

Magnetic resonance coupling for 5G WPT applications

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ABSTRACT

Inductive Wireless Power Transfer (IWPT) is the most popular and common technology for the resonance coupling power transfer. However, in 2007 it has experimentally demonstrated by a research group from Massachusetts Institute of Technology (MIT) that WPT can be improved by using Magnetic Resonance Coupling Wireless Power Transfer (MRC WPT) in terms of the coupling distance and efficiency. Furthermore, by exploiting the unused, high-frequency mm-wave band which are ranging from 3~300 GHz frequency band, the next 5G generations of wireless networks will be able to support a higher number of devices with the increasing data rate, higher energy efficiency and also compatible with the previous technology. In this work, a square planar inductor with the dimension of 6.1 x 6.1 mm is designed, and the resonators have the same self-resonance frequency at 14 GHz. The coil resonators have been laid on Silicon and Oxide substrate to reduce the loss in the design. From the CST software simulation and the analytical model in MATLAB software, it has been shown that the MRC WPT design has improved the performance of IWPT design by 40% power transfer efficiency. MRC WPT design also has larger H-Field value which is 705.5 A/m, as compared to the IWPT design which has only 285.6 A/m when both Transmitter(Tx) and Receiver(RX) is at 0.3 mm coupling distance.

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1. INTRODUCTION

The technology of magnetic resonant coupling wireless power transfer (MRC-WPT) takes advantage of two electromagnetic systems with the same resonance coil frequency to transfer energy at a certain distance. In general, when two electromagnetic system is a weak coupling at a certain distance, the system can excite strong magnetic resonance if the natural resonance frequency is the same [1]. Inductive coupling was the most popular and common technology before the resonance coupling evolution. The idea of transmitting power through the air has been found over a century with Nikola Tesla pioneering the experiments and the ideas [2] However, inductive coupling could transmit power only in a short distance as compared to the magnetic resonance coupling as the system efficiency is significantly affected by the coil's axial and angular misalignment[2]. In 2007, a research group from Massachusetts Institute of Technology (MIT) has experimentally demonstrated an efficient non-radiative power transfer over distance up to 8 times the radius of the coils using a 4-coils strongly coupled magnetic resonance magnetic system, and transferred 60 Watts of power with over 40% efficiency up to 2 meters in distance [3,4].

Fifth generation (5G) technology is the next step in the evolution of wireless power transfer technology which aims to provide connectivity for any electrical devices, increasing data rate, higher energy efficiency as well as having compatibility with the previous technologies. The ultimate goal of 5G technology is successful in managing future wireless devices requirements. Varieties of 5G enabling technologies have been developed which includes extending the wireless communication to the higher frequency band, the advances development of multi-band antenna as well as wireless power transfer system [5]. Also, to realise the vision of the Internet of Things/Internet of Everything(IoT/IoE), the 5G technology is aimed to be able to support the significant number of devices connected with reduced cost per information transfer [6]. According to [7], the mobile traffic is expected to increase by 60% per year due to the increasing number of electronic devices. Thus, the critical essence of the next 5G generation wireless networks is to explore and exploit the unused high-frequency mm-wave band which ranging from 3~300 GHz frequency band [8].

Furthermore, as stated by [9] when the operating frequency of coil approaches the self-resonance frequency of the coil, the parasitic resistance will increase drastically. Furthermore, the coil also behaves as a capacitor for a frequency higher than a the self-resonance frequency. Thus it cannot be used as an inductor. In this system, the coil can be used for the 5G WPT applications which the operating frequency is below than the self-resonance frequency of the coil which is 14 GHz in order to have a maximum power transfer efficiency.

Previous work has been done in wireless power transfer application in RF Identification devices in the GHz frequency band. However, the size is too small, and most of the works are on the complementary-metal-oxide-semiconductor (CMOS) technology using an on-chip antenna (OCA) [10]. Also, the OCA UHF tags are using inductive coupling as a power transfer method in the CMOS system. For instance, at 4.7 GHz frequency, [11] has reported the OCA design which is fabricated using 65 nm-CMOS technology with the coil area of 0.01 mm² with the read range at 1.2 mm distance. At 2Ghz frequency, [12] has design OCA with the coil antenna area 0.04 mm² with the read distance at 1.1 mm. At 2.45 GHz frequency [13-16] has reported the OCA design using 130nm-CMOS and post-processing with coil antenna area 0.5 mm² and the read range is at 0.5 mm distance.

In this work, a square planar inductor coil with the size of 6.1 mm x 6.1 mm which is laid on Silicon and Oxide is designed for both IP and MRC WPT systems. The size of the resonators is much larger as compared to the resonators that have been reported before, so the applications of the 5G WPT are not only limited into the OCA and CMOS system. Analytic equations are used to explain the design for both IWPT and MRC WPT system. Furthermore, 3-Dimensional (3-D) and B-Field Electromagnetic (EM) simulation in CST software shown that the four-coils WPT system has outperformed the 2-coils WPT by up to 40% power transfer efficiency at 0.3 mm distance. Both efficiencies of IWPT and MRC WPT designs in CST are also compared in the theoretical calculation in MATLAB, and the efficiencies versus distance differential errors are not more than 5%.

2. RESEARCH METHOD

Several closed-form equations have to be considered in designing the PSCs MCR-WPT system. Figure 1 shows the design of schematic square spiral coils in CST software. Figure 2 and Figure 3 shows the equivalent circuit model of the IWPT and MRC-WPT system respectively by taking into account all mutual inductance in the MRC-WPT for 5G applications [17-19]. According to [18, 20, 21] an accurate expression for inductance value L is:

$$L = \frac{\mu_0 n^2 D_{avg} C_1}{2} \left(\ln \left(\frac{C_2}{\rho} \right) + C_3 \rho + C_4 \rho^2 \right) \quad (1)$$

Where the magnetic permeability of free space, μ_0 can be defined as $4\pi \times 10^{-7}$ H/m, and the fill ratio, ρ and can be calculated as below:

$$\rho = \frac{D_{out} - D_{in}}{D_{out} + D_{in}} \quad (2)$$

While the average diameter, D_{avg} is and can be calculated as:

$$D_{avg} = \frac{D_{in} + D_{out}}{2} \quad (3)$$

Besides C_1, C_2, C_3 , and C_4 , the layout depending factors are being shown in Table 1[22].

Table 1. Coefficients factors for square inductor

| Layout | C_1 | C_2 | C_3 | C_4 |
|--------|-------|-------|-------|-------|
| Square | 1.27 | 2.07 | 0.18 | 0.13 |

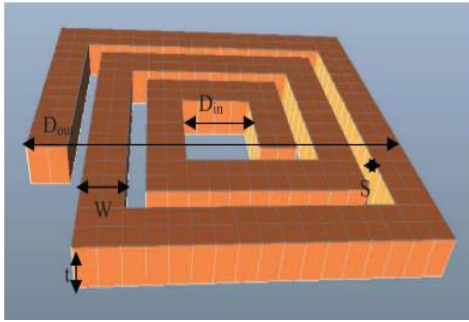


Figure 1. Square spiral coils schematic design

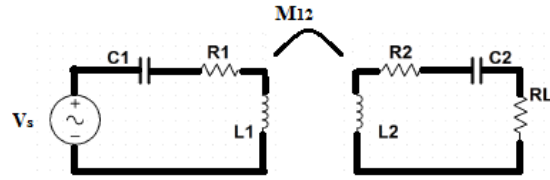


Figure 2. Equivalent Circuit Model for IWPT

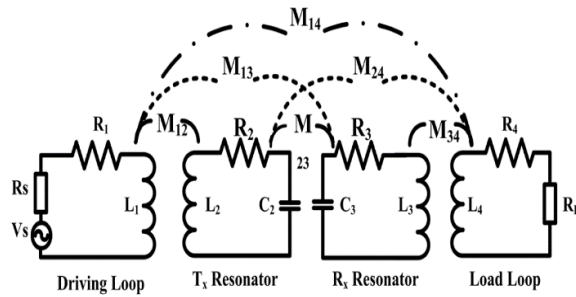


Figure 3. Equivalent circuit model for MRC WPT

According to [23] the self-capacitance in each spiral coils due the distance between the turns in the square spiral coil can be calculated by:

$$C_s = n W^2 \left(\frac{\epsilon_{ox}}{t_{ox, M1-M2}} \right) \tag{4}$$

Where n is the turn's numbers, W is the metal width, $t_{ox, M1-M2}$ is the distance between the turns and $\epsilon_{ox} = 3.45 \times 10^{-11}$ F/m is the oxide permittivity. The metal loss mechanism modelled by series resistance in the inductor is:

$$R_s = \frac{\rho l}{W \delta [1 - e^{-\frac{t}{\delta}}]} \tag{5}$$

Where l the total length of the inductor, the resistivity of the metal is called ρ , the metal thickness in micron meter is called t , and the the skin effect depth is called δ , which can be calculated as:

$$\delta = \sqrt{\frac{\rho}{\pi \mu f}} \text{ (}\mu\text{m)} \tag{6}$$

Where the frequency in GHz is called f and the magnetic permeability is called μ .

The mutual inductance between the planar inductors can be expressed using the Neumann's equation [24].

$$M = \frac{\mu_0}{4\pi} \oint_{c1} \oint_{c2} \frac{1}{R} d\vec{l}_1 \cdot d\vec{l}_2$$

Where $R = \sqrt{a^2 + b^2 + z^2 - 2abc \cos(\varphi_1 - \varphi_2)}$. Thus, M can be expressed as:

$$M = \frac{\mu_0 ab}{4\pi\sqrt{a^2 + b^2 + z^2}} \int_{\varphi=0}^{\varphi=2\pi} \frac{\cos(\varphi_1 - \varphi_2)}{1 - \frac{2ab}{a^2 + b^2 + z^2}} \cos(\varphi_1 - \varphi_2) \quad (7)$$

The mutual inductance can be further simplified into (8) as in wireless applications, the distance in the middle of the coils usually is smaller as compared to the radius coil [7].

$$M = \frac{\mu_0 \pi a^2 b^2}{2(a^2 + b^2 + z^2)^{\frac{3}{2}}} \left(1 + \frac{15}{32} \gamma^2 + \frac{315}{1024} \gamma^4 \right) \quad (8)$$

If the separation between the coils is huge ($z \gg r_{min}$, where r_{min} is the minimum radius of the primary coil or secondary coil), the equation can be further reduced again to (9)

$$M = \frac{\mu_0 \pi a^2 b^2}{2(a^2 + b^2 + z^2)^{\frac{3}{2}}} \quad (9)$$

The square inductor (6.1 mm x 6.1 mm) is designed on the Silicon substrate layer (7mm x 7mm) with a thickness of 0.2 mm, an oxide layer (7mm x 7mm) with the thickness of 0.05 mm. For small coils design, it is essential to choose the substrate and material to obtain low loss design. Besides, due to the gap in between the inductor and the substrate, outflow current to the substrate is zero and eddy current in the in the substrate will be reduced to zero hence the losses are also reduced [25]. The critical parameters in designing the coils are space between the turns (S), width of the coil (W), number of the coils turn (N), metal thickness (t), the inductor shape (in this design it is square), and the total length of the inductor (L) which will determine the inductance value of the coil. Table 2 shows the parameters dimension for each coil in both IWPT and MRC-WPT designs.

Table 2. Parameter summary for 4-coils design

| Coil Parameters | Dimension |
|---------------------------|-----------|
| W, width (mm) | 0.2 |
| S, spacing (mm) | 0.15 |
| N turns | 2.5 |
| t, thickness (mm) | 0.035 |
| Dout, Diameter out (mm) | 6.1 |
| Lengths (mm) | 44.9 |
| L, Inductor (nH) | 72.056 |
| Rs, (parasitic) Ω | 0.926 |
| Cs, (parasitic) pF | 23 |
| d, distance Rx to Tx (mm) | 0.3 |
| Coupling Coeff. (k) | 0.0869 |

2.1. Modelling and analysis of two-coils coupling structure

The traditional inductive coupling wireless power transfer’s principle (IWPT) is based on the two coils position near to each other. As shown in Figure 2, the system consists of transmitting (Tx) resonance coil’s curcuit and a receiving (Rx) resonance coil’s curcuit. In the Tx and Rx, the resistors, capacitors and inductor are connected in series. L1 and L2 are the self-inductance of the Tx and Rx coil. R1 and R2 are the parasitic resistance of the Tx and Rx coils respectively, and C1 and C2 are the parasitic capacitance in the coils of Rx and Tx. Vs is the Sine voltage supply, and RL is the load. M is the mutual inductance between Tx coil and Rx coil [26]. An AC magnetic flux is produced when an AC current is flowing through the Tx coil or primary coil. The Rx coil or secondary coil is then picked up this flux and is converted into an AC voltage across it [27]. Using the circuit theory, the transmission coefficient (S_{21}) and (Z_{in}) can be obtained as equation below [1].

$$\begin{bmatrix} I_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} Z_{11} & j\omega M_{12} \\ Z_{22} & j\omega M_{12} \end{bmatrix}^{-1} = \begin{bmatrix} V_s \\ 0 \end{bmatrix} \quad (10)$$

We assumed that the impedance of each coil is:

$$Z_{11} = R_1 + j\omega L_1 + \frac{1}{j\omega C_1} \quad (11)$$

$$Z_{22} = R_2 + j\omega L_2 + \frac{1}{j\omega C_2} \quad (12)$$

The coefficient of mutual inductance in the middle of Tx and Rx coils can be calculated using (13).

$$M_{12} = K_{12}\sqrt{L_1 L_2} \quad (13)$$

In conclusion, the system efficiency of the system in this work is defined by the scattering parameters (S_{21}) of the two-port network which can be calculated as below:

$$S_{21} = 2 \frac{V_0}{V_s} \left(\frac{R_1}{R_2} \right)^{\frac{1}{2}} \quad (14)$$

2.2. Modelling and analysis of four-coils coupling structure

The MRC-WPT system as shown in Figure 3 consists of four components which are; a source coil, a transmitting and receiving resonating coils, and a load coil. In this system, the energy is transferred via inductive coupling through the driver loop and the transmitter resonator. Then, the energy is transferred from the Tx resonator coil to the Rx resonator coil via magnetic resonance coupling. Both resonators from the Tx and Rx are resonated at the same frequency which is in this work the self-resonance frequency is at 14 GHz. The MRC-WPT system can transmit the energy in a longer distance as compared to the IWPT system. However, the efficiency of the MRC-WPT system will also decrease rapidly with the factor of optimal distance [28]. From [28,29] the transmission efficiency coefficient of four-port network scattering parameters (S_{21}) and (Z_{in}) can be calculated as equations below:

$$\begin{bmatrix} I1 \\ I2 \\ I3 \\ I4 \end{bmatrix} = \begin{bmatrix} Z11 & (j\omega M12)(j\omega M13) & (j\omega M14) \\ (j\omega M12) & Z22 & (j\omega M23) & (j\omega M24) \\ (j\omega M13) & (j\omega M23) & Z33 & (j\omega M34) \\ (j\omega M14) & (j\omega M24)(j\omega M34) & & Z44 \end{bmatrix}^{-1} \begin{bmatrix} V1 \\ V2 \\ V3 \\ V4 \end{bmatrix}$$

$$Z_{11} = (R_s + R_1 + j\omega L_1 + \frac{1}{j\omega C_1}) \quad (15)$$

$$Z_{22} = (R_2 + j\omega L_2 + \frac{1}{j\omega C_2}) \quad (16)$$

$$Z_{33} = (R_3 + j\omega L_3 + \frac{1}{j\omega C_3}) \quad (17)$$

$$Z_{44} = (R_4 + R_L + j\omega L_4 + \frac{1}{j\omega C_4}) \quad (18)$$

Where C_1 , C_2 , C_3 and C_4 are the parasitic capacitances of each inductor. Both R_{Source} and R_{Load} is 50Ω [29]. Thus, According to [1, 30]:

$$Z_{in} = \frac{V_s}{I_1} - Z_s \quad (19)$$

$$S_{21} = 2 \frac{V_0}{V_s} \left(\frac{R_1}{R_4} \right)^{\frac{1}{2}} \quad (20)$$

3. RESULTS AND ANALYSIS

For both IWPT and MRC WPT, all the coils have been designed with the same size and structure, without any tuning capacitance is being inserted in the coils. Each of the coils is resonated at 14 GHz self-resonance frequency. Figure 4 shows each of the square spiral resonator designed in CST system and Figure 5 shows the resonance frequency in CST simulation software for each resonator coil.

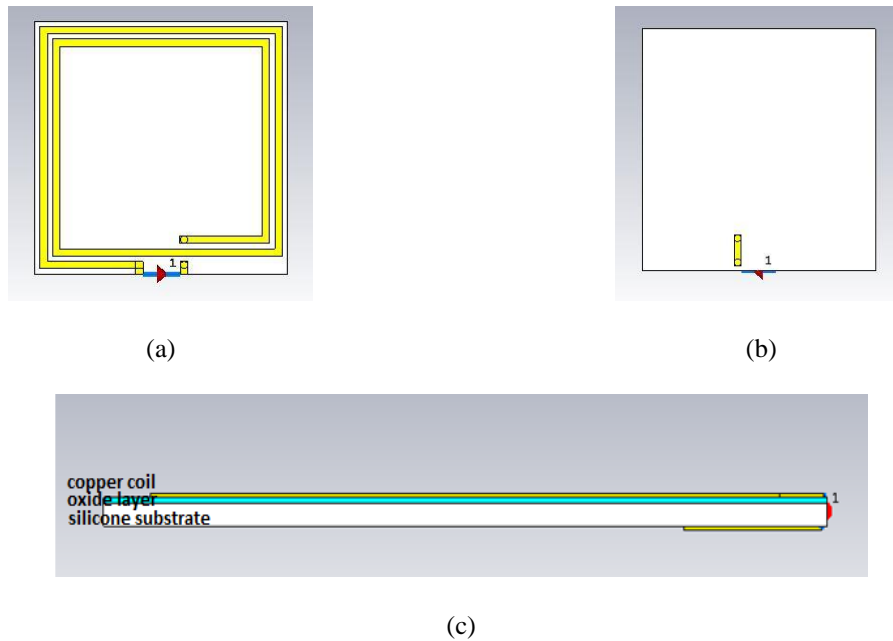


Figure 4. Square spiral coil in CST, (a) Front-view, (b) Back-view, (c) Side-view

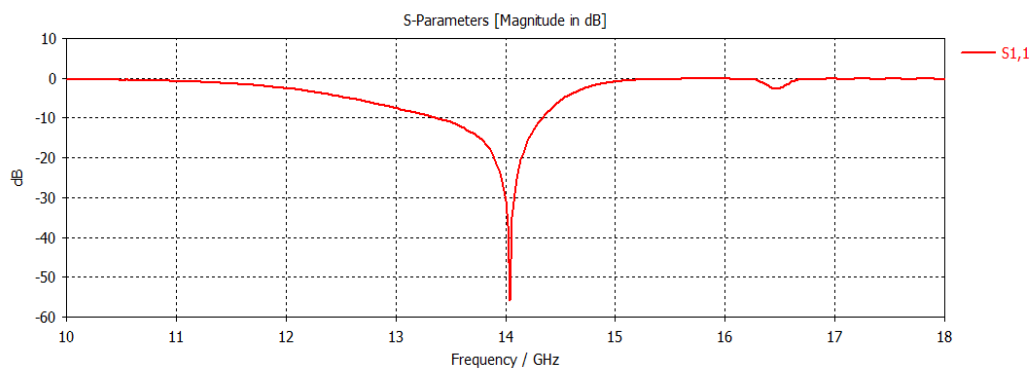


Figure 5. The self-resonance frequency of each coil

3.1. Two-coils IWPT EM simulations and MATLAB results

The IWPT design consists of 2-coils which are positioned near to each other. Each of the coils is referred to as a transmitting (Tx) coil and receiving (Rx) coil (represented as 1 and 2 in the Figure 6(a)). The distance between the Tx coil and the Rx coil is fixed at 0.3 mm, so the performance can be compared with the 4-coils system. Figure 6(b) shows the H-field of IPWPT design in CST software. At lower frequency from the self-resonance which at 5.8 GHz frequency, it can be seen that the maximum H-field of 2-coils IPWPT is 285.6 A/m when the distance between Tx and Rx is 0.3 mm. It also can be seen from the CST simulation as in Figure 7, the highest efficiency achieved for 2-coils IWPT is 80% at 0.1mm distance. However, the efficiency only works for a short distance, and it is rolled down too quickly below than 20% when the coupling distance is at 0.3 mm.

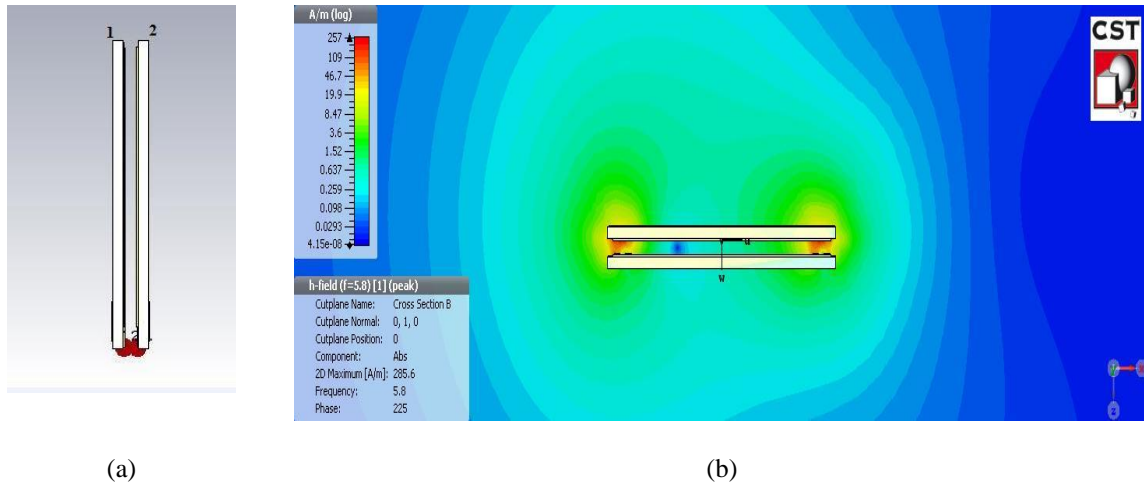


Figure 6. (a) IWPT coils in CST, (b) H-field of IWPT in CST

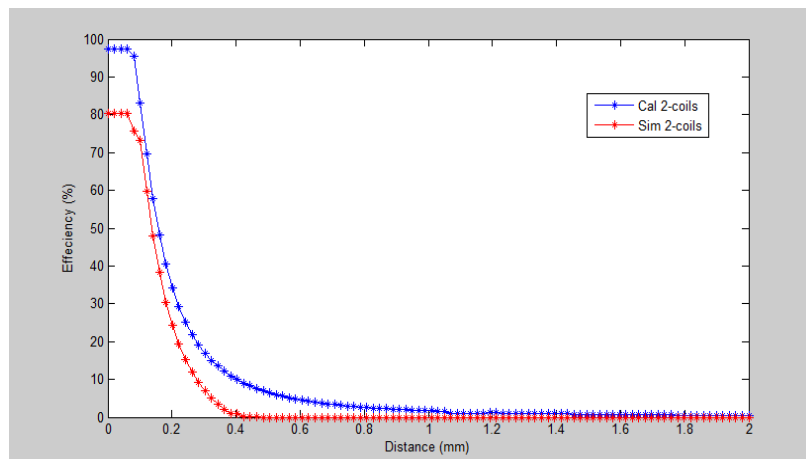


Figure 7. IWPT efficiencies at different distance, calculated versus simulated

3.2. Four-coils IWPT EM simulations and MATLAB results

As compared to the IWPT design system, the MRC WPT design system in figure consist of 4-coils, which each of the coils is referred as driver coil, primary coil, a secondary coil, and load coil (represent as 1,2,3,4 in Figure 8(a)). Also, the Figure 8(b) shows the H-field for the 4-coils MRC-WPT design in CST software. The most region around the 4-coils MRC-WPT system is green in colour. The maximum intensity of H-field when the frequency is at 5.8 GHz is 705.5 A/m when the coupling (k) between the Transmitter (Tx) and Receiver (Rx) is at 0.3 mm in the distance.

Besides, from the observation in CST software, when the distance is varied, there are some variations in resonance frequency. However, maximum efficiency does not change. From Figure 9, it can be seen that the highest efficiency achieved is 61.38 % when Tx and Rx are at 0.3 mm distance. Also, the comparison between mathematical and simulation is made, and the results are significant as they gave a clear expression of the system behaviour in order to prepare for the measurement testing in the real environment.

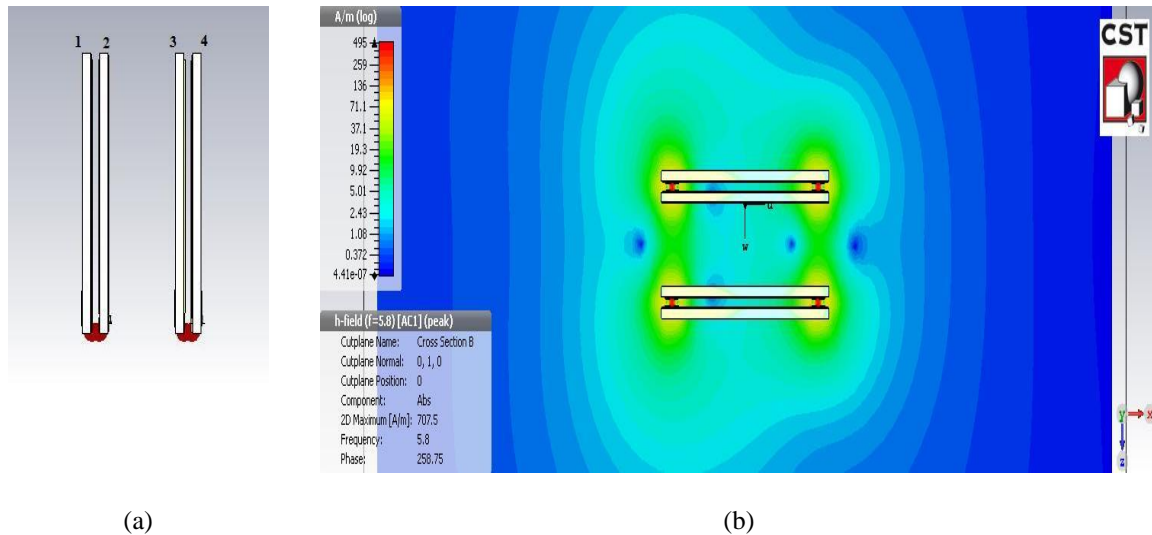


Figure 8. (a)MRC-WPT coils in CST, (b) H-Field of MRC-WPT in CST

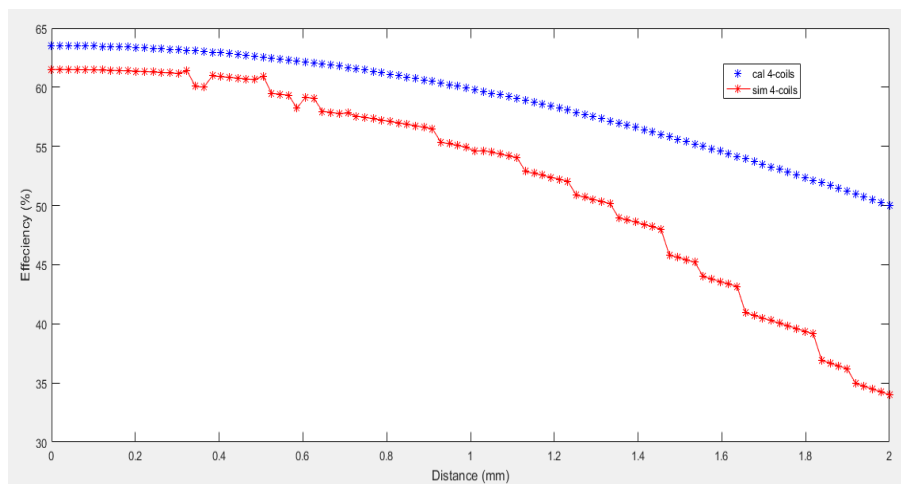


Figure 9. MRC-WPT efficiencies at different distance, calculated versus measured

4. CONCLUSION

To summarised, the 2-coils IWPT and 4-coils MRC WPT for 5G wireless power transfer applications have been simulated and analysed in the CST and MATLAB software. From the results, it can be proved that the 4-coils MRC WPT design has outperformed the 2-coils IWPT design by up to 40% of power transfer efficiency. The 4-coils MRC WPT has 61.38% power transfer efficiency when the Tx and Rx are at 0.3 mm distance, while the 2-coils IWPT dropped to below 20% power transfer efficiency at the same coupling distance of Tx and Rx. It can also be seen that the IWPT efficiency rolled down faster to 0% efficiency when the coupling distance is at 1 mm while 4-coils MRC WPT still having more than 40% power transfer efficiency when the coupling distance is at 1 mm. Furthermore, the square coil resonators dimension are 6.1x6., which they are much larger than the previously reported design so that the applications by using these resonator coils are not only limited into the OCA and CMOS system power transfer.

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