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Use of Bi-Polygonal Antenna Model to Explain Antenna Work Frequency Shifts Due to Changes in Antenna Geometry Shape

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Abstract—**One way to improve the efficiency of antenna design is to use mathematical models. The polygonal antenna model is a mathematical model for designing antennas with a polygonal structure. This article explains the application of the bi-polygon antenna model to account for the frequency shift of the micro-strip antenna due to changes in the design of the antenna shape from two sides, from two hexagons to two octagons. The antenna's operating frequency is determined from the FDTD simulation results based on bi-quad, bi-hexagonal, and bi-octagonal antenna design parameters. This research aims to test the theoretical model of a bi-polygon antenna by analyzing changes in the antenna's operating frequency due to changes in the shape of the antenna design. The novelty of this research lies in applying the theoretical model of a bi-polygonal antenna to analyze changes in the antenna's operating frequency due to changes in the antenna shape design. The research results show that applying the theoretical model of a 2-polygonal antenna can explain the causes of changes in the antenna's operating frequency due to changes in geometric design from bi-quad, bi-hexagonal to bi-octagonal antennas. However, the bi-polygonal antenna model still produces different results from the simulation results. Therefore, further research is needed to improve it. Model improvements include adding factors that were previously ignored or unavailable, adding assumptions about changes in antenna capacitance, and improving modeling data based on direct measurement data of antenna parameters.**

Keywords— **Bi-polygonal antenna; working frequency; bi-quad; bi-hexagonal; bi-octagonal.**

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I. INTRODUCTION

Communication and information are the main needs of today's modern society. Wireless technology is a technology that is closely related to communication and information and continues to develop. One of the key components of wireless technology is the antenna. The antenna functions as the part that transmits and receives electrical signals and data. So that communication and data transmission can run smoothly and quickly, antenna performance must be guaranteed [1], [2].

Modern society increasingly needs communication and information, so antennas have become an important component in information and communication technology (ICT). The antenna design should be convenient, compact, and portable. Micro-strip antennas are one way to meet these needs. Much research has been carried out to obtain more reliable micro-strip antenna designs. As part of micro-strip antenna research, the Department of Physics of the Institut Teknologi Sepuluh Nopember (ITS) has developed a dual three-slot micro-strip antenna array [3], a V-shaped CPS micro-strip antenna [4], and a new method for designing CPW. We examined the analysis methods—micro-strip antenna [5].

This article presents the results of a micro-strip antenna study regarding the influence of antenna geometric design on the operating frequency characteristics of the antenna. For this purpose, three antenna design geometries are investigated: bi-quad antenna design, bi-hexagon antenna design, and bi-octagon antenna design. A bi-quad antenna is an antenna made in the form of a pair of rectangles with the same side length. Bi-quad antennas are widely used in wireless communication systems because of their many advantages [6], [7]. One of the advantages of a bi-quad antenna is that it can be used as a broadband antenna [8], [9], [10]. A bi-hexagonal antenna design is shaped like a pair of hexagons with the same side length [11]. Some applications of hexagonal antennas, such as biomedical applications, can be used as implants to transmit and receive microwave signals related to bodily functions in living organisms [12]. Another application example is the choice of a hexagonal fractal shape to expand the bandwidth of the antenna used as an ultra-wideband antenna [13]. A bi-octagonal antenna is an antenna that consists of two equal sides. The octagonal geometric antenna design is suitable for high-bandwidth antennas, especially wideband antennas [14], [15], ultra-wideband (UWB) antennas [16], [17], [18], [19], and band antennas width [20].

The novelty of this research is applying the bi-polygon antenna model to explain the effect of changes in the geometry of the bi-polygon antenna design on the antenna operating frequency. The polygon antenna model is a model developed by Bustomi et al. [21] proposed antenna model. The bi-polygon antenna model is based on the bi-circular antenna design as a design reference. The bi-circular antenna is an antenna with a circular design [22]. An example of an antenna design with circular geometry is taken from Sen et al. [23] and Hamed and Bashir's design [24].

II. MATERIALS AND METHOD

The object in this study is a micro-strip antenna with a double polygonal or bi-polygonal shape. The study sampled three bi-polygonal antenna designs: bi-polygonal quadrilateral or bi-quad, bi-polygonal hexagon or bi-hexagonal, and bi-polygonal octagon or bi-octagonal. The three forms of antenna design are used in this study to see the effect of changes in antenna geometry from double quadrangle, double hexagon, to double-octagonal to changes in the working frequency of each antenna.

A. Antenna Design

The three antenna designs studied were bi-quad, bi-hexagonal, and bi-octagonal antenna designs. The shape and dimensions of each antenna design are shown in Figure 1.

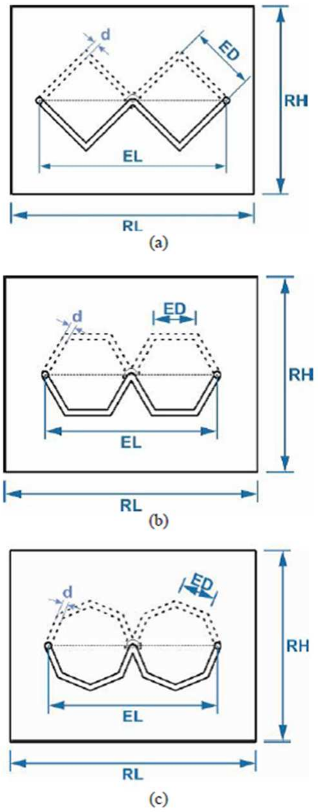

Fig. 1 (a) bi-quad antenna, (b) bi-hexagonal antenna, (c) bi-octagonal antenna

In each antenna design, the antenna design parameter values are as follows:

- The basic material Teflon (PTFE) has a dielectric constant of 2.1.
- Base thickness 1.54 mm.
- Antenna circumference 93.93 mm.
- Copper thickness (T) 0.03 mm.
- Copper diameter (d) 2 mm.
- Antenna board length (RL) 86.11 mm.
- The antenna panel width (RH) is 66.98 mm.

The geometric parameter values of the bi-quad antenna are:

- The length of each side of the rectangle (ED) is 23.48 mm.
- Bi-quad antenna length (EL) 66.42 mm.

The geometric parameter values of the bi-hexagon antenna are [11]:

- The length of each side of the hexagon (ED) is 15.66mm.
- The double-sided antenna length (EL) is 31.32 mm.

The geometric parameter values of the bi-octagonal antenna are:

- The length of each side of the octagon (ED) is 11.74 mm.
- Octagonal antenna length (EL) 30.68 mm.

B. Stages of Research

The method for studying the effect of changing the antenna shape from bi-quad, bi-hexagonal to bi-octagonal on changes in the working frequency of the antenna is by simulating each antenna design using the finite difference time domain (FDTD). The FDTD simulation results for each bi-polygon antenna design will provide data on the relationship between the shape of the bi-polygon antenna expressed by the number of polygon sides and the working frequency of each bi-polygon antenna.

In previous research, a theoretical antenna model for a polygonal micro-strip antenna has been developed [21]. The bi-polygon antenna model is developed based on the RLC equivalent circuit model of the bi-polygon antenna. Each antenna equivalent component, namely antenna resistance (R), inductance (L), and capacitance (C), is obtained from several proposed formulas for these three components [25]. This research will use a bi-polygon antenna model to interpret data obtained from FDTD simulation results to determine the working frequency of bi-quad, bi-hexagonal, and bi-octagonal antennas.

The research stages include the initial, method application, and evaluation stages. The first research stage is to prepare supporting materials for designing two-sided antennas, namely bi-quad, bi-hexagonal, and bi-octagonal. The research steps are to use the FDTD simulation method and apply a bi-polygon antenna model. The evaluation step includes comparing the modeling results with the FDTD simulation results on the antenna design. This comparison was carried out to evaluate the accuracy of the polygonal antenna model. Model evaluation was carried out to improve the polygonal antenna model. Data collection, interpretation, and analysis techniques based on the research conceptual framework were used. The evaluation step includes comparing the results of the two methods to cross-check the data to obtain more valid results regarding the relationship between the number of polygon sides and the working frequency of the antenna. Figure 2 shows a diagram of the research steps.

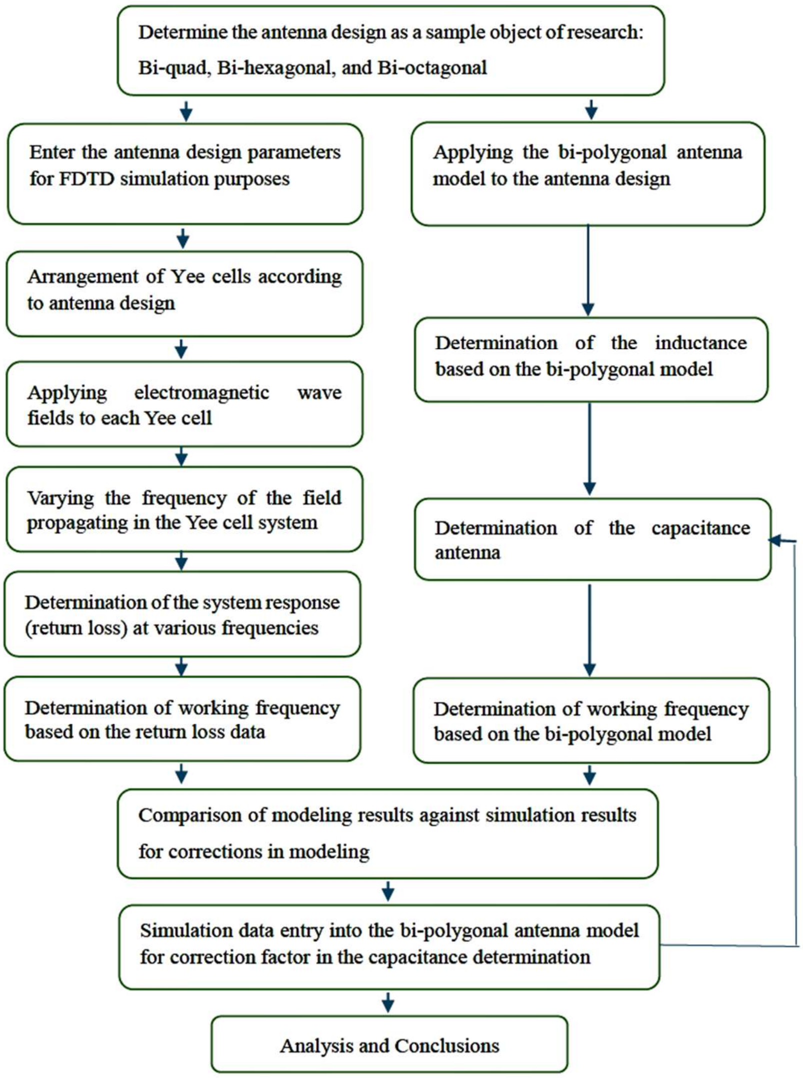

Fig. 2 Research flow chart

C. *Simulation Method of Working Frequency Determination*

The simulation method is based on the phenomenon of propagation of electromagnetic waves with short wavelengths (microwaves), which propagate in an antenna design that acts as a wave propagation medium. The analysis is carried out by applying Maxwell's equations to the antenna media. Antenna characteristics are obtained by solving Maxwell's equations for microwaves propagating in the antenna medium. There are many methods to solve Maxwell's equations for antennas. The method that is widely used in electromagnetic wave propagation problems is the Finite Difference Time Domain (FDTD) method [26].

Figure 2 shows a flow chart for determining the working frequency of the antenna based on the simulation method. The first stage of the FDTD simulation method is to enter the antenna design parameters required in the FDTD simulation. The second stage is the arrangement of the Yee cells according to the shape and design parameters of the antenna. The third stage is to apply an electromagnetic wave field to the Yee cell system and solve the Maxwell equation for each Yee cell using the FDTD method. The fourth stage is to repeat the FDTD simulation process at various frequencies of electromagnetic waves. The fifth stage is the determination of the response of the Yee cells antenna design system at each variation of the frequency of the electromagnetic waves. The calculated system response is the return loss value from the system [27]. The last step is determining the antenna's working frequency based on the antenna design's return loss system characteristics. The working frequency is the frequency that causes the minimum antenna return loss.

D. *Application of the Bi-polygonal Antenna Model*

Bi-polygon antenna modeling is based on the calculation formula for the inductance of a bi-polygon wire antenna. When calculating the inductance of a conductor of two polygons, several approaches are applied to simplify the calculations, namely [21]:

- The length of the wire or perimeter of the polygon is fixed.
- The wire diameter is considered very thin.
- - The magnetic field distribution is assumed to be uniform
- The influence of the external magnetic field on the wire is considered very small and can be ignored.

- The capacitance and resistance values of the antenna wire are assumed to be constant.

In this approach, the magnetic field at the center of the polygon is the result of all the magnetic fields produced by each side of the polygon:

$$B = \frac{\mu_0 I n^2}{\pi s}\frac{\cos\alpha}{\tan\alpha} \quad (1)$$

and polygonal cross-sectional area:

$$A = \frac{s^2}{4n}\tan\alpha \quad (2)$$

so that the inductance of the polygonal wire:

$$L = \frac{BA}{I} = \frac{\mu_0 n s}{4\pi}\sin\left(\frac{180^0}{n}\right) \quad (3)$$

with

$$\alpha = 90^0 - \frac{180^0}{n}$$

s = polygonal circumference length
n = number of polygonal sides

Based on the results of calculations using the polygonal wire antenna inductance formula and the RLC circuit model, the antenna bandwidth formula can be obtained:

$$\Delta f = \frac{1}{2\pi}\sqrt{\frac{R^2}{L^2}(x^2-1)+\frac{4}{LC}} \quad (4)$$

and the working frequency of the antenna:

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \quad (5)$$

with

$$x = \frac{\sqrt{10}}{\sqrt{10}-1}$$

C = antenna capacitance
R = antenna resistance

Figure 2 presents a diagram for determining the working frequency of an antenna based on the bi-polygon antenna model. The first step in antenna modeling is to apply the polygonal antenna model to analyze the antenna design. The application is carried out by providing parameter values for the bi-polygon antenna model according to the antenna design to be analyzed, namely bi-quad, bi-hexagonal and bi-octagonal antenna designs. The second step is determining the antenna inductance value based on the bi-polygon antenna model. Determining the induction value in the antenna model is carried out by providing parameter values for the bi-polygon antenna model that correspond to each antenna design. The third step is to determine the antenna capacitance value. The antenna capacitance value is determined based on the parameters of the bi-polygonal antenna model with additional corrections based on the simulation data. Correction of the antenna capacitance value is carried out by iterating the antenna capacitance value until the minimum error is obtained between the antenna working frequency data from the simulation and modeling results. The final stage is to determine the working frequency of each antenna design based on the bi-polygonal antenna model. These working frequencies are the antenna working frequencies calculated based on the capacitance value and each design inductance value.

III. RESULTS AND DISCUSSION

A. *Simulation Result Data*

The results of the FDTD simulation for determining the working frequency of the bi-quad, bi-hexagonal, and bi-octagonal antennas are shown in Table 1. Table 1 also shows the results of the FDTD simulation for determining the working frequency of a bi-circular antenna. The bi-quad antenna is a quad or polygonal pair antenna with four sides. The bi-hexagonal antenna is an antenna in the form of a hexagonal or polygonal pair with six sides. The bi-octagonal antenna is an octagonal or polygonal pair with eight sides (Fig. 1). The bi-circular antenna is a circular pair antenna. A circle can be viewed as a polygonal with infinite sides.

TABLE I
THE SIMULATION RESULT OF THE WORKING FREQUENCY OF VARIOUS ANTENNA DESIGNS

Antenna Design	**Number of Sides**	**Working Frequency (GHz)**
Bi-quad	4	2.62
Bi-hexagonal	6	2.64
Bi-octagonal	8	2.56
Bi-circular	∞	2.45

The bi-circular antenna design in this research is a reference design used to develop other antenna designs, especially bi-quad, bi-hexagonal, and bi-octagonal antenna designs. Bi-circular antenna radius (R) 14.95 mm, copper diameter (d) 2 mm, antenna panel length (RL) 86.11 mm, and antenna panel width (RH) 66.98 mm. The values of copper diameter (d), antenna panel length (RL), and antenna panel width (RH) for each antenna design used in this research are similar to the bi-circular antenna design.

The bi-circular antenna in this research is designed to operate at a frequency of 2.45 GHz. The frequency, especially around 2.45 GHz, is a frequency that is widely used as the working frequency for micro-strip antennas in communication and data transmission systems using microwaves. Other antenna designs are based on this bi-circular antenna design by changing its geometric shape from circular to rectangular, hexagonal, or octagonal.

Data on the relationship between the number of polygon sides and the working frequency of several antenna designs simulated by FDTD in Table 1 can be used to determine the working frequency of antenna designs with a number of sides ranging from 4 to 10. To this end, there are two things to consider. In the simulation data, determining the working frequency is an anomaly in the bi-hexagonal antenna working frequency data. The first thing to note is that the anomaly data on the bi-hexagonal antenna is not used in the following procedure. The second consideration is the bi-circular antenna design method, such as designing a 24-sided polygonal antenna. Based on the data in Table 1 and these two considerations, using Lagrange interpolation, we can determine the working frequency of a bi-polygonal antenna with different sides from 4 to 10 sides. Table 2 presents the results of the interpolation of working frequencies of polygonal antennas with different sides based on FDTD simulation data.

TABLE II
THE SIMULATION AND INTERPOLATION RESULT OF THE WORKING FREQUENCY OF VARIOUS ANTENNA DESIGNS

Antenna Design	Number of Sides	Working Frequency (GHz)
Bi-quad	4	2.6200
	5	2.6038
Bi-hexagonal	6	2.5884
	7	2.5738
Bi-octagonal	8	2.5600
	9	2.5470
Bi-decagonal	10	2.5349

B. Modeling Result Data

The results of antenna modeling to determine the working frequency of the bi-polygon antenna are presented in Table 3. Table 3 also presents the results of antenna inductance calculations based on the bi-polygon antenna model. The table shows the inductance values and working frequencies of several bi-polygon antenna designs, starting from an antenna with a number of polygon sides n = 4 (bi-quad antenna), an antenna with a number of polygonal sides n = 5, and an antenna with a number of polygonal sides n = 6 (bi-hexagonal antenna), and so on until the antenna has a number of polygon sides n = 10.

TABLE III
THE MODELING RESULTS OF THE INDUCTANCE VALUE AND WORKING FREQUENCY OF THE ANTENNA

Number of Sides	Inductance (nH)	Working Frequency (GHz)
4	26.5872	2.6200
5	27.6259	2.6038
6	28.2000	2.5884
7	28.5496	2.5738
8	28.7778	2.5600
9	28.9349	2.5470
10	29.0476	2.5349

From Table 3, it can be seen that the bi-polygonal antenna with the number of sides n = 4 (the bi-quad antenna) has an inductance of 26.5872 nH, the bi-polygonal antenna with the number of sides n = 6 (the bi-hexagonal antenna) has an inductance of 28.2 nH, and the bi- polygonal with the number of sides n = 8 (bi-octagonal antenna) has an inductance of 28.7778 nH. Based on the data in Table 3, a bi-polygonal antenna inductance graph can be made from the number of polygonal sides n = 4 to n = 10. The graph form of the inductance value of the bi-polygonal antenna vs. the number of polygon sides is shown in Fig. 3.

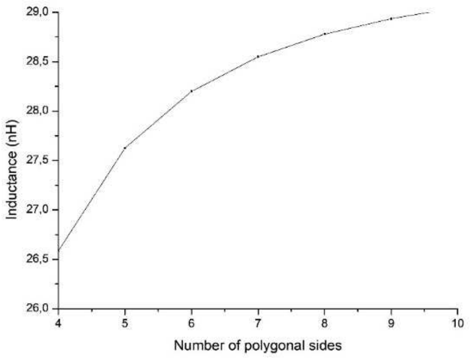

Fig. 3 Graph of Antenna inductance vs. number of polygonal sides

From Table 3, it can be seen that the bi-polygonal antenna with the number of sides 4 (bi-quad) has a working frequency of 2.6218 GHz, and the bi-polygonal antenna with several sides 10 has a lower working frequency of 2.5083 GHz. Based on the data in the table, a graph of the working frequency of a wire bi-polygonal antenna with the number of polygonal sides from n = 4 to n = 10. The graph of the working frequency of the bi-polygonal antenna vs. the number of polygon sides is shown in Fig. 4.

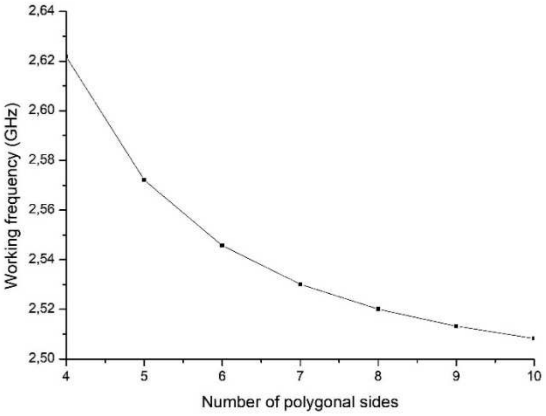

Fig. 4 Graph of Antenna working frequency vs. number of polygonal sides

C. Discussion

The conceptual framework used in this research is that changes in the geometry of a polygonal antenna will cause changes in the inductance and capacitance values of the antenna. Apart from that, this change also causes a change in the working frequency of the antenna. In this research, further investigation was carried out regarding changes in antenna induction due to changes in the shape of the bi-polygonal antenna. The results of determining antenna inductance based on the bi-polygon antenna model are presented in Table 3 and illustrated in Figure 3. These results show that the greater the number of polygon sides, the higher the antenna inductance value. Two factors that determine the inductance of a bi-polygon antenna are the intensity of the magnetic field that appears at the polygon's center point and the polygon's area [21].

The strength of the magnetic field at the center point of the polygonal depends on the distance of each side of the polygonal to the center point. The farther the distance, the weaker the magnetic field will be. In rectangular polygons, the distance of each side to the center of the rectangle is the closest compared to other polygons used in this research. In the tenth polygonal, the distance of each side to the center of the tenth polygonal is the furthest compared to the other polygonal used in this research. The greater the number of polygonal sides, the stronger the magnetic field at the center point of the polygonal. Increasing the magnetic field strength at the polygon's center point increases the inductance value of the two polygon antennas.

The opposite happens to the second element, namely the area of the polygonal plane. The greater the distance between each side of the polygon and the center of the polygon, the greater the area of the polygon. In a polygonal quadrilateral, the distance from each edge to the center of the quadrangle is the closest, so the area of the polygonal quadrilateral is the smallest. In the tenth polygon, the distance of each side to the center of the tenth polygon is the largest, so the area of the tenth polygon is the largest. The more sides a polygon has, the larger the area of the polygon. Increasing the area of the polygonal area is a factor causing the decrease in the inductance of the bi-polygonal antenna. Based on the data in Table 3 and the graphic illustration in Figure 3, it can be seen that the first factor has a superior effect compared to the second factor in increasing the inductance of the bi-polygon antenna due to the increase in the inductance of the bi-polygonal antenna vs. the number of polygonal sides.

The change or shift in the working frequency of the two-sided antenna due to the change in the shape of the antenna design from bi-quad to bi-octagonal is shown in Tables 2 and 3. Table 2 presents data on the shift in the bi-polygonal antenna's working frequency vs. the polygonal antenna's working frequency obtained from the FDTD simulation results. Table 3 presents antenna working frequency shift data obtained from the results of bi-polygonal antenna modeling. The data in both tables shows the differences in results between simulation and modeling. To get a visual overview of the differences in simulation and modeling results, the data in Table 2 and Table 3 are presented as a graph of working frequency vs. number of polygonal sides in one frame in Figure 5.

The working frequency is related to the number of edges of the simulated polygon, which usually decreases. Likewise, it can be seen in Figure 4 that the emergence of working frequency is a function of working frequency. The number of polygon sides obtained from the model is generally reduced. This means that the working frequency of the antenna will decrease as the number of polygon sides increases. Thus, based on the bi-polygon antenna model, the cause of the bi-polygon antenna frequency shift can be determined from the bi-quad, bi-hexagonal, to bi-octagonal antenna designs. The main reason for changes in the working frequency of the antenna is that the antenna inductance value increases due to the increase in the number of polygon sides. Increasing the antenna inductance value will cause the antenna's working frequency to shift to a lower working frequency.

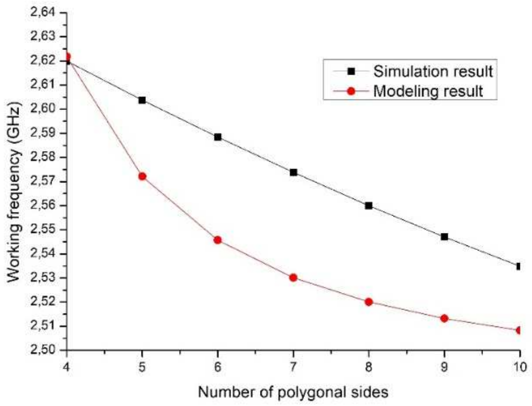

Fig. 5 Graph of antennas vs. number of polygonal sides based on simulation and modeling results

The working frequency relative to the initial number of simulated polygon edges decreases slowly over a small number of polygon edges. Moreover, the graph's curve decreases rapidly as the number of polygon sides increases. On the other hand, the shape of the working frequency versus the number of polygon edges in the initial model decreases rapidly for a small number of polygon edges. In addition, the graph curve obtained from the model decreases over a large number of polygon edges. This means that, based on the simulation results, the working frequency of the antenna will move slowly towards the fewer polygon edges, and the working frequency of the antenna will move quickly towards the fewer polygon edges. On the other hand, based on the modeling results, the working frequency of the antenna will decrease quickly with a small number of polygon edges, and the working frequency of the antenna will move slowly with a smaller number of polygon edges.

This research found that several bi-polygonal antenna modeling factors are unknown. These factors can be grouped into two categories: factors that are ignored when preparing the bi-polygon antenna model and unknown factors, so they are not included when preparing the bi-polygon antenna model. In the bi-polygon antenna model used in this research, the antenna capacitance is assumed to be constant (constant value) concerning changes in the name of the antenna design geometry. Moreover, antenna operating frequency data from the FDTD simulation should also be reinforced with data from direct experimental measurements on the antenna design. To measure antenna design parameters, it is necessary to fabricate each antenna design that will be implemented during the measurement process.

The upcoming study is needed to refine polygonal antenna models by considering previously overlooked factors and investigating previously unknown factors. Improvements to the polygonal antenna model must also be made by making a new assumption that the capacitance of the polygonal antenna changes as the shape of the antenna design changes. It is also necessary to carry out a manufacturing process for each antenna design to directly measure the antenna parameters in the antenna design.

IV. CONCLUSION

FDTD simulation and regular bi-polygonal antenna modeling give similar results, namely that the working frequency of the antenna will decrease as the number of polygonal sides increases. Based on the results of bi-polygon antenna modeling, the main cause of the antenna frequency shift is the increase in the antenna inductance value due to the increase in the number of polygon sides. The research results show that applying the bi-polygon antenna model can explain the causes of changes in the working frequency of the antenna due to changes in the antenna geometry design from bi-quad, bi-hexagonal to bi-octagonal.

Further research is required to improve the polygonal antenna model by adding various previously ignored or absent elements. In the bi-polygon antenna model, it is necessary to add a new assumption that the capacitance of the bi-polygon antenna also changes along with changes in the antenna design geometry. To complete the modeling data, supporting data obtained by directly measuring antenna parameters during the antenna design process is necessary.

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