Research Article

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Design and analysis of a 2.4 GHz whip antenna for tyre pressure monitoring system

Abstract

This paper presents the performance analysis of a quarter-wave monopole antenna radiating at a frequency of 2.4 GHz. Two antenna models were proposed. The whip monopole antenna (WMA) at length l-equal to $\lambda/4$, and the improved whip monopole antenna (IWMA) at a length l slightly less than $\lambda/4$. To get the IWMA, the length of the antenna was gradually reduced by a factor of 0.25 mm until the optimum length of the antenna was achieved. The antennas were modelled and analyzed using a 3D electromagnetic solver known as HFSS. Simulation results show that the IWMA has excellent performance over the WMA. The WMA resonated at 2.3 GHz, with a reflection coefficient of -12.36 dB, a VSWR of 1.65, an impedance bandwidth of 2.17–2.47 GHz and a gain of 5.9 dB. But by slightly reducing the length of the monopole antenna, the IWMA resonated at 2.4 GHz. The reflection coefficient of the IWMA was 1.99 dB better than the WMA. The IWMA had a wider impedance bandwidth than the WMA. It was only in the antenna gain that the WMA was better. The IWMA can function as a tyre pressure monitoring system (TPMS) antenna because it is compact and have excellent antenna parameters.

Keywords: Whip monopole antenna, TPMS, VSWR, reflection coefficient, impedance bandwidth

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Introduction

Tyre pressure monitoring system (TPMS) has become an essential requirement in vehicles in some parts of the world. Starting from 2007, it has become mandatory for all passenger cars in the US to have TPMS installed.[1–3] In Europe, it was compulsory since November 2014 for all passenger cars to have a TPMS.[4] Korea had also made TPMS compulsory since in January 2013.[5,6] The mandatory use of TPMS in China occurred in 2020. Other countries around the globe are also seeking to make TPMS mandatory.

TPMS enables the driver to know the pressure and sometimes the temperature of the tyre. The use of TPMS helps the vehicle to have proper inflation pressure which increases tyre lifespan, improves fuel economy and ensures better vehicle handling.[7] There are two types of TPMS: Direct and indirect TPMS. Indirect TPMS (iTPMS) does not require a pressure sensor to monitor tyre pressure. It uses other sensory devices in the vehicle to determine the tyre pressure. Although it is cost-effective, it is less accurate.[7,8] Direct TPMS requires a pressure sensor module fitted to the wheel or tyre to monitor tyre pressure. It is a more accurate method of monitoring tyre pressure and mainly uses a wireless link to transmit pressure information.[9–16] TPMS RF bands for America, Europe, and the rest of the world are 315 MHz, 433 MHz, and 2.4 GHz, respectively.[17–19]

To effectively transmit and receive TPMS signals, antennas are required. An antenna is a metallic device for radiating or receiving radio waves.[20] Different types of antennas have been designed for TPMS applications such as whip, loop, helix, and some other modified antennas. Each of these antennas had been investigated to determine its efficiency. He S et al.[21] designed and fabricated a novel compact printed antenna radiating at 315 MHz. Genoyesi S et al.[22] developed a double–loop antenna that radiates at 433 MHz and 868 MHz. Sun BH et al.[23] used planar structures and microstrips to implement a 433 MHz receiver antenna that operates in two modes: a top-loaded monopole and a planar dipole close to the conducting plane. Zeng H et al.[24] investigated the radiation efficiency of a loop and whip antenna at 315 MHz. They observed that the whip antenna has a higher radiation efficiency compared to the loop antenna. Zeng H et al.[25] investigated the radiation efficiency of a loop, whip, and helix antenna. They found out that the Helix antenna exhibits the best performance of all three if not for the complexity and cost of implementation. Dinh NQ et al.[26] analyzed the radiation pattern of a normal mode helical antenna at 915MHz. The gain and radiation efficiency of a dipole and loop antenna was investigated by Grosinger J et al.[27] Their results show that the dipole performed better than the loop antenna with a higher gain and radiation efficiency. From these works, it was observed that the whip antenna performs better than the loop antenna. However, none of these researchers addressed the performance of a whip antenna radiating at 2.4 GHz, which is the frequency of operation of TPMS outside America, and Europe. One major challenge of the antenna radiating at 315 MHz or 433 MHz is that they are not self-resonant because they are electrically small.[25,28] But at 2.4 GHz, it is much easier to develop a resonant antenna while still maintaining the small size requirement of a TPMS.

This paper investigated the performance of a whip antenna radiating at a frequency of 2.4 GHz. A whip antenna is a form of monopole antenna made up of a straight wire. Several papers have analyzed the performance of whip antennas used for TPMS at a frequency of 315 MHz or 433 MHz.[28–31] However, the performance of whip antenna radiating at a frequency of 2.4 GHz which is the radiation frequency for TPMS applications outside America, Europe and Asia, lacks in the literature. Hence the goal of this paper is to design and analyze a whip antenna radiating at a 2.4 GHz frequency that can be applied as a TPMS antenna. TPMS antenna can be trace elements in a PCB (printed circuit board) or a separate metallic structure.[25] The latter is the most commonly used type and thus, was adopted for this research. A whip monopole antenna was proposed, simulated, and analyzed using a 3D electromagnetic solver, called HFSS (high-frequency structure simulator). The proposed model was then improved upon to radiate at the frequency of interest. Section 2 describes the methodology of the research. It highlights the detailed design of the whip antenna and its improved version. The design parameters of the antenna to achieve the resonant frequency were examined in section 2 as well. The simulation results and analysis of both antennas were presented in section 3. The parameters analyzed to determine the efficiency of the antennas were the gain, reflection coefficient, impedance bandwidth, and VSWR (voltage standing wave ratio). Finally, section 4 presents the conclusion of the paper.

Whip antenna design and simulation

This section described the methodology used for the study. A software known as HFSS (high-frequency structure simulator) was used to simulate the antennas. Two whip monopole antennas were designed and presented. The first antenna was modelled as a quarter-wavelength $\lambda/4$ monopole $(l = \lambda/4)$ referred to as a whip monopole antenna (WMA). The parameters of the design are given in Equations 1-3.

Equation 1 shows the wavelength of the antenna.

$$\lambda = \frac{c}{f} \quad (1)$$

where, c = velocity of light given as 3×10^8 m/s

f = frequency chosen as 2.4 GHz

Substituting these parameters into Equation 1 gives the value of $\lambda = 0.125\ m$

$$\lambda = \frac{c}{f} = \frac{3\times10^8}{2.4\times10^9} = 0.125m$$

The length l of the monopole antenna is shown in Equation 2.

$$l = \frac{\lambda}{4} \quad (2)$$

$$l = \frac{\lambda}{4} = \frac{0.125}{4} = 0.03125\ m = 31.25\ mm$$

Equation 3 was used to compute the radius r of the monopole. According to Balanis CA,[20] the radius of wire antennas is typically less than the $\frac{\lambda}{200}$ So, in this design, a value less than $\frac{\lambda}{200}$ was chosen as shown in Equation 3.

$$r = \frac{\lambda/4}{60} \quad (3)$$

$$r = \frac{\lambda/4}{60} = \frac{\lambda}{240} = 0.52\ mm$$

Simulating the antenna

Design equations 1-3 were used to model the antenna in HFSS. There are existing models in HFSS that can be imported for analysis. However, for specific designs, it is best for the user to model the antenna to have greater flexibility in setting the antenna parameters and analyzing its performance. HFSS uses adaptive tetrahedral mesh for the electromagnetic structure to ensure high precision of simulation results. Hence, HFSS was chosen for this design. The first step was to model the antenna as a cylindrical shape by setting the radius and height of the antenna. Then material assignment was done. The antenna material was chosen as copper.

After creating the model, boundary conditions were set. The boundary conditions were in two modes: excitations and surface approximations. Before the excitation, a rectangular port was created at the base of the antenna. A port allows energy to flow in and out of the antenna structure. The port was excited as a lumped port since it was a single-mode transmission. The antenna port was assigned $\lambda/4$ to match the transmission line.

After the excitation, surface approximation or radiation boundary was done. Accurate simulation results are achieved when the radiation boundary is set to an airbox placed at least one-quarter wavelength at the radiation frequency from the antenna.[32–35] Whyte GMW[36] also mentioned that the boundary should follow the shape of the antenna. Thus, the radiation boundary was chosen as a cylindrical shape at $\lambda/4$ away from the antenna. The next stage was to set the solution frequency and the frequency sweep. The solution frequency was set to 2.4 GHz at 20 maximum passes with at least three minimum converged passes. An interpolative frequency sweep with 101 points from 1.2 GHz to 3.6 GHz was set up. After that, the structure was validated and solved. Figure 1 shows the monopole antenna, its excitation and the meshed model in the radiation boundary. The numbers of elements in the meshed model are 9601 and 2088 for the medium and antenna, respectively.

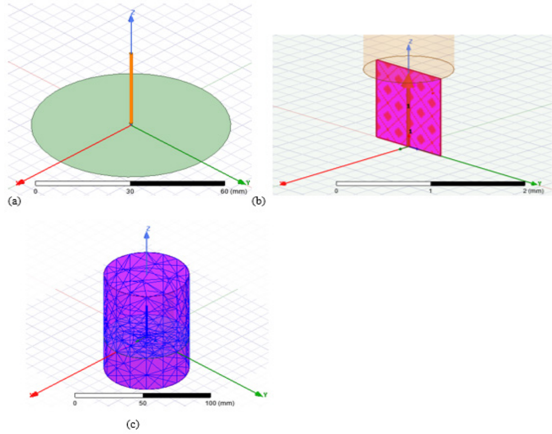

Figure 1 Whip monopole antenna (WMA) showing (a) model (b) lumped port excitation (c) meshed model in radiation boundary

The second monopole antenna was modelled with a length l slightly less than $\lambda/4$, referred to as the improved whip monopole antenna (IWMA). According to Balanis Ca,[20] resonance for a monopole antenna is achieved for a length (l) somewhat less than $\lambda/4$. Different sizes of the antenna were investigated to determine the optimum point where the antenna could radiate at the resonant frequency. To achieve this, the length of the antenna was gradually reduced in steps of 0.25 mm until Equation (4), was arrived at which gives the length of the antenna that resonated at 2.4 GHz.

Figure 2 shows the monopole antenna and a meshed model of the antenna in the radiation boundary. The numbers of elements in the meshed model are 10293 and 2355 for the medium and antenna, respectively.

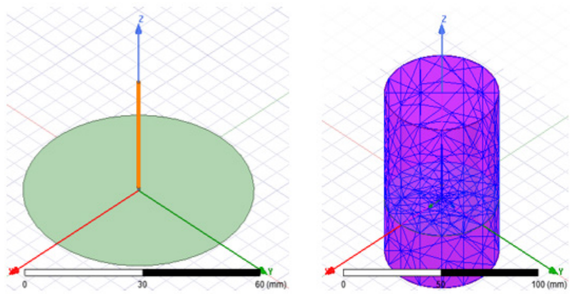

Figure 2 Improved whip monopole antenna (IWMA) showing (a) model (b) meshed model in radiation boundary

Equation (4) shows the length l_0 of the improved monopole antenna.

$$l_o = \frac{\lambda}{4} - 0.00125 = 0.03\ m = 30.00\ mm \quad (4)$$

Result and discussion

The simulation results for the WMA are shown in Figures 3-5. Figure 3 shows the reflection coefficient of the antenna, which resonated at 2.3 GHz with a bandwidth of 2.17 – 2.47 GHz. The result indicates that the antenna can operate within the bandwidth requirement of the Institute of Electrical and Electronics Engineers (IEEE 802.15.4) standard. The frequency band of IEEE 802.15.4 is 2.4–2.4835 GHz.[35] The acceptable reflection coefficient for an antenna is less than -10 dB and it is at -10 dB the impedance bandwidth is measured.[20,36] The acceptable VSWR (voltage standing wave ratio) lies between 1< VSWR< 2.[29] The reflection coefficient for the antenna at 2.4 GHz is -12.36 dB, which is less than -10 dB. At the same time, the VSWR is 1.65, which is less than 2, as shown in Figure 4. The radiation pattern, as shown in Figure 5, conforms to the radiation pattern of a standard monopole antenna.[20] The far-field gain of the antenna is 5.9 dB, as shown in Figure 6.

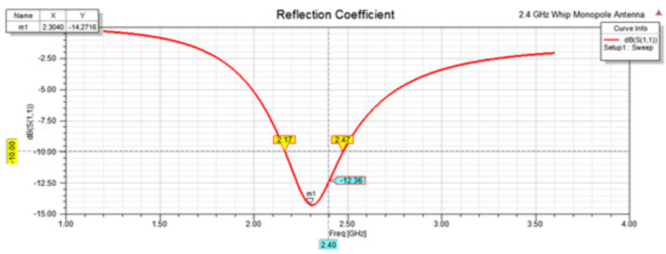

Figure 3 Reflection coefficient of the WMA

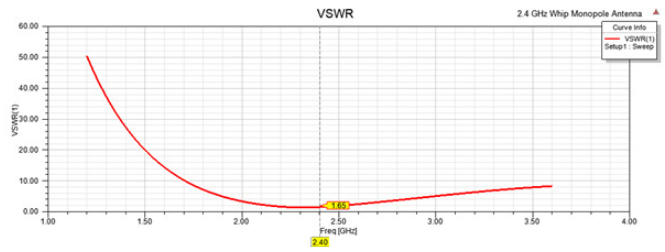

Figure 4 SWR of the WMA

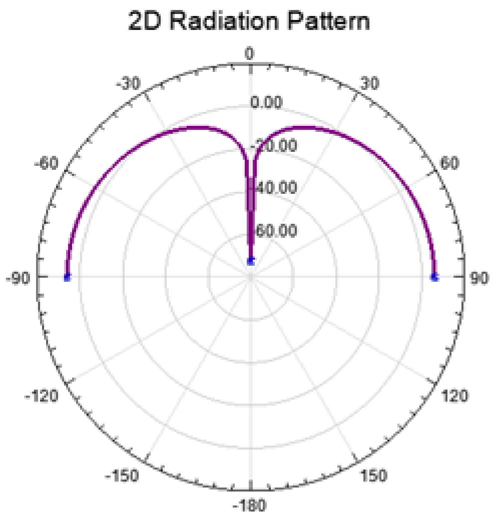

Figure 5 The 2D radiation pattern of the WMA

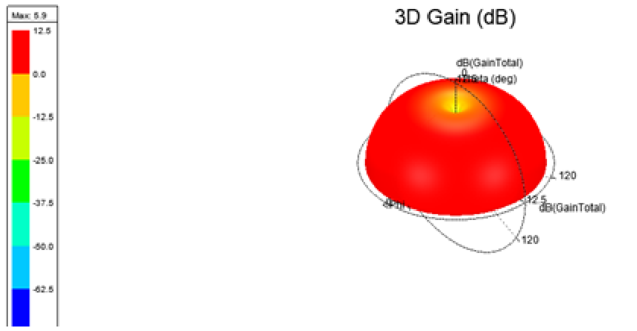

Figure 6 The 3D radiation pattern of the WMA

The comparative reflection coefficients are shown in Figure 7. The results of the IWMA are shown in Figure 8-11. Figure 8 gives the reflection coefficient of the antenna as -14.85 dB with an impedance bandwidth of 2.24–2.57 GHz. The resonant frequency of the antenna was 2.4 GHz. The VSWR, as shown in Figure 9, is 1.44. The value lies within the acceptable range for VSWR. Figure 10 shows the 2D radiation pattern, while Figure 11 indicates that the antenna has a far-field gain of 5.6 dB.

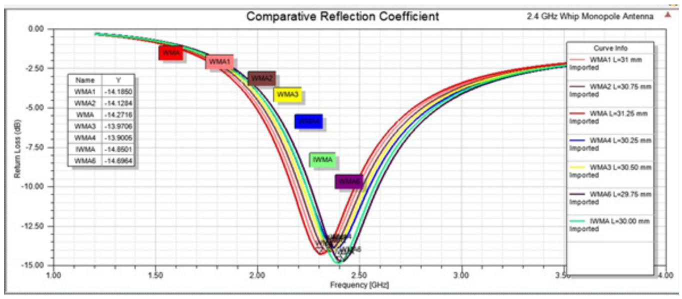

Figure 7 Comparative reflection coefficients of the seven antennas

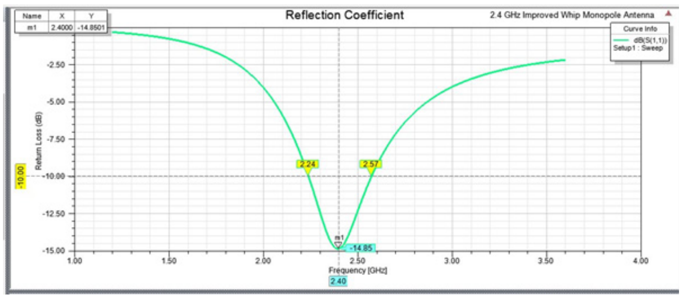

Figure 8 Reflection coefficient of the IWMA

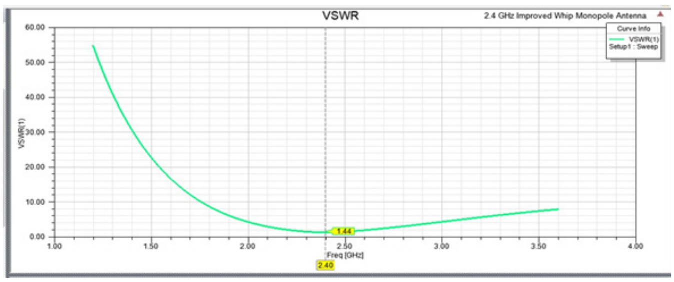

Figure 9 VSWR of the IWMA

An improvement of -2.49 dB was observed in the reflection coefficient of the IWMA over the WMA. The resonant frequency of the antenna also shifted from 2.3 GHz in the WMA to 2.4 GHz in the IWMA. The antenna was designed to radiate at 2.4 GHz, which was achieved by the IWMA and not the WMA.

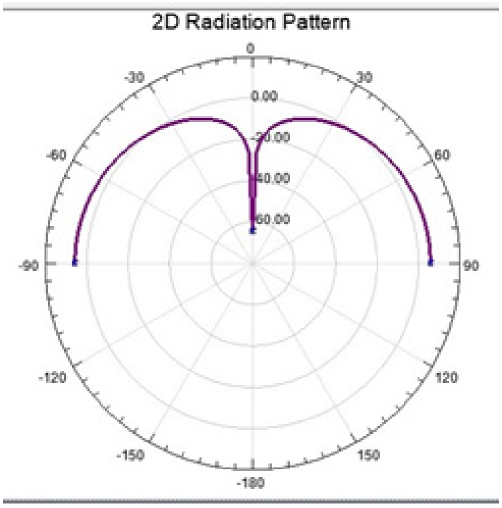

Figure 10 2D radiation pattern of the IWMA

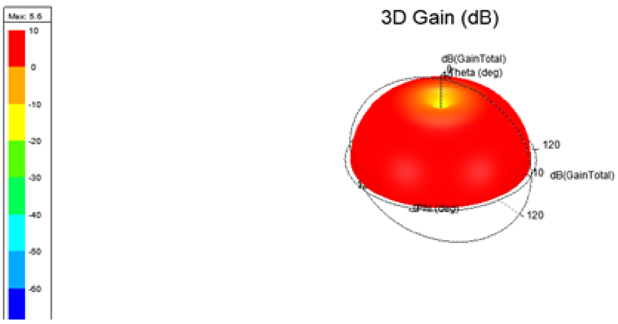

Figure 11 3D radiation pattern of the IWMA

The impedance bandwidth moved from 2.17-2.47 GHz for the WMA to 2.24-2.57 GHz for the IWMA with a bandwidth improvement factor of 10% as shown in Equation 5.

$$BW_{WMA} = (2.47 - 2.17)\ GHz = 0.3\ GHz$$

$$BW_{IWMA} = (2.57 - 2.24)\ GHz = 0.33\ GHz$$

$$BW\ improvement\ factor = \frac{BW_{IWMA} - BW_{WMA}}{BW_{WMA}} = \frac{(0.33 - 0.3)}{0.3} = 0.1 \quad (5)$$

Again, this was a significant improvement factor as the bandwidth was not only wider but covered the bandwidth requirement for IEEE 802.15.4 standard better. According to He S et al.[21], because of the variable and complex environment of TPMS, the impedance bandwidth should be wide enough to prevent the operating frequency from shifting away from the bandwidth. The IWMA satisfies this requirement better than the WMA. It was observed that the IWMA has a wider bandwidth than the WMA. This wider bandwidth would ensure that the operating frequency of 2.4 GHz would never shift away from the bandwidth. Since this is an important requirement for a TPMS antenna, it shows that the IWMA would function well as a TPMS antenna.

Also, the VSWR of the IWMA, which is 1.44, is better than the 1.65 of the WMA. The IWMA was also slightly smaller than the WMA, further reducing the size of the antenna which is an essential requirement for a TPMS antenna. However, there was a slight reduction in gain from 5.9 dB for the WMA to 5.6 dB for the IWMA. These results indicate that the IWMA has an improved performance over the WMA and thus can be deployed as a TPMS antenna. Table 1 gives the performance summary of the two antennas.

Table 1 Performance parameters of the two developed antennas

Parameters	WMA	IWMA
Resonant frequency	2.3 GHz	2.4 GHz
Reflection coefficient	-12.36 dB	-14.85 dB
Impedance bandwidth	2.17-2.47 GHz	2.24-2.57 GHz
VSWR	1.65	1.44
Gain	5.9 dB	5.6 dB

From the simulation done we found out that using the quarter-wavelength ($\lambda / 4$) monopole ($l = \lambda / 4$), it was difficult to achieve the optimum performance of the 2.4 GHz antenna. The antenna did not resonate at the desired frequency (2.4 GHz) and also did not cover the operation frequency of IEEE 802.15.4. To achieve optimum performance the length of the antenna was reduced gradually until a length of antenna that radiated at the desired frequency was achieved. This shows that for a monopole antenna to radiate at the radiation frequency and also have better bandwidth, it is necessary to reduce the length of the antenna slightly. Antennas used for TPMS purposes must have wider bandwidth to be able to function properly in the complex and ever-changing environment of the tyres where they are deployed. We have designed and simulated such an antenna in this research.

Significantly, the improved wire monopole antenna performed better in terms of the reflection coefficient and the VSWR. Reflection coefficients and VSWR tells how much of the power from an antenna is radiated and how much is reflected back. For better performance the reflection coefficient should be much less than -10 dB. It was observed that the IWMA had a better reflection coefficient compared to the WMA. It further proves that reducing the size of the antenna did not alter the reflection coefficient and the VSWR. The designed antenna can efficiently radiate at 2.4 GHz frequency and can be used in applications as TPMS antenna.

Conclusion

This research is an important step towards developing an antenna that can be used in TPMS applications. Antennas help in radiating the signal from the tyre to an appropriate display system in the vehicle. Designing the antenna to achieve efficient radiation of the tyre pressure is key towards detecting and monitoring the tyre pressure status of each tyre. A wire monopole antenna radiating at 2.4 GHz has been designed and analyzed using HFSS. The wire monopole antenna (WMA) was designed as a wavelength ($\lambda / 4$) monopole. Although it had a good impedance bandwidth and VSWR, the antenna did not resonate at the desired frequency of 2.4 GHz. The bandwidth of the WMA also did not cover the upper limit of the IEEE 802.15.4 standard bandwidth requirement (2.4-2.4835 GHz). The length of the monopole antenna was then reduced slightly to get an improved wire monopole antenna (IWMA). The IWMA had excellent performance over the WMA. It resonated at 2.4 GHz and had an impedance bandwidth of 2.24-2.57 GHz, which covers the bandwidth requirement of IEEE 802.15.4 standard better and an improved reflection coefficient and VSWR of –14.85 dB and 1.44 respectively. The IWMA can be used in applications requiring a 2.4 GHz resonant frequency such as a TPMS antenna. The IWMA is more compact compared to the WMA, which is a primary requirement for a TPMS antenna. But, the gain of the IWMA was slightly less than that of the WMA. However, the IWMA was the most preferred option for the TPMS antenna since it resonated at the desired frequency of 2.4 GHz with a broader bandwidth than the WMA. The presented antenna is compact enough to function as a TPMS antenna. The performance of the antenna was satisfactory.

Acknowledgments

None.

Conflicts of interests

The authors declare no conflicts of interest.

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