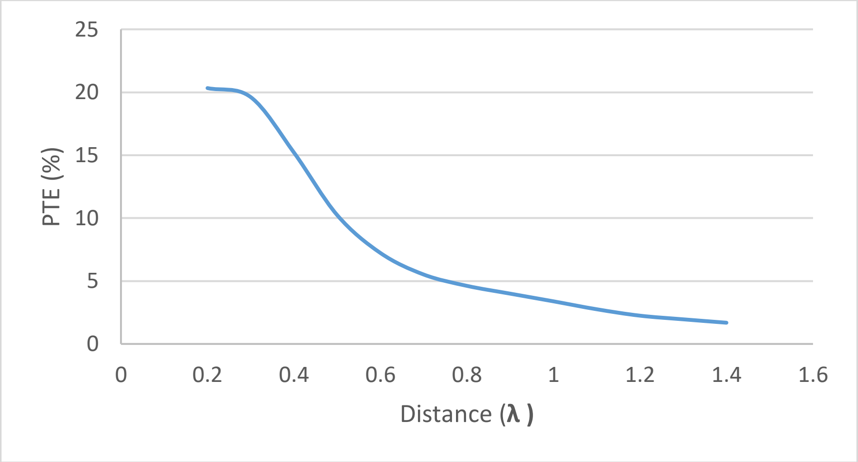


Figure 4.12 Graph of PWPT System Integrated with One Line in Rectangular Parasitic Wire.

From the result obtained above, the shape of the curve is decreasing with distance. The peak PTE is 20.01 % at distance of 0.2 λ. The effective distance is 0.5 λ.

4.2.5 Comparison of Different Shapes of PWPT Models

After all the models are simulated and recorded, a comparison in term of PTE and effective distance is done in the form of table and graph as shown in **Table 4.3** and **Figure 4.13** below respectively. The comparison includes model of CWPT system, PWPT system integrated with parasitic element with square, tall rectangle, wide rectangle, four straight line, and One Line in Rectangle.

Table 4.3 Comparison of PTE between CWPT, PWPT integrated with parasitic element in square, tall rectangular, wide rectangular, four straight line, and one line in rectangular shapes

Shapes	Peak PTE (%)	Effective Distance (λ)
Square	13.32	0.29 to 0.45
4Line	18.75	0.5
1Line In Rectangle	20.01	0.5
Tall Rectangle	18.50	0.23 to 0.5
CWPT	15.00	0.28
Wide Rectangle	9.10	-

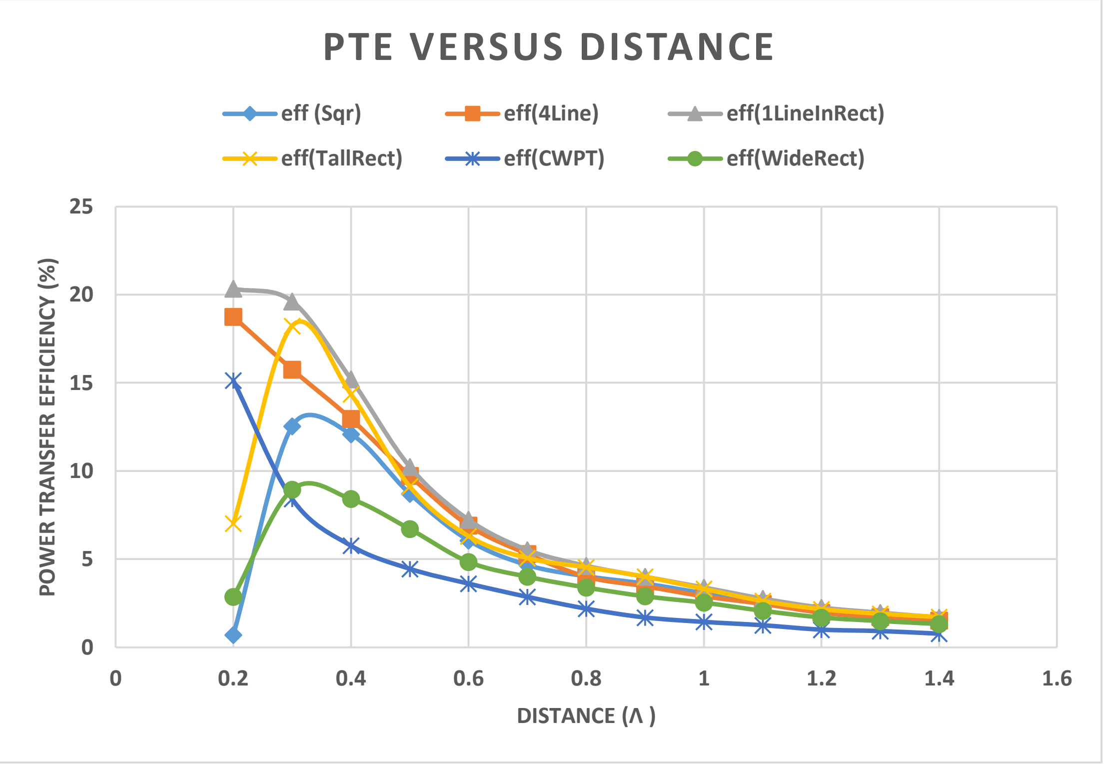


Figure 4.13 Comparison of PTE between CWPT, PWPT integrated with parasitic element in square, tall rectangular, wide rectangular, four straight lines, and one line in rectangular shapes.

From the result obtained above, PWPT system which is having highest peak of PTE is One Line in Rectangular Parasitic Wire. This model reaches effective distance of 0.5 λ which is also the highest value. The model of 4 line PWPT system has the second highest peak. However, the curve of the system is dropped rapidly. When the distance reaches 0.3 λ, where the peak of model of tall rectangle lies here, the PTE of model of tall rectangle PWPT system surpasses model of 4 line PWPT system. Since model of tall rectangle PWPT system has a longer distance of peak PTE, model of tall rectangle PWPT system is decided to be selected as better result than model of 4 line PWPT system. There is no effective distance found in model of PWPT system integrated with wide rectangle because the peak PTE of it not even reach 10 %. From the graph obtained in **Figure 4.13**, model of PWPT system integrated with One Line in Rectangular shape has the highest PTE along the curve.

4.3 PWPT System Integrated with Different Number and Formation of Parasitic Wire.

After different shapes of PWPT system are studied, the number of parasitic element is increased and the formation of it is changed in order to investigate the effect on PTE of the particular system. Indeed, there are some models can increase the PTE significantly while some models can result in the PTE remain unchanged.

4.3.1 PWPT System Integrated with 1 Front 2 Back Parallel Parasitic Wires

This model utilizes one tall rectangular parasitic wire by increasing extra one identical parasitic wires. Both parasitic wires are allocated side by side which are parallel to y-axis. The model view is shown in **Figure 4.14** below.

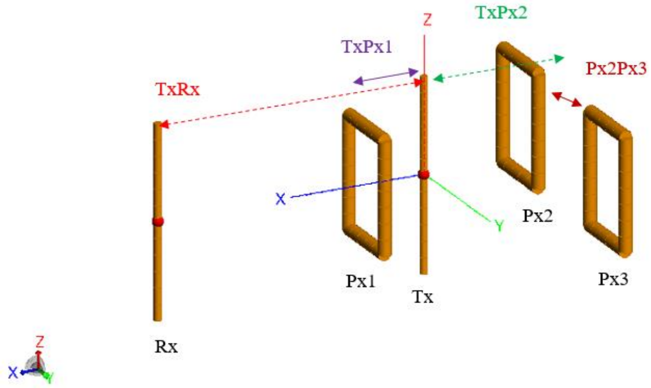


Figure 4.14 Model View of PWPT System Integrated with 1 Front 2 Back Parallel Parasitic Wires.

The first, second and third parasitic wires are labelled as Px1, Px2 and Px3 respectively. The height and width of the three parasitic wires are identical which are 0.3 λ and 0.2 λ respectively. The distance of Px1, which are labelled as TxPx1, from transmitter is fixed at 0.15 λ. The distances from Px2 and Px3, which is labelled as TxPx2, from transmitter is the same which is fixed at 0.37 λ. The distance between Tx2 and Tx3, which is labelled as Px2Px3, is 0.2 λ. The perimeter of parasitic wire is 1 λ. The other parameters of this PWPT system is shown in **Table 4.2** in **Section 4.2**. By moving receiver, Rx away from transmitter, Tx, the result is simulated and graph of PTE against distance is plotted as shown in **Figure 4.15** below.

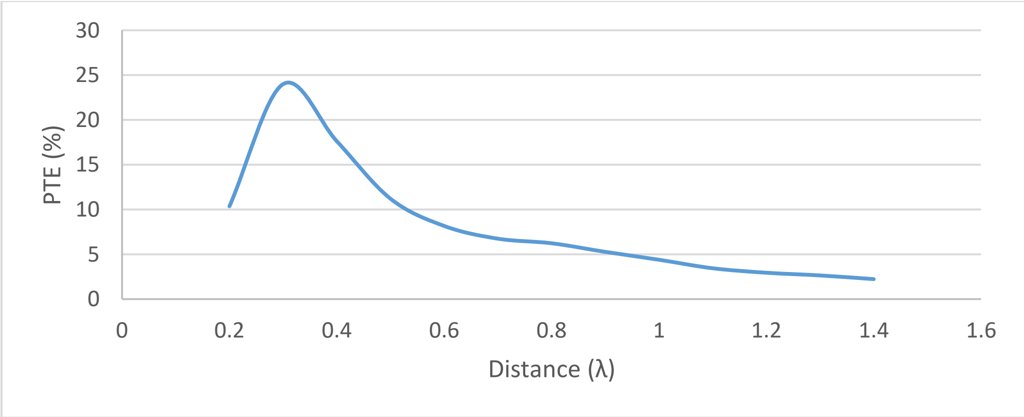


Figure 4.15 Result of PWPT System Integrated with 1 Front 2 Back Parallel Parasitic Wires.

From the graph obtained above, the curve is increased to a highest peak, then it decreasing gradually. The peak of PTE is 24.3 %. The effective distance 0.55 λ. This type of shape is having the same theory as the previous case. However, the highest peak obtained in this system is increased significantly compared to tall rectangular model.

4.3.2 PWPT System Integrated with 1 Front 3 Back Parallel Parasitic Wires

In this model, the only different with previous model is extra one parasitic wire is installed to the system. There are total three parasitic wires are arranged side by side behind the transmitter which are also parallel to y-axis at the same time. The model view of this system is shown in **Figure 4.16**.

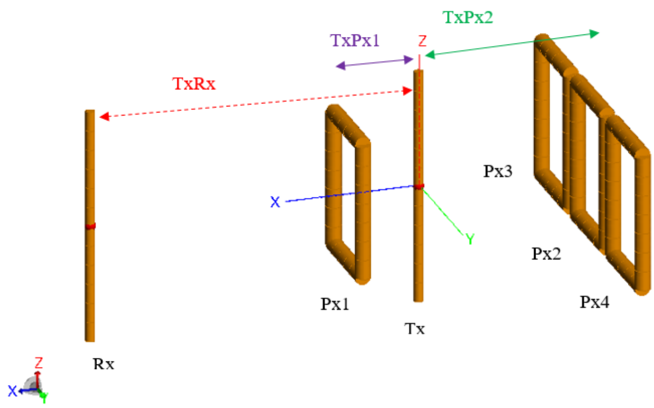


Figure 4.16 Model View of PWPT System Integrated with 1 Front 3 Back Parallel Parasitic Wires

The first, second, third and fourth parasitic wires are labelled as Px1, Px2, Px3 and Px4 respectively. The height and width of the four parasitic wires are identical which are 0.3 λ and 0.2 λ respectively. The distance of Px1, which is labelled as TxPx1, from transmitter is 0.15 λ. The distances of Px2, Px3 and Px4, which is labelled as TxPx2, from transmitter is the same and fixed at 0.37 λ. The perimeter of parasitic wire is 1 λ. The other parameters of this PWPT system is shown in **Table 4.2** in **Section 4.2**. By moving receiver, Rx away from transmitter, Tx, the result is simulated and graph of PTE against distance is plotted as shown in **Figure 4.17** below.

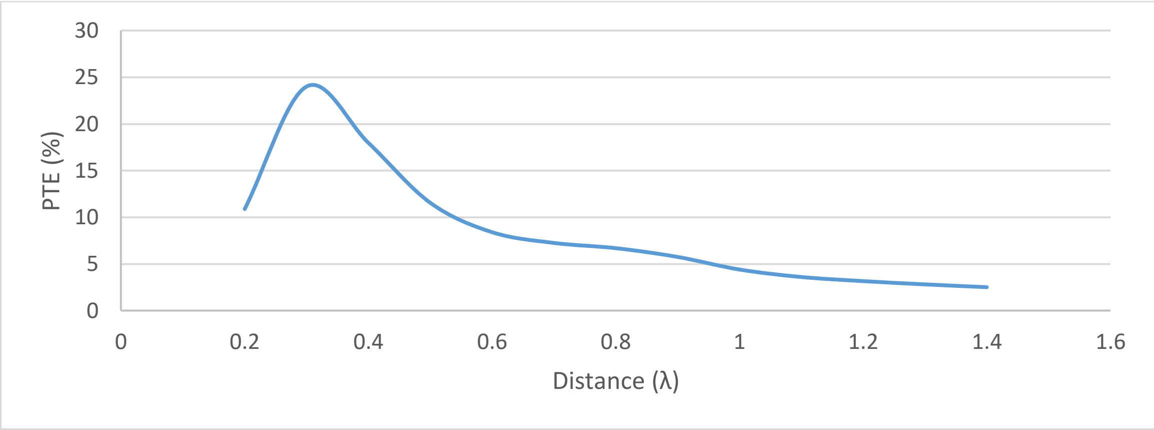


Figure 4.17 Result of PWPT System Integrated with 1 Front 3 Back Parallel Parasitic Wires

From the graph obtained above, the curve is increasing to the highest peak, it then decreasing gradually. The peak of PTE is 25.3 %. The effective distance is 0.54 λ.

4.3.3 PWPT System Integrated with 2 Side 1 Front 1 Back Parasitic Wires

There are two identical parasitic wires are allocated beside the transmitter with equal distances in this model designed. The 3D model view and top view are shown in **Figure 4.18** and **Figure 4.19** below.

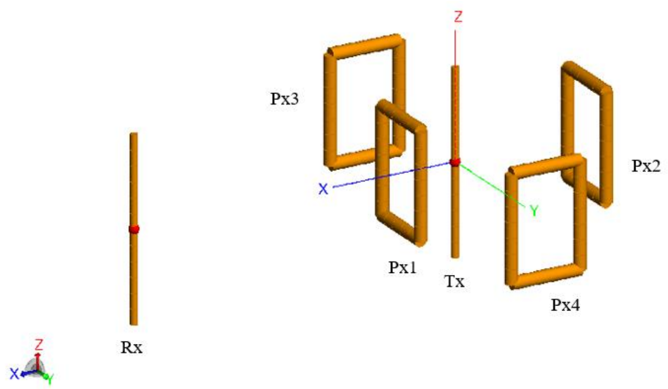


Figure 4.18 3D Model View of PWPT System Integrated with 2 Side 1 Front 1 Back Parasitic Wires.

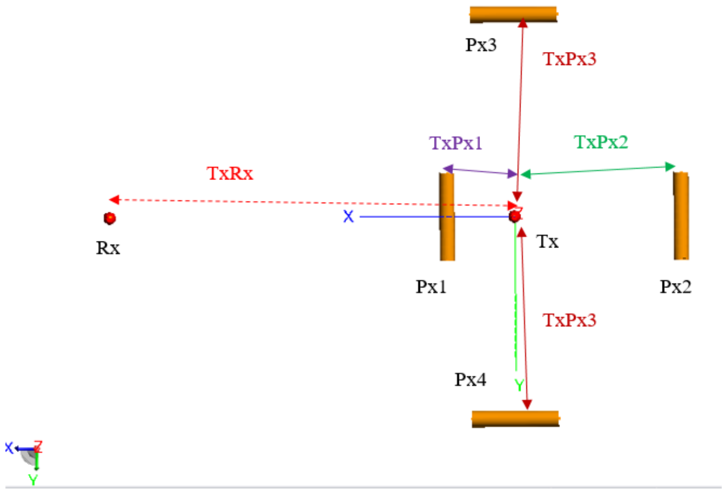


Figure 4.19 Top Model View of PWPT System Integrated with 2 Side 1 Front 1 Back Parasitic Wires.

The first, second, third and fourth parasitic wires are labelled as Px1, Px2, Px3 and Px4 respectively. The height and width of the four parasitic wires are identical which are 0.3 λ and 0.2 λ respectively. The distances of Px1, Px2, Px3 and Px4 from transmitter, which are labelled as TxPx1, TxPx2, TxPx3 and TxPx4 respectively, from transmitter are fixed at 0.15 λ, 0.37 λ, 0.45 λ and 0.45 λ respectively. The perimeter of parasitic wire is 1 λ. The other parameters of this PWPT system is shown in **Table 4.2** in **Section 4.2**. By moving receiver, Rx away from transmitter, Tx, the result is simulated and graph of PTE against distance is plotted as shown in **Figure 4.20** below.

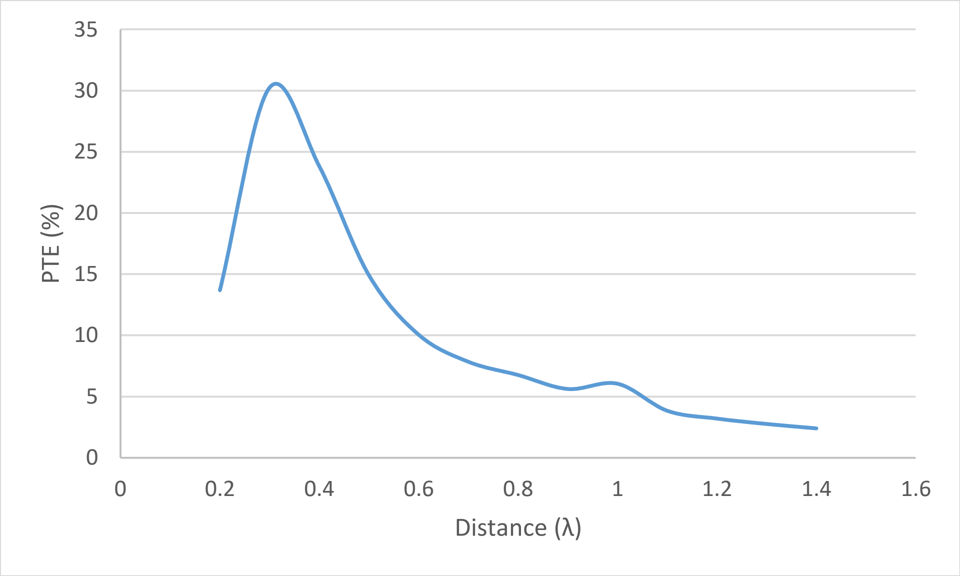


Figure 4.20 Result of PWPT System Integrated with 2 Side 1 Front 1 Back Parasitic Wires.

From the graph obtained above, the curve is increased to a highest peak, it then decreasing gradually. The peak of PTE is 31.7 %. The effective distance is 0.6 λ.

4.3.4 PWPT System Integrated with 1 Front 5 flat Parasitic Wires

There are total of 6 parasitic wires in this PWPT system. One of the parasitic wire is allocated in front of transmitter, the other five parasitic wire are allocated behind which is parallel to y-axis: one at the centre point, two of it arranged beside the centre parasitic wire and the other two allocated at top and bottom of the centre parasitic wires respectively. The five parasitic wires behind forms a shape that is similar to a flat wall. The model view of the system is shown in **Figure 4.21** below.

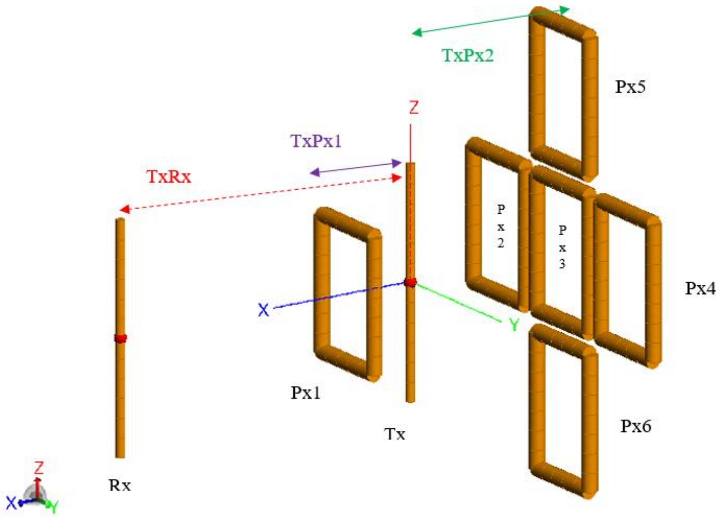


Figure 4.21 Model View of PWPT System Integrated with 1 Front 5 flat Parasitic Wires

The first, second, third, fourth, fifth and sixth parasitic wires are labelled as Px1, Px2, Px3, Px4, Px5 and Px6 respectively. The height and width of the six parasitic wires are identical which are 0.3 λ and 0.2 λ respectively. The distance of Px1, which is labelled as TxPx1, from transmitter is fixed at 0.15 λ. The distance from Px2, Px3, Px4, Px5 and Px6, which is labelled as TxPx2, from transmitter is the same which is 0.37 λ. The perimeter of parasitic wire is 1 λ. The other parameters of this PWPT system is shown in **Table 4.2** in **Section 4.2**. By moving receiver, Rx away from transmitter, Tx, the result is simulated and graph of PTE against distance is plotted as shown in **Figure 4.22** below.

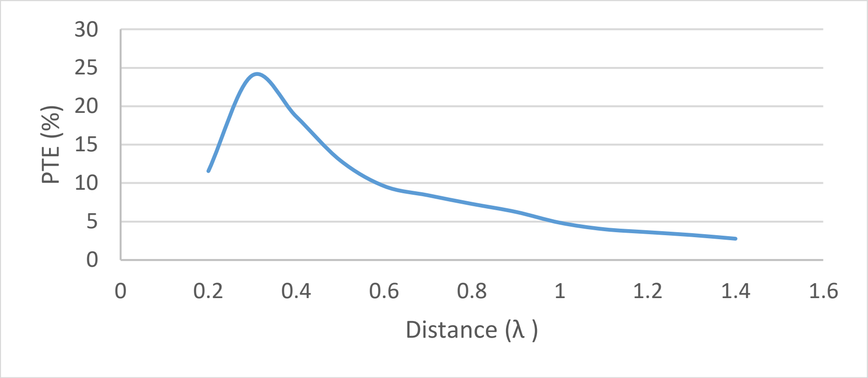


Figure 4.3.4.2: Result of PWPT System Integrated with 1 Front 5 flat Parasitic Wires

From the graph obtained above, the curve is increased to a highest peak, it then decreasing gradually. The peak of PTE is 25.16 %. The effective distance is 0.54 λ.

4.3.5 PWPT System Integrated with two One Line in Rectangular Parasitic Wires

This model is an upgraded version of PWPT system integrated with One Line in Rectangular Parasitic Wires. In this system, there is another identical parasitic wire which is allocated behind the transmitter to form a total of two parasitic elements. The model view of the system is shown in **Figure 4.23** below.

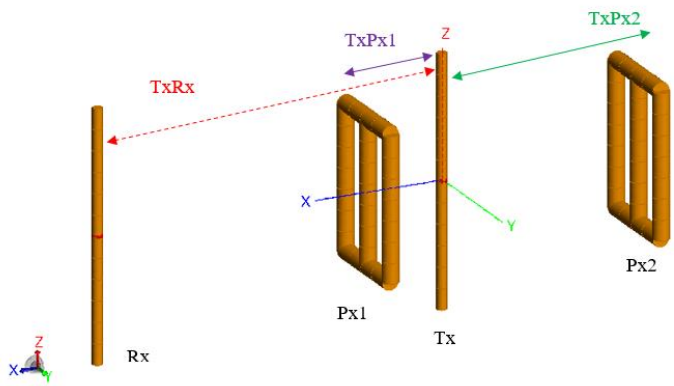


Figure 4.23 Model View of PWPT System Integrated with two One Line in Rectangular Parasitic Wires

The parasitic wire 1 and parasitic wire 2 are labelled as Px1 and Px2 respectively. The distances from Px1 and Px2, which labelled as TxPx1 and TxPx2, from transmitter are 0.167 λ and 0.37 λ respectively. The perimeter of parasitic wire is 1.3 λ. The other parameters of this PWPT system is shown in **Table 4.2** in **Section 4.2**. By moving receiver, Rx away from transmitter, Tx, the result is simulated and graph of PTE against distance is plotted as shown in **Figure 4.24** below.

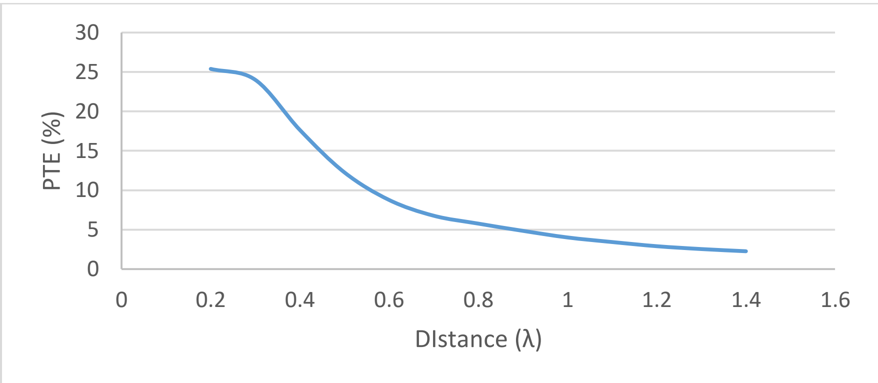


Figure 4.24 Result of PWPT System Integrated with two One Line in Rectangular Parasitic Wires

From the graph obtained above, the curve is decreasing gradually. The peak of PTE is 26.11 %. The effective distance is 0.54 λ. The curve do not show a shifted shape like previous case due to the existence of One line in Rectangle parasitic wire.

4.3.6 Comparison between PWPT System of Different Numbers and Formations

After all the models are discussed individually, a comparison of PTE and effective distance for each of the models is concluded. A list of table which contains the peak PTE and a graph of PTE versus distance are shown in **Table 4.4** and **Figure 4.25** respectively.

Table 4.4 Comparison between PWPT System of Different Numbers and Formations

Models	Peak PTE (%)	Effective Distance (λ)
1 Front 2 Back Parallel	24.30	0.55
1 Front 3 Back Parallel	25.30	0.54
2 Side 1 Front 1 Back	31.70	0.60
1 Front 5 Flat	25.16	0.54
2 One Line in Rectangle	26.11	0.54

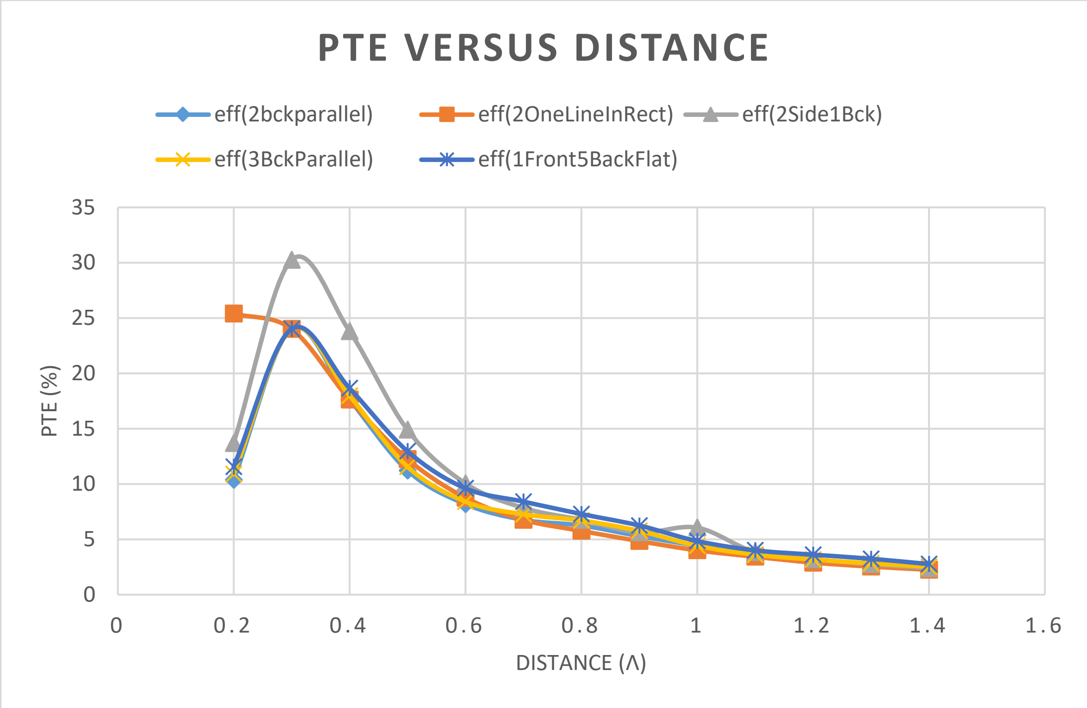


Figure 4.25 Comparison between PWPT System of Different Numbers and Formations

From the table obtained above, the best model belongs to PWPT system with 2 Side 1 Back Parasitic Wires. The peak PTE of the model is 31.70 % and the effective distance is 0.6 λ. From the graph obtained above, model of PWPT system with 2 Side 1 Back Parasitic Wires is having a curve which is better compared to other. Its PTE is overwhelming other models. The second highest peak PTE is two One Line in Rectangular Parasitic Wire model. This model achieves peak PTE of 26.11%. However, the peak PTE lies at distance of 0.2 λ which is the shortest distance from transmitter. Model of 3 Back Parallel PWPT system is also having a good peak PTE, however, if comparing to model of 2 Back Parallel PWPT system, the peak PTE is just increased from 24.30% to 25.30% by adding extra one more parasitic wire only. On the other hand, the effective distance of model of 3 Back Parallel PWPT system is shorter than model of 2 Back Parallel PWPT system. Hence, model of 2 Back Parallel is more worth than model of 3 Back Parallel PWPT system. For the last PWPT model which is 5 Back flat Parasitic wires, the peak PTE is almost same with other models.

However, the number of parasitic wires inserted is too much compare to other PWPT system. Hence, this model is not worth in term of costing or resource saving.

4.4 Enhancement of PWPT System Integrated with Different Number and Formation of Parasitic Wire.

After different shape, number and formation of parasitic elements are investigated, research of optimization of PWPT system is now further enhanced by increasing number of parasitic element, and the orientation and formation of it.

4.4.1 PWPT System Integrated with 4 Rectangular Parasitic Wires

This model is created from idea of PWPT system integrated with tall rectangular parasitic wire by concatenating total of four rectangular parasitic wires. Two parasitic wires are allocated in front of the transmitter whereas the other two are allocated behind of the transmitter. The model of this PWPT system is shown in **Figure 4.26** below.

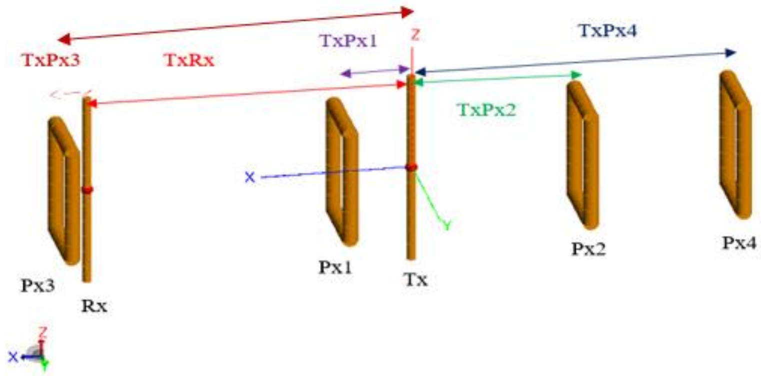


Figure 4.26 Model of PWPT System Integrated with 4 Rectangular Parasitic Wires

The first, second, third and fourth parasitic wires are labelled as Px1, Px2, Px3 and Px4 respectively. The height and width of the four parasitic wires are identical which are 0.3 λ and 0.2 λ respectively. The distances of Px1, Px2, Px3 and Px4 from transmitter, which are labelled as TxPx1, TxPx2, TxPx3 and TxPx4 respectively, from transmitter are fixed at 0.15 λ, 0.37 λ, 0.75 λ, and 0.90 λ respectively. The perimeter of parasitic wire is 1 λ. The other parameters of this PWPT system is shown in **Table 4.2** in **Section 4.2**. By moving receiver, Rx away from transmitter, Tx, the result is simulated and graph of PTE against distance is plotted as shown in **Figure 4.27** below.

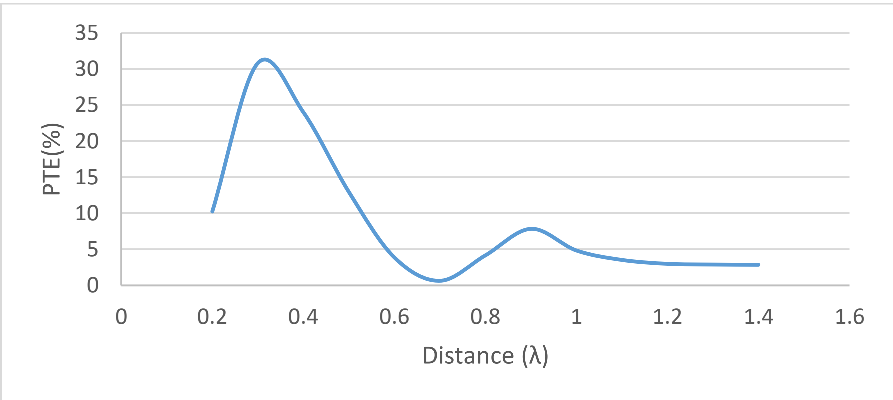


Figure 4.27 Graph of PWPT System Integrated with 4 Rectangular Parasitic Wires

From the graph obtained above, the curve is increasing to a highest peak, then it drops to lowest point. After that, it increases again to second peak and finally decreases gradually to the end. The first peak and 2nd peak of PTE is 31.58 % and 7.84 % respectively. The effective distance is covered from 0.2 λ to 0.52 λ. A total of four parasitic wires concatenating together give rises a high peak PTE compare to previous section. On the other hand, there is a phenomena that PTE is dropped drastically after the first peak and rises again after the first global minimal. This is due to the existence of the Px3 in the system. As the receiver getting away from the transmitter, it get closer toward the Px3 which result in the sudden drop of PTE. However, after the receiver passes by Px3, the PTE resume back its original track. Hence increasing of PTE occurs. After that the PTE is still decreasing because of the distance between transmitter and receiver is too far away from each other.

4.4.2 PWPT System Integrated with 2 Front 4 Back Parallel Parasitic Wires

This model is an enhanced version of PWPT system from previous section. The idea is modified from PWPT System Integrated with 2 Back Parallel Parasitic Wire. There are total of six tall rectangular parasitic wires are included in this system. Two of it are allocated in front of transmitter and the rest are allocated behind the transmitter. The 3D model view and side view of the system are shown in **Figure 4.28** and **Figure 4.29** below.

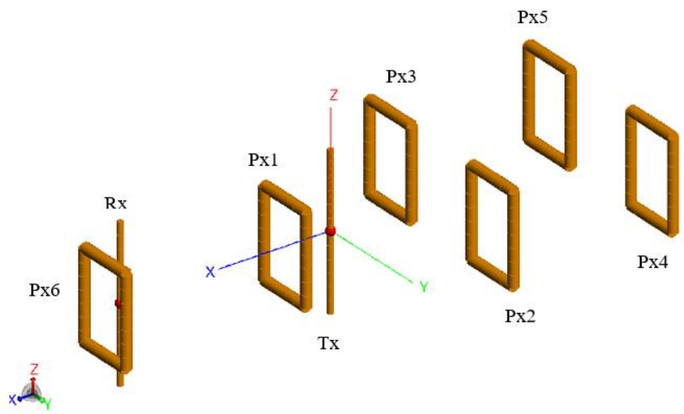


Figure 4.28 3D Model View of PWPT System Integrated with 2 Front 4 Back Parallel Parasitic Wires.

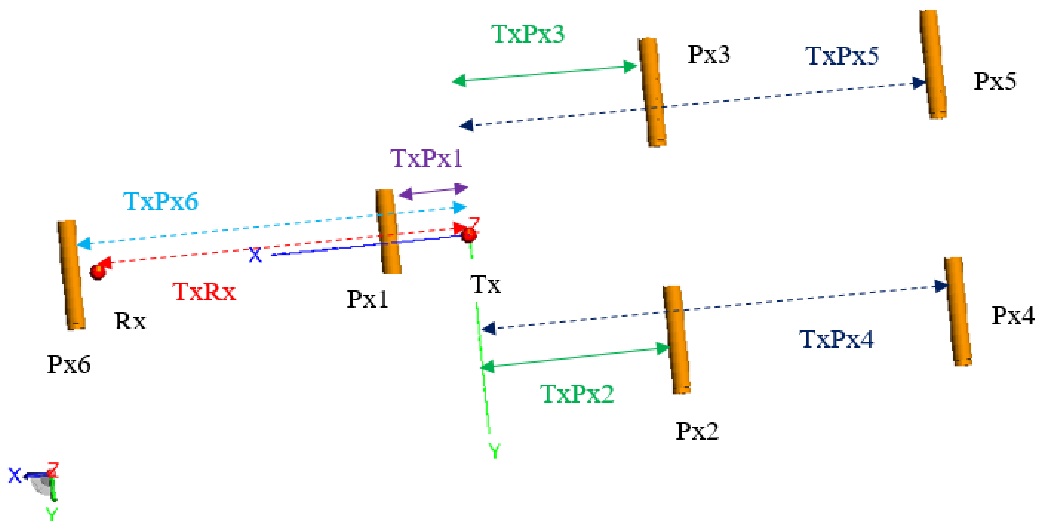


Figure 4.29 Top Model View of PWPT System Integrated with 2 Front 4 Back Parallel Parasitic Wires.

The first, second, third, fourth, fifth, and sixth parasitic wires are labelled as Px1, Px2, Px3, Px4, Px5 and Px6 respectively. The distances of Px1, Px2, Px3, Px4, Px5 and Px6, which are labelled as TxPx1, TxPx2, TxPx3, TxPx4, TxPx5 and TxPx6 respectively, from transmitter are fixed at 0.15 λ, 0.37 λ, 0.37 λ, 0.9 λ, 0.9 λ and 0.75 λ respectively. The distances of Px2 to Px3 and Px4 to Px5 are 0.2 λ and 0.25 λ respectively. The perimeter of parasitic wire is 1 λ. The other parameters of this PWPT system is shown in **Table 4.2** in **Section 4.2**. The PTE is obtained by moving receiver away from transmitter, which is labelled as TxRx. A graph of PTE versus distance is plotted as shown in **Figure 4.30** below.

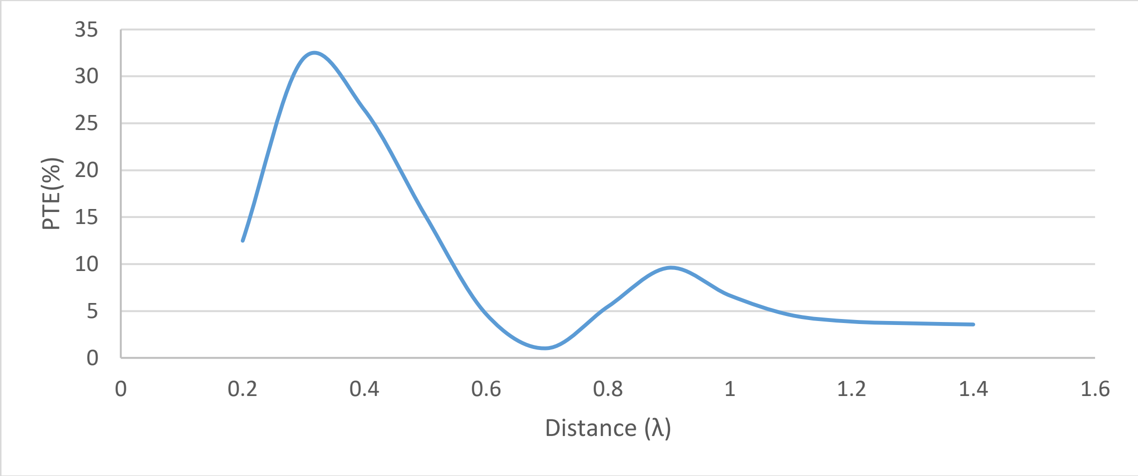


Figure 4.30 Result of PWPT System Integrated with 2 Front 4 Back Parallel Parasitic Wires.

From the graph obtained above, the shape of the curve is almost similar to the result from previous model. The first peak of PTE is 33.29 % whereas the second peak is 9.67. The effective distance of this model is 0.2 λ to 0.53 λ. The existence of high number of parasitic wires in this system become the factor of high PTE obtained. The drop of PTE at 0.69 λ is due to the existence of Px6 which having the same explanation as previous model.

4.4.3 PWPT System Integrated with 4 Side 2 Front 2 Back Rectangular Parasitic Wires.

This type of model is an enhanced version of PWPT system integrated with 2 Side 1 Back Rectangular Parasitic Wires. There are totally eight tall rectangular parasitic wires are included in this model. Four parasitic wires are allocated evenly to the left and right side of the transmitter. The other two parasitic wires are allocated behind of transmitter whereas the rest of two are allocated in front of transmitter. The 3D model view and top model view are shown in **Figure 4.31** and **Figure 4.32** below.

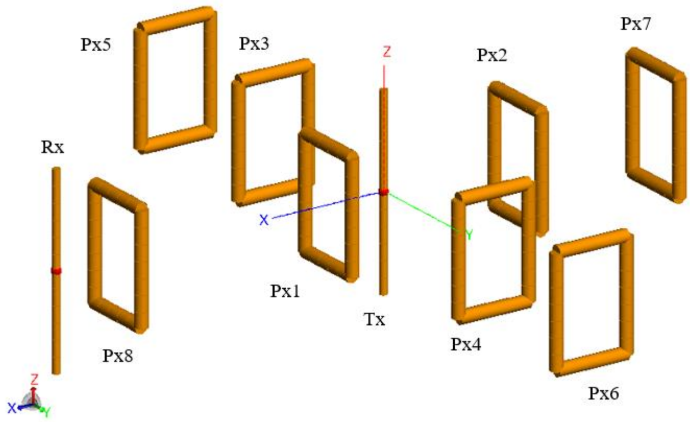


Figure 4.31 3D Model of PWPT System Integrated with 4 Side 2 Front 2 Back Rectangular Parasitic Wires.

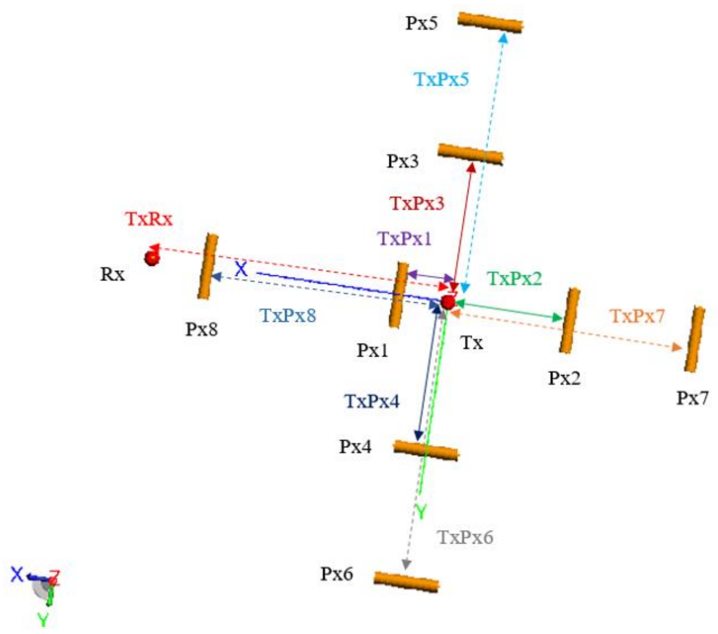


Figure 4.32 Top Model View of PWPT System Integrated with 4 Side 2 Front 2 Back Rectangular Parasitic Wires.

The first, second, third, fourth, fifth, sixth, seventh and eighth parasitic wires are labelled as Px1, Px2, Px3, Px4, Px5, Px6, Px7 and Px8 respectively. The distances of Px1, Px2, Px3, Px4, Px5, Px6, Px7 and Px8, which are labelled as TxPx1, TxPx2, TxPx3, TxPx4, TxPx5, TxPx6, TxPx7 and TxPx8 respectively, from transmitter are fixed at 0.15 λ, 0.37 λ, 0.45 λ, 0.45 λ, 0.85 λ, 0.85 λ, 0.9 λ, and 0.73 λ respectively. The other parameters of this PWPT system is shown in **Table 4.2** in **Section 4.2**. The PTE is obtained by increasing the distance of transmitter from receiver, which is labelled as TxRx. The graph obtained is plotted as shown in **Figure 4.33** below.

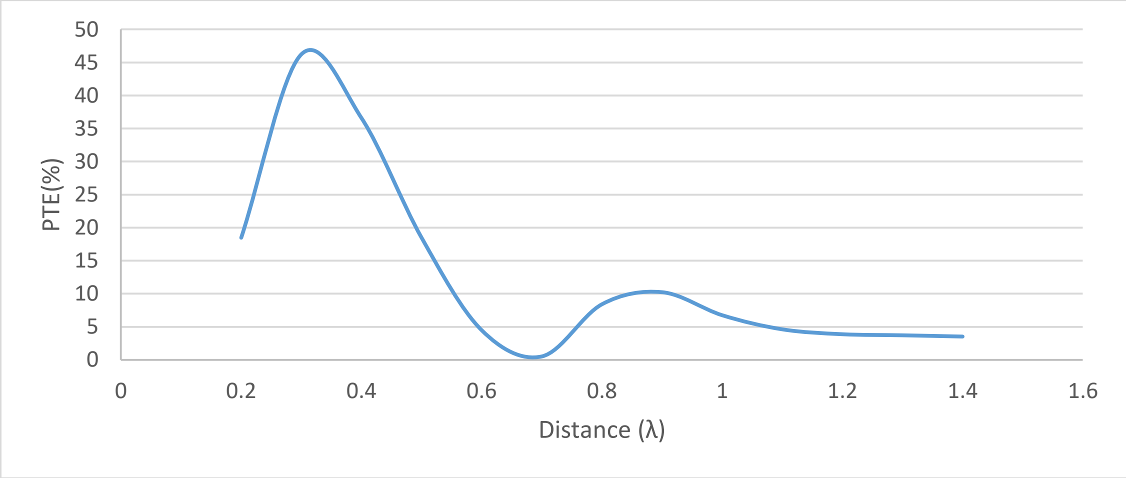


Figure 4.33 Result of PWPT System Integrated with 4 Side 2 Front 2 Back Rectangular Parasitic Wires.

Again, a similar shape of curve as previous model is obtained. The first peak PTE is 47.20 % and the second peak PTE is 11.29 %. The effective distance is from 0.2 λ to 0.55 λ and from 0.85 λ to 0.9 λ. However, there is a significant increasing of peak PTE because of existence of the side parasitic wires. In this system, the global minimum is dropped until almost zero PTE. A hypothesis can be assumed for this case is due to the effect of existence of side parasitic element.

4.4.4 PWPT System Integrated with 4 Side Rectangle 2 Front 2 Back One Line in Rectangular Parasitic Wires.

This system is modified from the previous model. The parasitic rectangles behind and in front of transmitter are replaced with One Line in Rectangular parasitic wires while the parasitic rectangles which located beside the transmitter remain unchanged in shape. The 3D model view and top view are shown as **Figure 4.34** and **Figure 4.35** below.

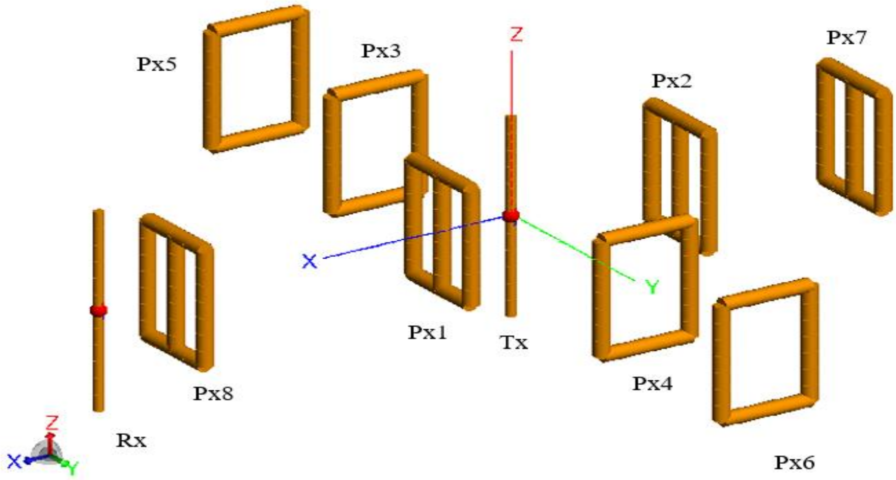


Figure 4.34 3D Model View of PWPT System Integrated with 4 Side Rectangle 2 Front 2 Back One Line in Rectangular Parasitic Wires.

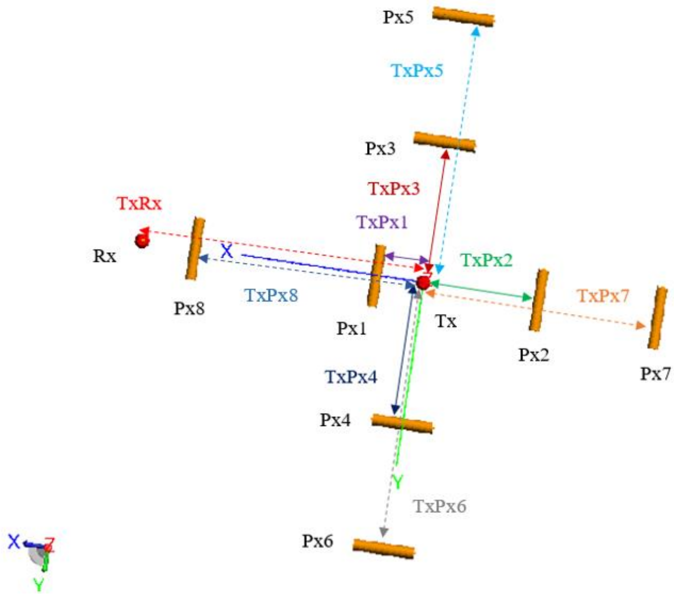


Figure 4.35 Top View of PWPT System Integrated with 4 Side Rectangle 2 Front 2 Back One Line in Rectangular Parasitic Wires.

The first, second, third, fourth, fifth, sixth, seventh and eighth parasitic wires are labelled as Px1, Px2, Px3, Px4, Px5, Px6, Px7 and Px8 respectively. The distances of Px1, Px2, Px3, Px4, Px5, Px6, Px7 and Px8, which are labelled as TxPx1, TxPx2, TxPx3, TxPx4, TxPx5, TxPx6, TxPx7 and TxPx8 respectively, from transmitter are fixed at 0.15 λ, 0.37 λ, 0.45 λ, 0.45 λ, 0.85 λ, 0.85 λ, 0.9 λ, and 0.73 λ respectively. The perimeters of rectangular parasitic wire and one line in rectangular parasitic wire are 1 λ and 1.3 λ. The other parameters of this PWPT system is shown in **Table 4.2** in **Section 4.2**. The PTE is obtained by increasing the distance of transmitter from receiver, which is labelled as TxRx. The graph obtained is plotted as shown in **Figure 4.36** below.

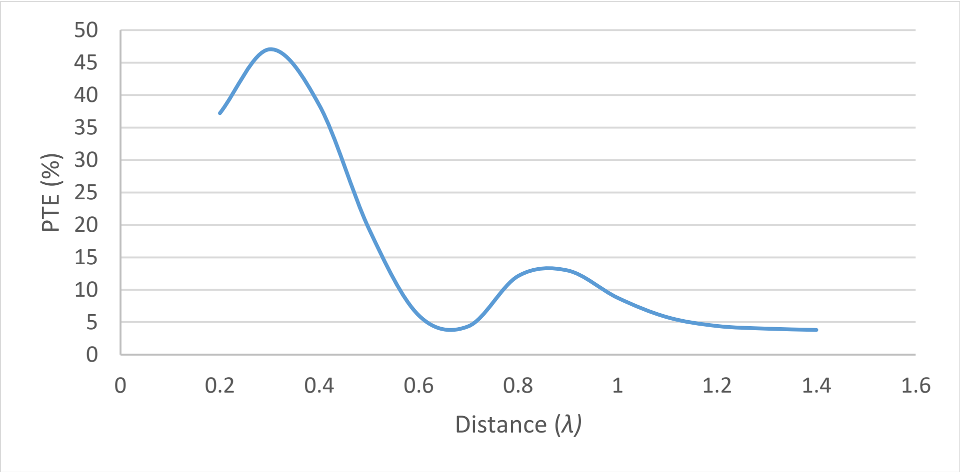


Figure 4.36 Result of PWPT System Integrated with 4 Side Rectangle 2 Front 2 Back One Line in Rectangular Parasitic Wires.

The curve is still the same shape as previous model. The first peak PTE is 47.33 % and the second peak PTE is 13.69%. The effective distance is from 0.2 λ to 0.56 λ and from 0.77 λ to 0.96 λ. With such high numbers of parasitic elements, this model obviously is having good effective distance as well as archives highest peak PTE.

4.4.5 Comparison between Different Enhanced Models of PWPT System.

After discussion of all the models of PWPT system individually, comparison of four types of enhanced models is made. The comparisons of peak efficiency and effective distance are shown in **Table 4.5** and **Figure 4.37** below respectively.

Table 4.5 Comparison of Different Enhanced Models of PWPT System.

Shapes	1st Peak PTE (%)	2nd Peak PTE (%)	Effective Distance (λ)
2 Front 4 Back Parallel	33.29	9.67	0.2 to 0.53
4 Side 2 Front 2 Back Rectangle	47.20	11.29	0.2 to 0.55 and 0.85 to 0.9
4 Side Rectangle 2 Front 2 Back One Line Rectangle	47.33	13.69	0.2 to 0.56 and 0.77 to 0.96
4 Rectangle	31.58	7.84	0.2 to 0.52

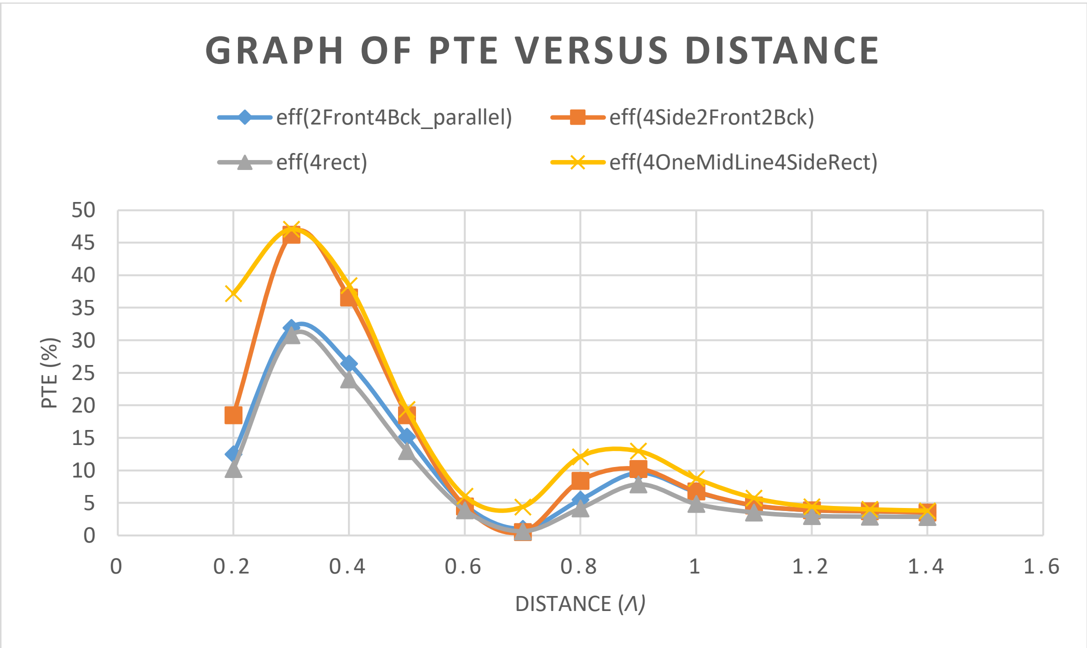


Figure 4.37 Comparison of Different Enhanced Models of PWPT System.

From the result obtained above, the highest first peak belongs to PWPT system integrated with 4 Side Rectangle 2 Front 2 Back One Line in Rectangle model which reaches 47.33 %. The highest second peak belongs to the same model which reaches 13.69 %. This model is also having a better effective distance which is from 0.2 λ to 0.56 λ and 0.77 λ to 0.96 λ. Model of PWPT system integrated with 4 Side 2 Front 2 Back Rectangular Parasitic Wires achieve the second highest first and second peak in this comparison. However, the perimeter used in PWPT system integrated with 4 Side 2 Front 2 Back Rectangle is shorter than PWPT system integrated with 4 Side Rectangle 2 Front 2 Back One Line in Rectangle model. Shorter perimeter of parasitic wire means less resource is needed in a particular system. Since model of 4 Side 2 Front 2 Back PWPT system has second highest first peak which is very near to the model of 4 Side Rectangle 2 Front 2 Back One Line in Rectangle PWPT system, hence they both belongs to the best PWPT system. From here, we can conclude that by locating parasitic element to both side of the transmitter able to increase both the peak PTE and effective distance of the PWPT system significantly.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The WPT system has been studied and optimized. The most effective way of transmitting energy wirelessly can be obtained by concatenating a few rectangular parasitic elements together and placing it in between the transmitter and receiver. By increasing the number of parasitic elements with this geometry in the system, the efficiency and effective distance can be further enhanced. The PTE and effective distance of all the models are obtained and discussed. The overall performance of all type of PWPT systems is summarized in **Table 5.1** below.

Table 5.1 Summary of Peak PTE and Effective Distance of All Model of PWPT System and CWPT system.

Configuration	Peak PTE (%)	2nd Peak PTE (%)	Best PTE Result	Effective Distance (λ)	Best Effective Distance Result
Square	13.32	-		0.29 to 0.45	
4Line	18.75	-		0.50	
1Line In Rectangle	20.01	-		0.50	
Tall Rectangle	18.50	-		0.23 to 0.5	
CWPT	15.00	-		0.28	
Wide Rectangle	9.10	-		-	
1 Front 2 Back Parallel	24.30	-		0.55	
1 Front 3 Back Parallel	25.30	-		0.54	
2 Side 1 Front 1 Back	31.70	-		0.60	✓
1 Front 5 Flat	25.16	-		0.54	
2 One Line in Rectangle	26.11	-		0.54	
2 Front 4 Back Parallel	33.29	9.67		0.20 to 0.53	
4 Side 2 Front 2 Back	47.20	11.29	✓	0.2 to 0.55 and 0.85 to 0.9	
4 Side Rectangle 2 Front 2 Back One Line Rectangle	47.33	13.69	✓	0.2 to 0.56 and 0.77 to 0.96	✓
4 Rectangle	31.58	7.84		0.2 to 0.52	

Among all the shapes of PWPT system, model of PWPT system integrated with One Line in Rectangular Parasitic Wires is the best shape and model of PWPT system integrated with tall rectangular parasitic is also a good option for improved version of PWPT system. After all the models are enhanced, model of 4 Side Rectangle 2 Front 2 Back One Line in Rectangle PWPT system has the best peak PTE and effective distance. Model of 4 Side 2 Front 2 Back PWPT system has the second highest PTE and good effective distance with shorter length used of perimeter in parasitic wires. Hence, this two models are outperforming in this project. However, the whole model size of these two systems are space consuming. Hence, a smaller version of 2 Side 1 Front 1 Back PWPT system can be replaced which is also having a good PTE. The effective distance is also the best among all the PWPT system. In short, each models is having their own advantage. The best three models are PWPT system integrated with 4 Side Rectangle 2 Front 2 Back One Line in Rectangle, PWPT system integrated with 4 Side 2 Front 2 Back Rectangle and PWPT system integrate with 2 Side 1 Front 1 Back rectangle.

5.2 Recommendation

In this project, the PTE of PWPT system able to achieve a good result which is 47.2 %. However, the size of the overall system is large which is not so applicable in real life. The distances allocated of parasitic elements are far away from transmitter. Hence, PWPT system which utilized small space is hope to be designed and optimization of wireless power transfer efficiency is carry on continuously at the same time to achieve a new milestone in the future.

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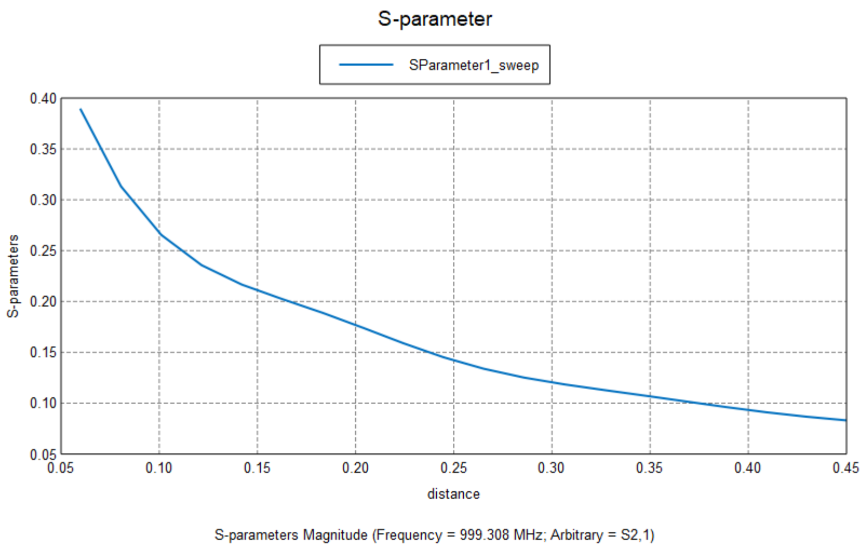
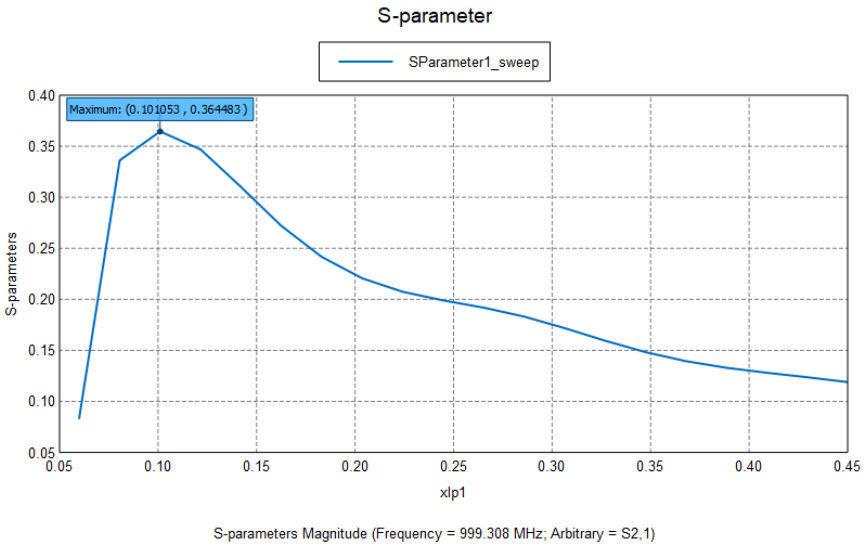
APPENDICES

APPENDIX A: Graph of S-parameter Obtained from FEKO

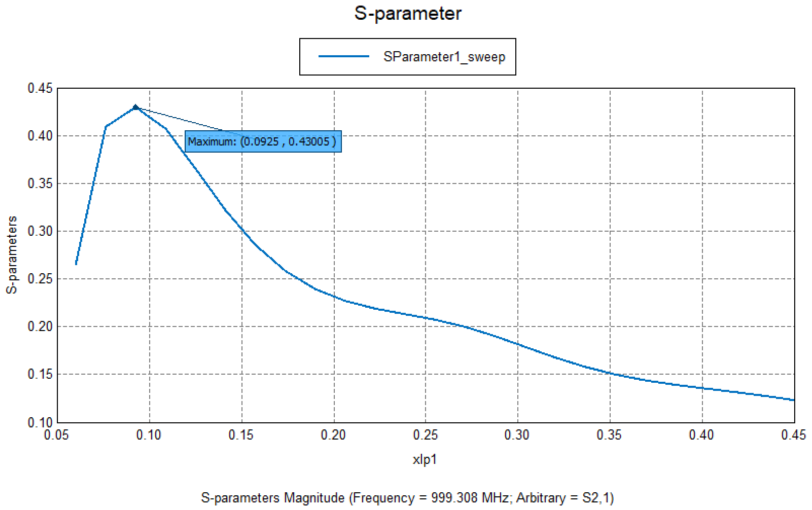
Graph of CWPT System



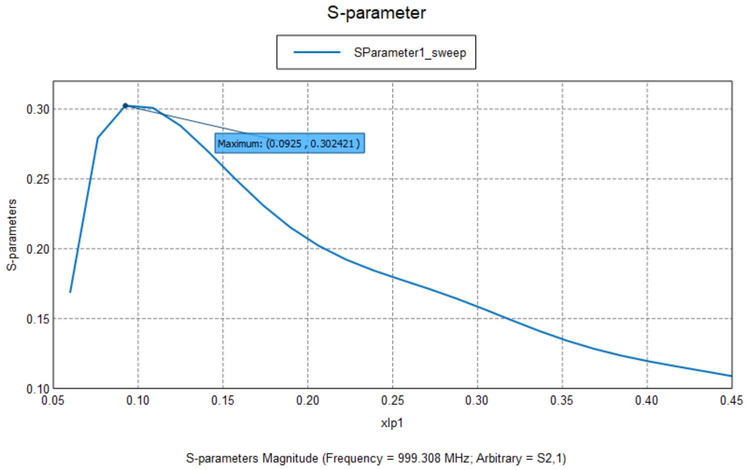
Graph of PWPT System with One Square Parasitic Wire



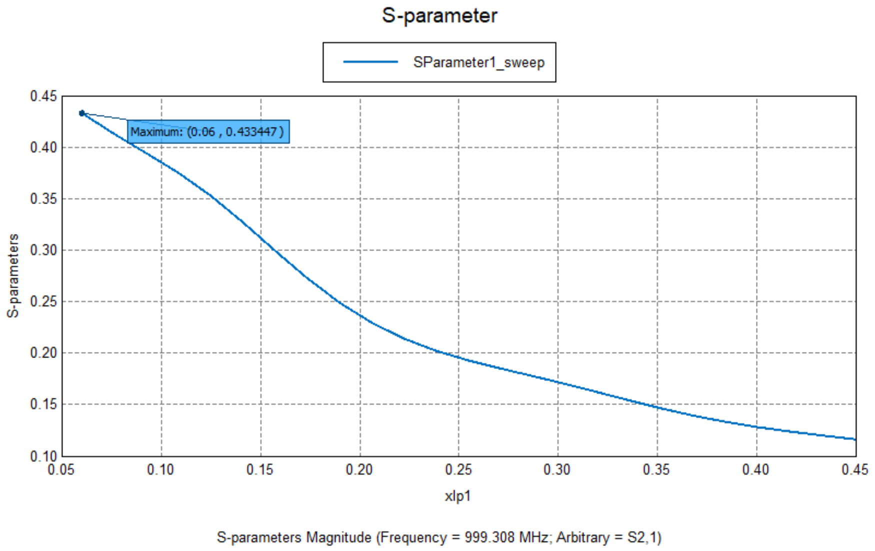
Graph of PWPT System Integrated with Tall Rectangular Parasitic Wire



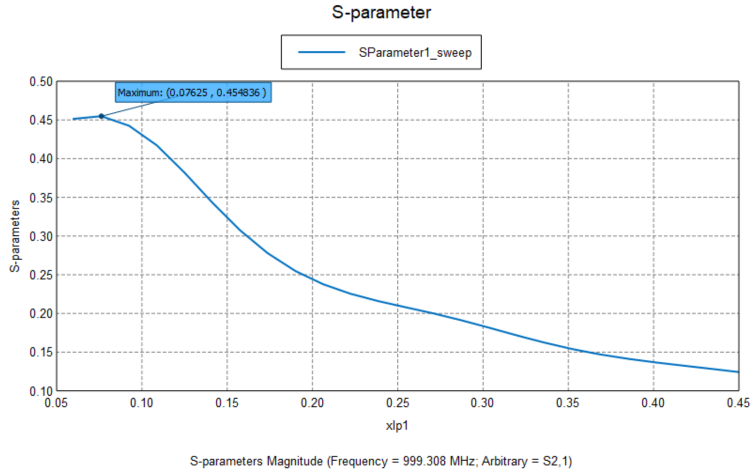
Graph of PWPT System Integrated with Wide Rectangular Parasitic Wire



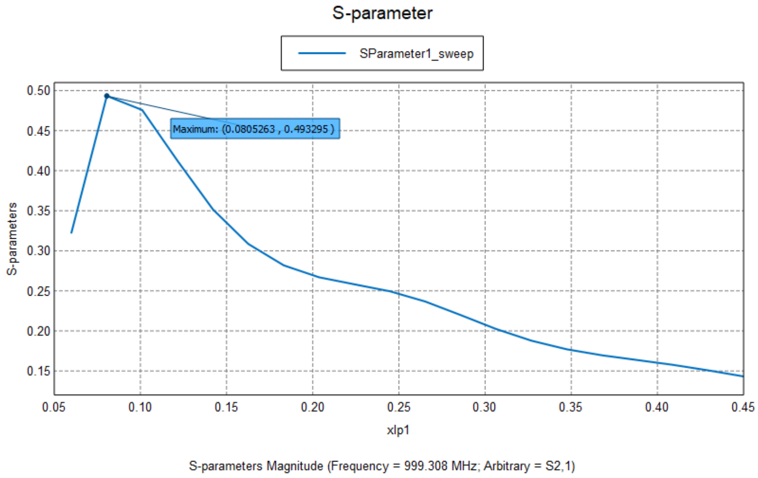
Graph of PWPT System Integrated with Four Line Parasitic Wire



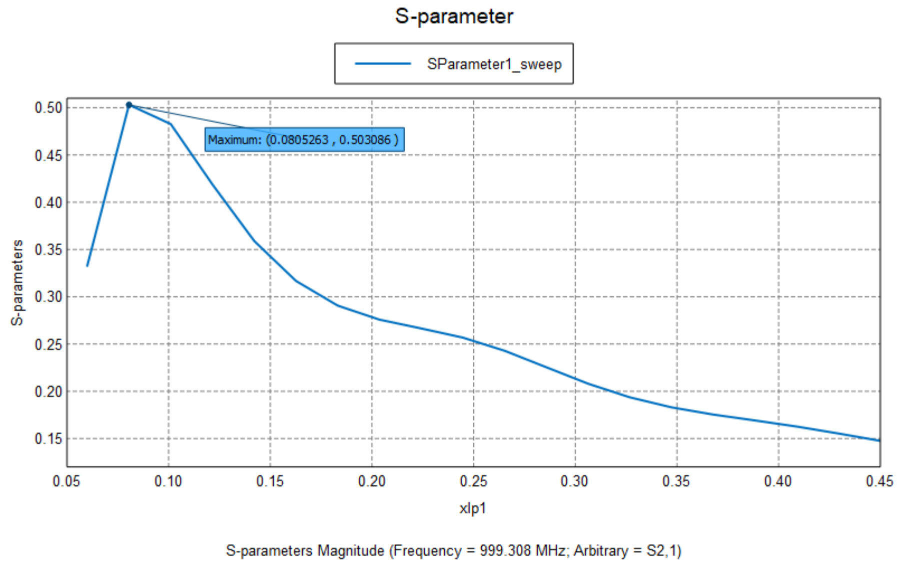
Graph of PWPT System Integrated with One Line in Rectangular Parasitic Wire



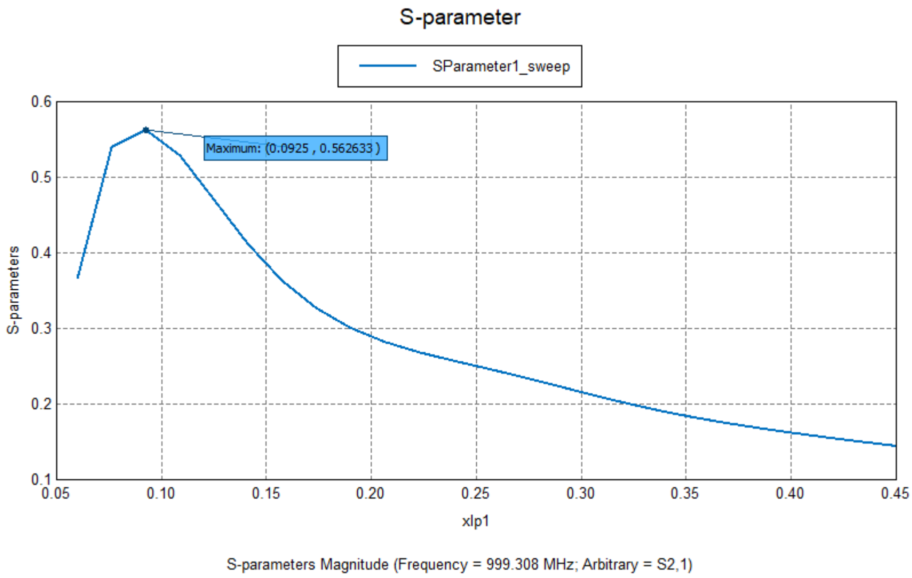
Result of PWPT System Integrated with 1 Front 2 Back Parallel Parasitic Wires



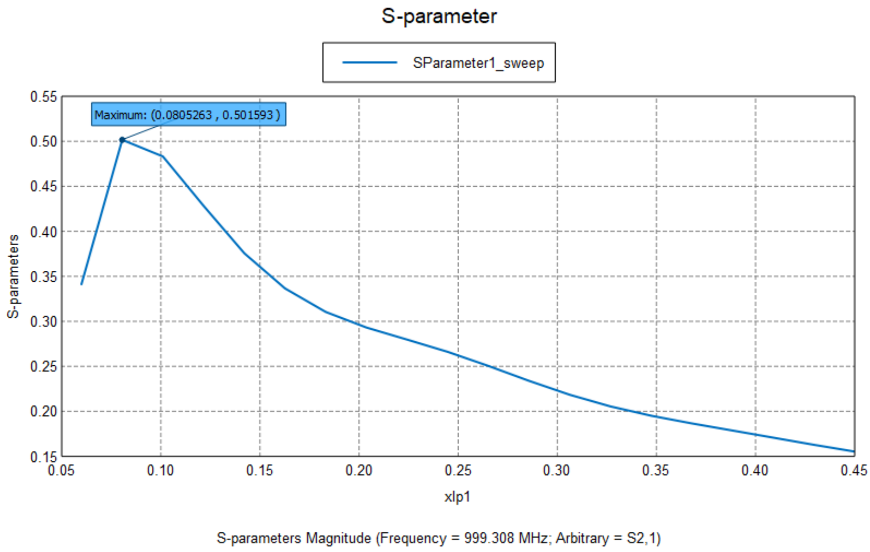
Result of PWPT System Integrated with 1 Front 3 Back Parallel Parasitic Wires



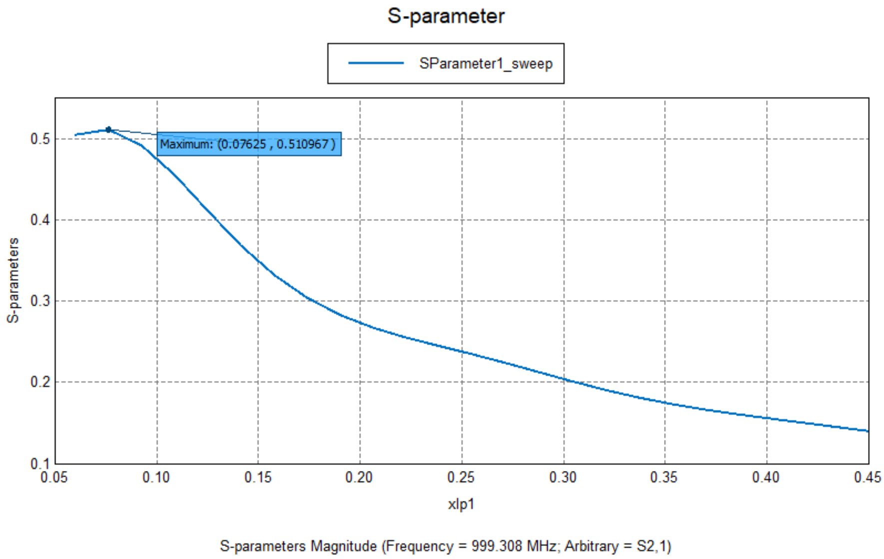
Result of PWPT System Integrated with 2 Side 1 Front 1 Back Parasitic Wires



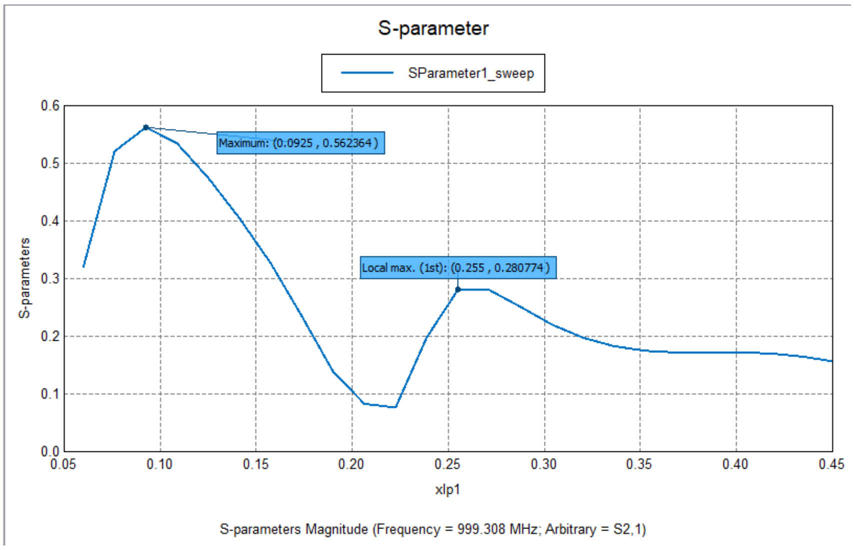
Result of PWPT System Integrated with 1 Front 5 flat Parasitic Wires



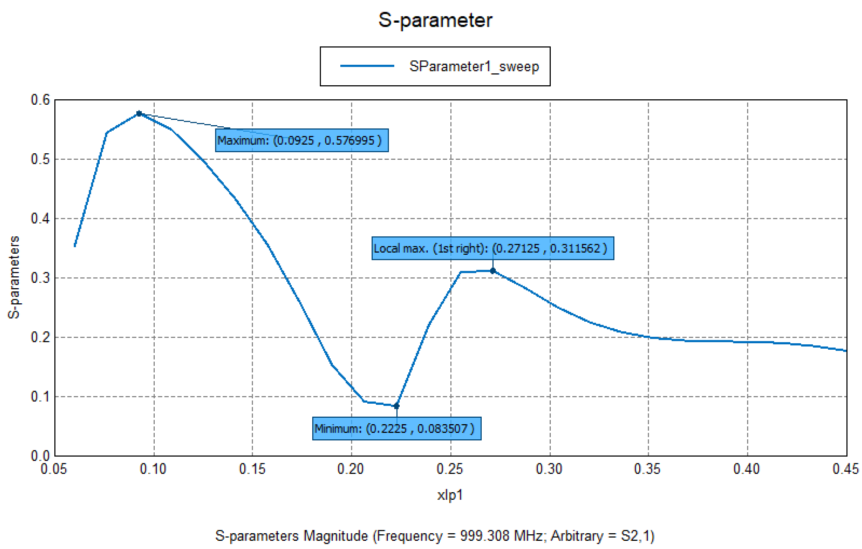
Result of PWPT System Integrated with two One Line in Rectangular Parasitic Wires



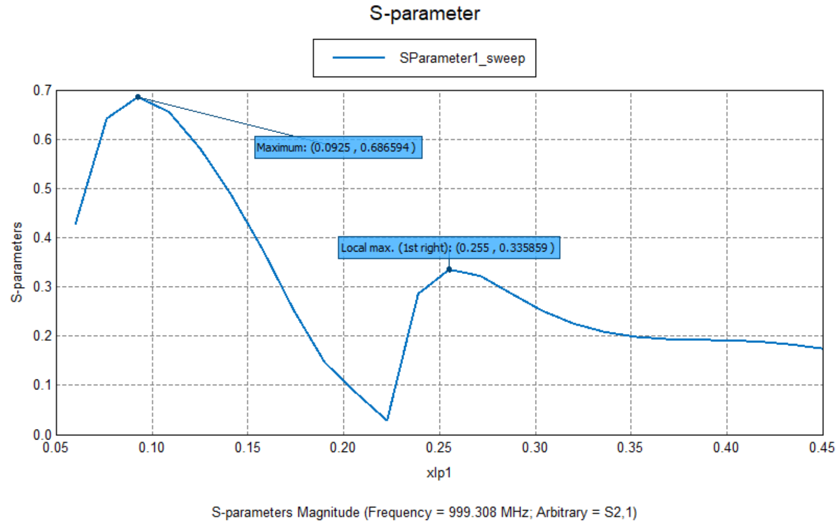
Graph of PWPT System Integrated with 4 Rectangular Parasitic Wires



Result of PWPT System Integrated with 2 Front 4 Back Parallel Parasitic Wires



Result of PWPT System Integrated with 4 Side 2 Front 2 Back Rectangular Parasitic Wires



Result of PWPT System Integrated with 4 Side Rectangle 2 Front 2 Back One Line in Rectangular Parasitic Wires