EXPERIMENTAL ANALYSIS OF A 2.4 GHZ ANTENNA FOR TYRE PRESSURE MONITORING SYSTEM

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Abstract: Antennas used for tyre pressure monitoring systems are usually enclosed by the tyre. On its own, the antenna may have excellent properties. However, the wheel and tyre may have an impact on the performance of the antenna. This paper investigated the performance of a simple 2.4 GHz whip antenna for a tyre pressure monitoring system. The antenna was modelled using HFSS, while the wheel and tyre were modelled using SolidWorks. The wheel and tyre can have an impact on the antenna performance. The reflection coefficients, VSWR, gain and radiation pattern were determined through simulations, using HFSS. The antenna operation was checked at different positions and configurations to the wheel to determine its' optimum position for effective signal radiation. The four different configurations were: antenna grounded to the middle of the rim, antenna ungrounded to the wheel's edge, antenna grounded to the wheel's edge, and antenna grounded to the wheel's edge enclosed by the tyre. The result shows that electrically grounding the antenna to the wheel by the edge improves its performance. Also, the tyre did not negatively impact the far-field gain of the antenna.

Keywords: 2.4 GHz antenna, VSWR, reflection coefficient, antenna gain, TPMS

1. INTRODUCTION

The tyre pressure monitoring system (TPMS) is important in a vehicle. TPMS helps the vehicle to maintain a proper tyre inflation pressure which can significantly affect the tyre rolling resistance, vehicle dynamics, tyre lifespan, effectiveness of the brakes, fuel economy and ultimately safety [1]. TPMS is usually of two types, which are direct and indirect TPMS. The indirect TPMS function without an additional sensor for pressure and temperature measurement. It uses the sensory mechanism already in the vehicle which makes it cost-effective but less accurate [2-3]. For the direct TPMS, specialized sensors installed on the wheel are used to measure pressure and/or temperature data. In most vehicles that employ direct TPMS, the sensor unit is placed on the wheel enclosed by the tyre, making it difficult to access it. The sensor unit transmits its signal wirelessly to the receiver which is placed behind the dashboard [4-6].

For effective transmission/reception of signals, TPMS antennas must be properly designed. An antenna is a metallic device for radiating or receiving radio waves [7]. Some of the antennas used for TPMS application includes the loop, whip, helix and other modified antennas. An important factor in the design of the antenna is the size requirement. The antenna must be electrically small to fit into the sensor module. Different researchers have

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proposed, designed and analysed these antennas for optimum performance. A compact printed antenna radiating at 315 MHz was proposed, designed, fabricated and analysed by He and Xie [8]. The radiation efficiency of a whip and loop antenna at 315 MHz was investigated by Zeng and Hubing [9]. [10] investigated the gain and radiation efficiency of a dipole and loop antenna. These papers showed that the whip antenna performs better than the loop antenna. However, these papers did not develop and analyse the performance of the antenna at 2.4 GHz. Besides, the reflection coefficients, VSWR and the electric field around an antenna were not given adequate coverage.

TPMS sensor units are usually installed on the wheel enclosed by a tyre. Since the main radiating element is the antenna, it is important to understand the impact the wheel and tyre would have on the antenna performance. Thus, the effect of the wheel and tyre on the antenna's performance must be considered in analysing a TPMS. Zeng and Hubing [9, 11] proposed a loop and whip antenna for TPMS and analysed its radiation efficiency and Q-factor including the wheel and tyre effect. Cheikh et al. [12] proposed a full characterization of the RF source for TPMS involving the wheel and tyre. Leng et al. analysed the gain and resistance of a proposed antenna [13]. These researchers only proposed and analysed the TPMS antenna radiating at 315 MHz and/or 433 MHz. They also did not analyse other antenna parameters such as the reflection coefficient and the voltage standing wave ratio (VSWR).

This paper proposed and analysed a simple whip monopole antenna (WMA) that resonated at a frequency of 2.4 GHz which can be used for TPMS and other similar applications. A whip monopole antenna was developed and analysed using a 3D electromagnetic solver, known as HFSS (high-frequency structure simulator). The effect of the wheel and tyre on the antenna was also analysed to get the optimum position for it to radiate efficiently. To ascertain the impact of the wheel and tyre on the antenna various scenarios were considered: The standalone antenna, antenna grounded to the wheel at the middle, antenna with no contact to the wheel by the edge, antenna with contact to the wheel by the edge and antenna with contact to the wheel by the edge enclosed by a tyre. Section 2 describes the models of the whip antenna and its improved version, the wheel and the tyre models as well as their simulation. In section 3, the simulation results and analysis for the different scenarios were presented. Finally, the conclusion of the paper was presented in section 4.

2. MODEL DESIGN AND SIMULATION

The geometric model of the antenna was produced using Ansoft HFSS (High-Frequency Structure Simulator) while the wheel and tyre models were created using SolidWorks. The analysis of the antenna in different scenarios was done using HFSS. HFSS is a well known software for analysing antenna performance hence the choice [14, 15].

2.1. Standalone antenna

The antenna was modelled as a quarter-wavelength (λ/4) monopole that radiates at a 2.4 GHz frequency. To achieve the best performance of the antenna, the length of the antenna was gradually reduced in steps of 0.25 mm. Seven different models were created and simulated, with the improved version referred to as IWMA (improved whip monopole antenna). Fig. 1 shows the model of the antenna. To analyse the antennas, an interpolative frequency sweep with 101 points from 1.2 GHz to 3.6 GHz was set up. The solution frequency was set to 2.4 GHz at 20 maximum passes with at least three minimum converged passes. After that, the structure was validated and solved. The parameters measured to determine the performance of the antenna were the reflection coefficient, VSWR, gain, and impedance bandwidth.

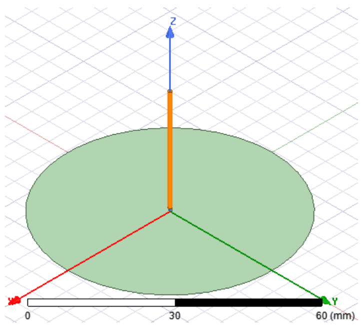


Fig. 1. Model of the antenna.

2.2. Wheel model

The wheel model was created using SolidWorks, to simulate the effect of the wheel on the antenna's signal propagation. It was modelled as a metal wheel with aluminium alloy chosen as the material because it is the commonest type of wheel. The dimension was 7.0J × 16 ET45 (7.0 inches or 177.8 mm wheel width, 16 inches or 406.4 mm wheel diameter, J stands for passenger cars, 45 mm wheel offset from the wheel centre line) with a Pitch Circle Diameter (PCD) of 5 x 114.3 and a centre bore of 60.1 all in metric scale. Fig. 2 shows the model of the wheel. To analyse the effect of the wheel on the antenna, the wheel model was imported into HFSS. Then the antenna was placed on the wheel at the middle with an electrical contact, edge with no electrical contact, and edge with electrical contact as shown in Fig. 3. The electrical contact was done through a thin conductor connected from the ground of the antenna to the wheel. The setup was validated and solved. In analysing the model, it was meshed to have accurate simulation results. The type of meshing used by HFSS is automatic adaptive meshing to generate accurate solutions based on the electromagnetics of the design [14]. The meshed model is shown in Fig. 4.

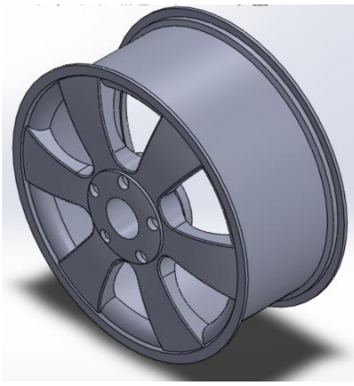
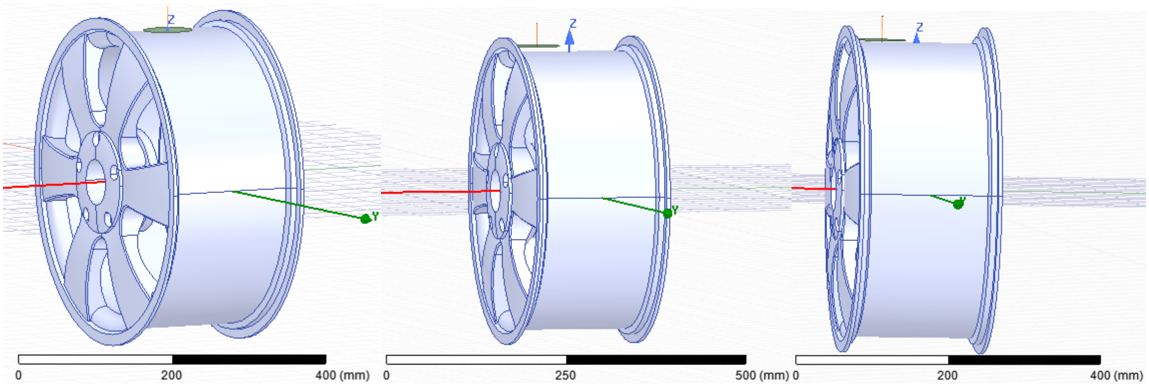


Fig. 2. Wheel model.



(a) (b) (c)

Fig. 3. The geometry of antenna placed on the wheel at the (a) middle with contact (b) edge without contact (c) edge with contact.

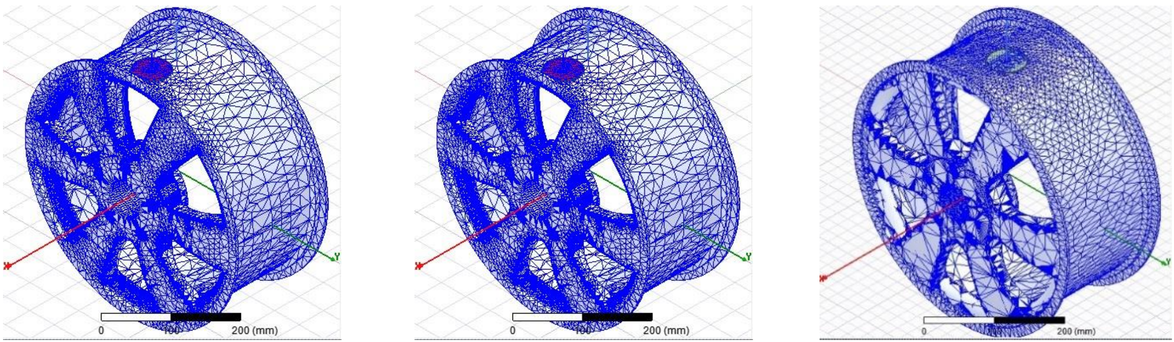


Fig. 4. Meshed models of the wheel.

2.3. Tyre model

SolidWorks was used to model the tyre as shown in Fig. 5. Tyre structure consists of the tread, sidewall and beads. Shown in Table 1 is the detailed dimension of the tyre. Its dimension of P205/60 R16 was based on an actual tyre dimension. Although different materials can be assigned to different parts of the tyre, this paper only considered natural rubber as the material for the tyre. Analysis of the effect of the tyre on the antenna was done by importing the tyre into HFSS and using it to enclose the antenna attached to the wheel by the edge. Afterwards, the setup was validated and solved.

Table 1. Tyre dimension.

Specification	**Dimension (mm)**
Section width	205
Section height	123
Rim diameter	406.4
Outer diameter	652.42

Fig. 5. Tyre model.

3. RESULTS AND DISCUSSION

As shown in Fig. 6, there was an improvement of 2.49 dB in the reflection coefficient of the IWMA over the WMA. Also, the resonant frequency of the antenna shifted from 2.3 GHz in the WMA to 2.4 GHz in the IWMA. Further observations showed that the impedance bandwidth shifted from 2.17 – 2.47 GHz for the WMA to 2.24 – 2.57 GHz for the IWMA which gave a bandwidth improvement factor of 10 %. The IWMA better achieved the bandwidth requirement for the IEEE 802.15.4 standard since it is a standard practice for the impedance bandwidth of a TPMS to be wide enough to prevent the operating frequency from shifting out of it [8]. For the VSWR, the IWMA was 1.44, which was better than that of the WMA at 1.65 as indicated in Fig. 7. These results indicate that the IWMA has an improved performance over the WMA. The simulated antenna is small enough to fit into the TPMS module. The radiation pattern follows the standard radiation pattern of a monopole antenna with an antenna gain of 5.6 dB as shown in Fig. 8. The results of the standalone monopole antenna were satisfactory. The IWMA was used for the remaining analysis.

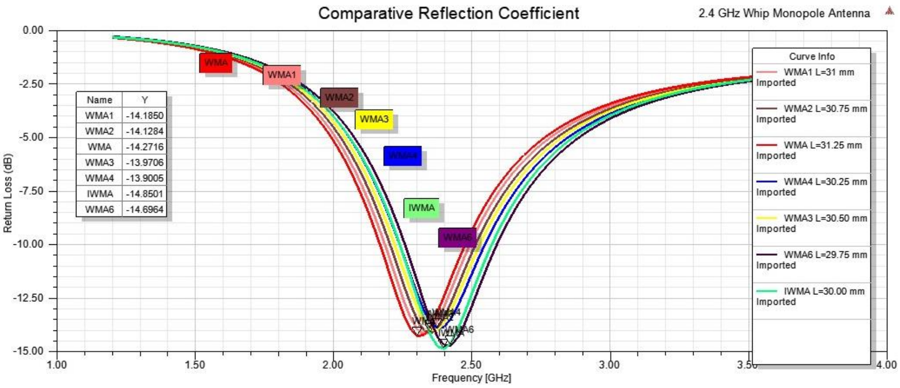


Fig. 6. Comparative reflection coefficient of the whip monopole antenna.

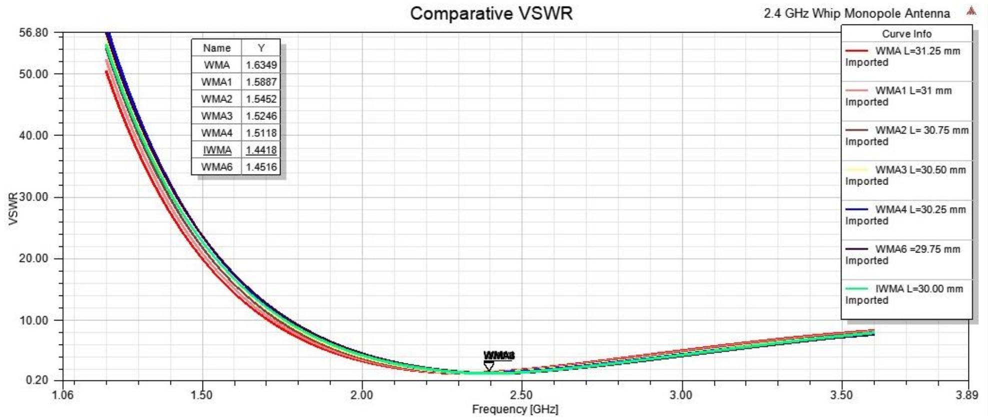


Fig. 7. Comparative VSWR of the whip monopole antenna.

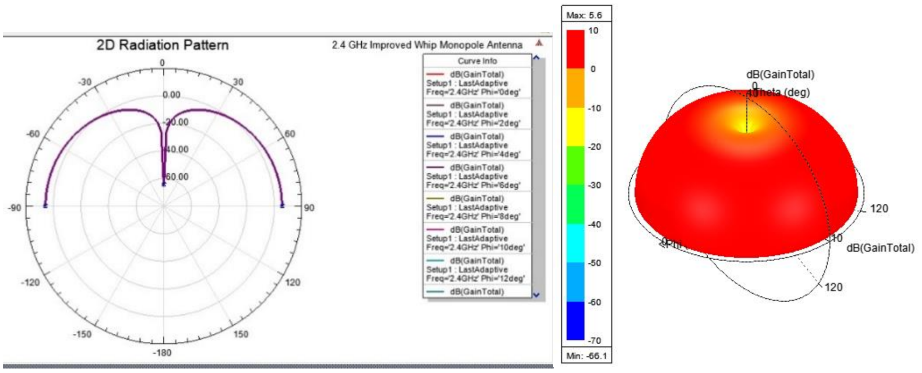


Fig. 8. Radiation pattern and gain of the whip monopole antenna.

Fig. 9 shows the antenna's comparative reflection coefficients in different settings. The best reflection coefficient was for the antenna grounded at the edge of the wheel and enclosed by a tyre (–19.09 dB), while the worst (-11.20 dB) was for the antenna positioned in the middle of the rim. In this configuration, there was a bandwidth improvement factor of 33.33% over the IWMA. Table 2 shows the impedance bandwidth for the various configurations of the antenna. It was observed that, besides the antenna positioned in the middle of the wheel, the other antenna configurations had impedance bandwidth that spans the bandwidth for the IEEE 802.15.4 standard. Another important antenna parameter analysed was the VSWR for the different configurations. Shown in Fig. 10 is the VSWR of the various antenna configurations. The VSWR in the frequency of interest lies in the range of 1 < VSWR < 2 for all antenna types. Although the worst VSWR was for the antenna ground to the middle of the wheel (1.76), the best was for the antenna ground to the edge of the wheel enclosed by a tyre (1.25). Shown in Table 3 is the radiation power for the antenna in different settings. The radiation power for the standalone antenna and the grounded antenna at the edge of the wheel is almost the same. In contrast, the radiation power for the grounded antenna at the edge of the wheel, enclosed by the tyre is 0.22 dBm less than the standalone antenna.

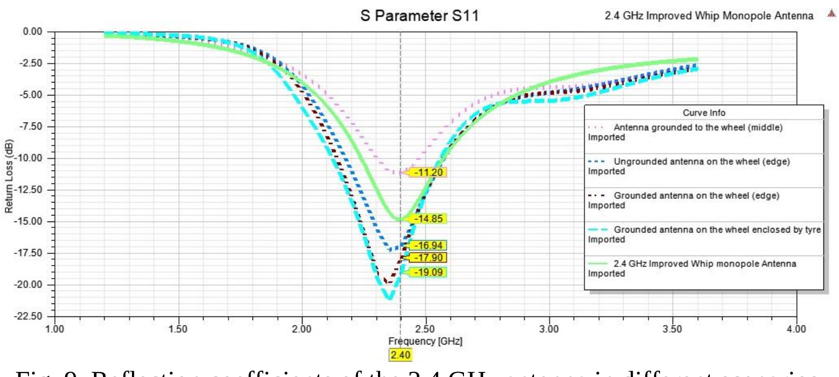


Fig. 9. Reflection coefficients of the 2.4 GHz antenna in different scenarios.

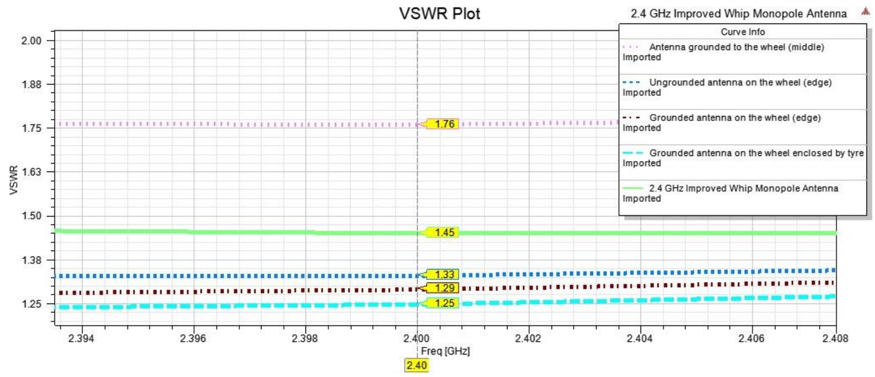


Fig. 10. VSWR of the 2.4 GHz antenna in different scenarios.

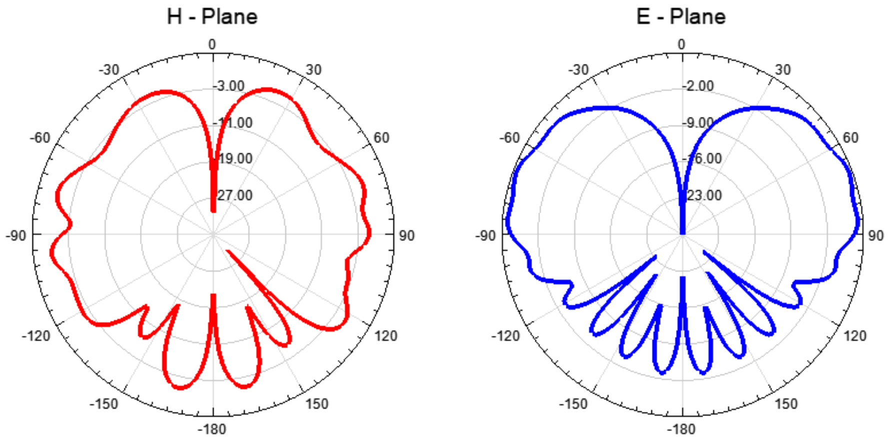
Table 2. Bandwidth of the antenna at different scenarios.

Antenna Configuration	**Bandwidth (GHz)**
Standalone antenna	2.24 – 2.57
Grounded antenna on wheel (middle)	2.30 – 2.47
Ungrounded antenna on wheel (edge)	2.17 – 2.57
Grounded antenna on wheel (edge)	2.14 – 2.57
Grounded antenna on wheel enclosed by tyre (edge)	2.12 – 2.56

Table 3. Radiation power of the 2.4 GHz antenna in different scenarios

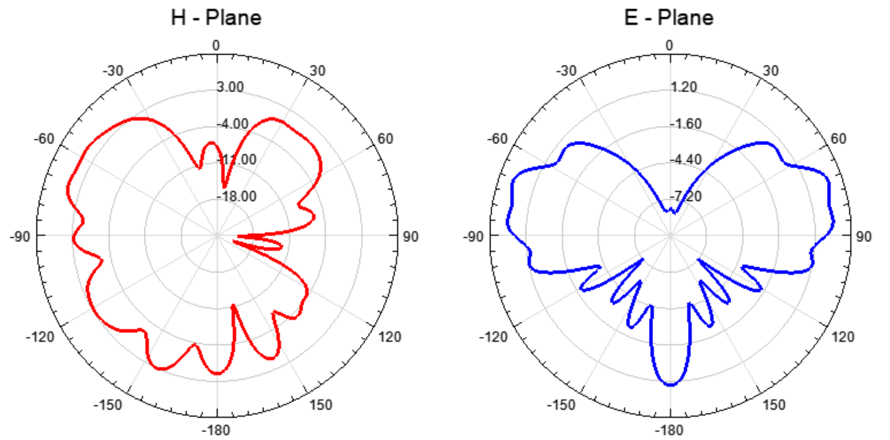
Type	**dB, (Radiated Power)**	**dBm, (Radiated Power)**
Standalone antenna	-0.032216	29.967784
Grounded antenna on wheel (middle)	-0.315549	29.684451
Ungrounded antenna on wheel (edge)	-0.063726	29.936274
Grounded antenna on wheel (edge)	-0.041803	29.958197
Grounded antenna on wheel enclosed by tyre (edge)	-0.25237	29.74763

The 2D radiation pattern and the 3D far-field gain of the antenna are shown in Fig. 12, while Fig. 13 shows the overlay of the far-field gain antenna on the wheel alone and wheel enclosed by a tyre. The Antenna radiation pattern gives the spatial orientation of the antenna. It gives the relative field strength received by or transmitted from the antenna [7]. Fig. 11a shows that the antenna radiates almost uniformly in all directions above the ground plane when placed in the middle of the wheel, while the region below the ground plane shows a non-uniform radiation pattern. Comparing Fig. 11a with Fig. 8 shows the influence of the wheel on the antenna's radiation pattern. There was a complete difference between the radiation pattern of the standalone antenna and that of the antenna placed on the wheel. Fig. 11b to Fig. 11d shows the radiation pattern of the antenna with no contact on the wheel (edge), with contact on the wheel (edge) and with contact on the wheel (edge) enclosed by a tyre. They all show a similar radiation pattern with the field strength more in the direction outside the wheel. For the gain of the antenna shown in Fig. 12, it was observed that there were variations in the antenna's gain from one setting to another. The antenna positioned in the middle of the wheel has a gain of 34.8 dBm, as shown in Fig. 12a. Fig. 12b shows a gain of 35.9 dBm for the antenna with no contact on the wheel at the edge. While for the antenna ground to the wheel at the edge, its gain was 36.1 dBm depicted in Fig. 12c. Lastly, the gain of the antenna grounded to the wheel and enclosed by a tyre was surprisingly higher than the other configurations which were similar to the works of [12, 16]. Its gain was 37.0 dBm, as seen in Fig. 12d.



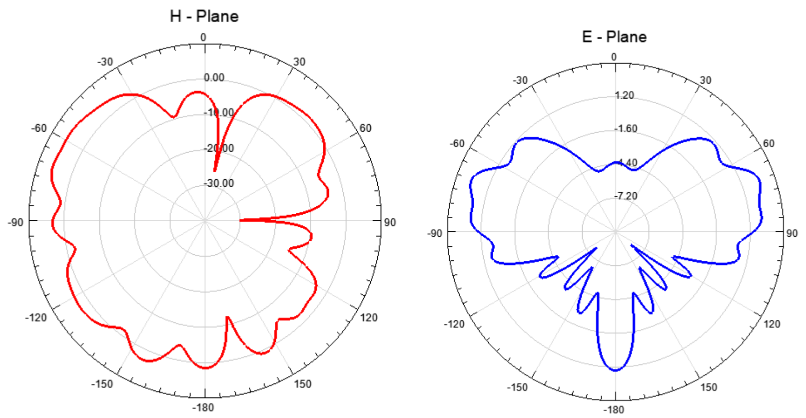
(a) (b)

The grounded antenna on the wheel (centre).



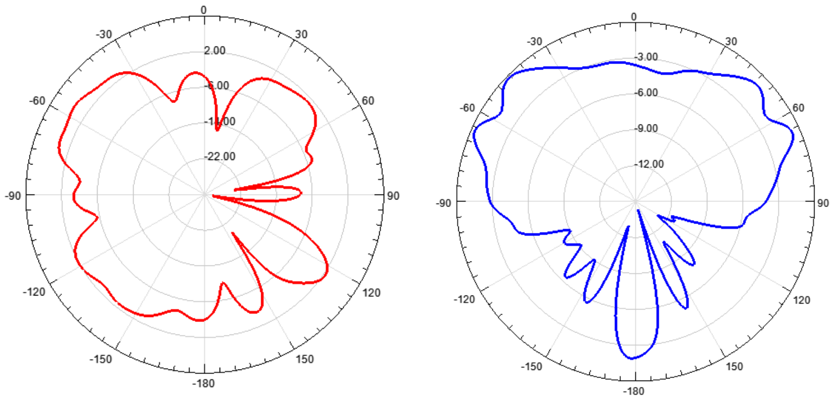
(a) (b)

The ungrounded antenna on the wheel (edge).



(a) (b)

The grounded antenna on the wheel (edge).

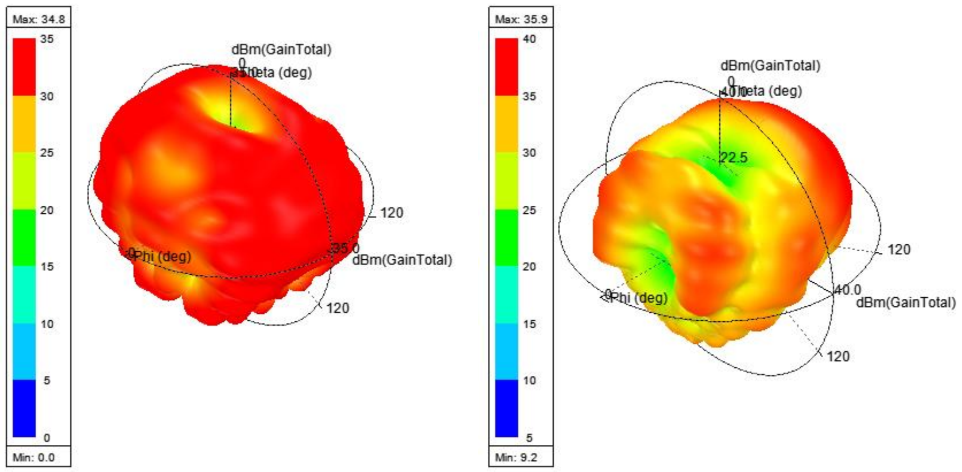


(a) (b)

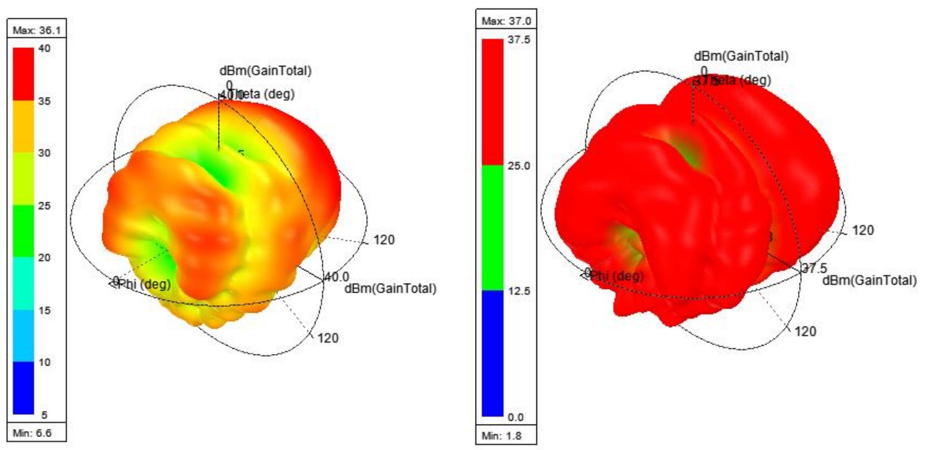
The grounded antenna on the wheel enclosed by the tyre.

Fig. 11. 2D radiation pattern of the antenna in different configurations:

(a) H – Plane (b) E – Plane.

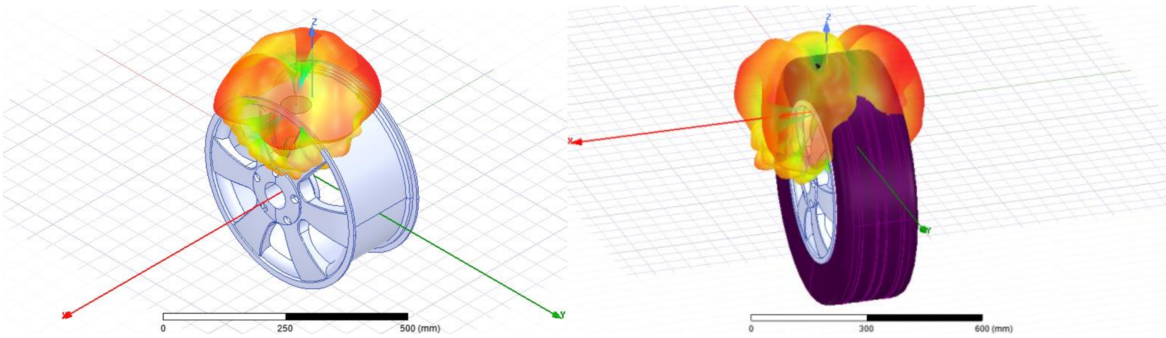


(a) Antenna grounded to the wheel (centre) (b) Antenna with no contact to the wheel (edge)



(c) Antenna grounded to the wheel (edge): (d) Antenna grounded to the wheel enclosed by the tyre

Fig. 12. 3D gain of the antenna in various scenarios.



(a) (b)

Fig. 13. Overlay of the far-field radiation on the antenna with contact on the:
(a) wheel; (b) wheel enclosed by the tyre.

4. CONCLUSION

Comparison of the reflection coefficients and the VSWR of the antenna in different scenarios shows that the antenna performs differently. The standalone antenna has good reflection coefficients and VSWR. When the antenna was placed on the wheel, its properties changed. For the antenna in the middle of the wheel, the reflection coefficient and VSWR at 2.4 GHz were 11.20 dB and 1.76 respectively. While the antenna at the edge with contact, enclosed by a tyre had a reflection coefficient and VSWR of –19.09 dB and 1.25 respectively. It shows that the tyre surprisingly enhanced the far-field performance of the antenna. These results show that the TPMS antenna should be placed at the edge of the wheel and it should make contact with the wheel for effective propagation of signals from inside the tyre to the dashboard of the vehicle. The radiation pattern of the standalone antenna was greatly influenced by the wheel but it had a similar pattern when the antenna position on the wheel was varied with only slight variations. The gain of the standalone antenna was 35.6 dBm which decreased to 34.8 dBm when the antenna made contact with the wheel at the middle. However, the gain increased to 37 dBm when the antenna made contact with the wheel at the edge enclosed by the tyre showing that the tyre did not degrade the antenna's gain. The bandwidth of the antenna also increased from 0.3 GHz for the standalone antenna to 0.44 GHz for the antenna with electrical contact with the wheel at the edge enclosed by a tyre. These simulation results show the impact of the wheel and tyre on the antenna's reflection coefficients, VSWR, gain and bandwidth. It was observed that the performance of the antenna improves significantly when the antenna made contact with the wheel. It shows clearly that in placing a TPMS antenna on the wheel, it should be by the edge with contact to the wheel. Also, the tyre did not degrade the far-field gain of the antenna.

Funding: This work was supported by the Tertiary Education Trust Fund (TETFund).

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