Investigation of Loop and Whip Antennas in Tire Pressure Monitoring Systems

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Abstract—**Tire Pressure Monitoring System (TPMS) modules that are mounted in tires are usually powered by batteries that cannot be replaced or recharged. Since most of the power consumed by these modules is due to the wireless communication, antenna efficiency is a primary concern. TPMS modules typically employ antennas that are much smaller than a wavelength at the frequency of operation. Peak efficiencies are obtained by antennas with a high quality factor, but high-Q antennas are susceptible to detuning caused by environmental factors beyond the control of the TPMS designer. This paper investigates the performance of loop- and whip-antenna designs commonly used in TPMS applications, and explores the environmental factors that affect the radiation efficiency and quality factor of these antennas.**

Keywords-TPMS; antennas, Q-factor

I. INTRODUCTION

Most vehicles with direct Tire Pressure Monitoring Systems (TPMS) employ battery powered sensors that are mounted in each tire and communicate wirelessly with a central receiving unit located behind the dashboard. The batteries in these sensors cannot be replaced; therefore it is necessary to replace the entire sensor module when the battery is too weak to provide a reliable signal. A number of functional issues have been documented with these systems, including false low-pressure warnings that occur when the TPMS signal is lost or interfered with. One of the most important issues faced by a TPMS designer is to choose an antenna design that ensures adequate sensor transmission/reception in the vehicle while using the limited sensor power efficiently.

S. He [1] introduced a novel compact printed antenna, and B.H. Sun [2] proposed a polarization-diversity antenna for TPMS applications. Y. Leng [3] proposed a wheel antenna and analyzed its impedance and gain pattern. N. Q. Dinh [4] analyzed the radiation pattern of a small normal mode helical antenna mounted on a wheel. However, these researchers did not address the antenna efficiency and quality factor, which are important parameters for analyzing tire sensor transmission and the power budget of the system.

The physical size of a TPMS sensor module is restricted and is generally much smaller than the operational wavelength. The TPMS antennas used in the North American market generally operate at 315 MHz ($\lambda \sim 1$ meter). They are usually not structurally self-resonant at this frequency and have a low radiation resistance and a large reactance. In order to improve efficiency, TPMS antennas utilize a matching network to cancel the reactance and transform the low radiation resistance to a larger input resistance.

Although matching networks can help to reduce the mismatch loss, any loss in the antenna structure, or in the matching network itself, can significantly reduce the overall transmission efficiency. Furthermore, for electrically small antennas, the value of the quality factor is high due to the low radiation resistance and high reactance. Higher quality factors imply narrower antenna bandwidths, making the antenna more difficult to match and more easily influenced by surrounding objects. Therefore, high radiation efficiencies and low quality factors are required.

Metal wheel rims can play an important role in a TPMS antenna's radiation efficiency. In order to evaluate the performance of any particular TPMS antenna design, it is important to consider the effect of the wheel rim.

This paper investigates the performance of generic antenna designs for TPMS applications. The radiation efficiency and quality factor of two simple antenna structures: a small loop and a whip antenna mounted on the rim inside a tire are evaluated. Based on the evaluation results, potential improvements for reducing the quality factor of the whip antenna to improve overall performance are discussed. In order to determine the impact of the wheel rim on a TPMS antenna's performance, three cases are discussed: an antenna without a rim, an antenna near a metal rim, and an antenna in electrical contact with a metal rim. The influence of the rim dimensions on antenna performance is also discussed. The dimensions of the rims selected in this paper have diameters from 14 inches to 18 inches and widths from 175 mm to 315 mm. Finally, a passive matching network is briefly described, and its influence on an antenna's total radiation efficiency is evaluated.

II. EVALUATION OF COMMON TPMS ANTENNAS

A TPMS module including both RF circuitry and an antenna must be implemented in a limited volume (e.g. 63 mm x 30 mm x 10 mm without encapsulation). The antenna may be a trace on a circuit board or a separate metal structure [5]. The latter antenna type will be addressed in this paper. Three different cases are discussed.

A. Antenna structure without rim (Case 1)

The most common TPMS antenna designs consist of a piece of metal that extends above the surface of a printed circuit board (PCB), as shown in Figure 1. These antennas are

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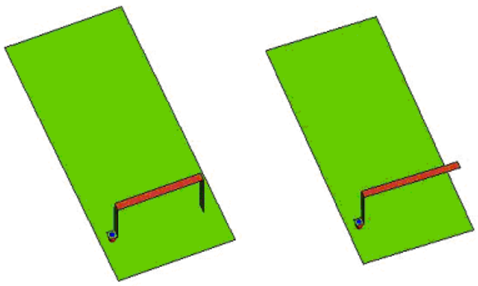
driven relative to a metal plane on the board and the far end is either left open (whip antenna) or shorted to the ground plane of the PCB (loop antenna). For the loop and whip antennas discussed in this paper, the height of the antenna above the plane is 10 mm and the length of the antenna (along the short edge of the PCB) is 20 mm. Both antennas are implemented close to the edge of the PCB in order to keep them away from the other circuitry.



(a) (b)

Figure 1. a) loop antenna, and b) whip antenna.

B. Antenna above rim with no electrical contact (Case 2)

In order to analyze these two types of antennas in their intended environments, a metal rim may be included in the model. In this case, as shown in Figure 2, the rim is 6 mm below the PCB. The rim geometry is based on an actual wheel structure. Its width ranges from 175 mm to 315 mm and its diameter from 14 inches to 18 inches. The PCB is placed near the location of the tire valve.

Figure 2. Model for loop antenna above a metal rim

C. Antenna electrically connected to a metal rim (Case 3)

Figure 3 illustrates an antenna located above the rim with electrical contact between the rim and the ground plane of the PCB. The model geometries are the same as in Case 2 except that a conducting wire, with a length of 6 mm and diameter of 0.4 mm, makes electrical contact between the rim and the PCB ground plane.

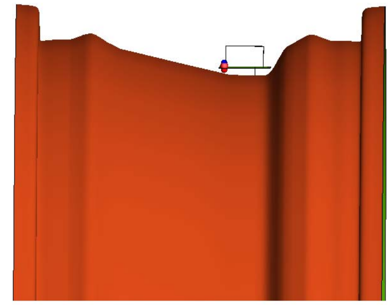


Figure 3. Model for loop antenna electrically connected to metal rim.

D. Overall performance of loop and whip antennas

The input impedances and radiation efficiencies at 315.0 MHz for both the loop antenna and whip antenna in each of the three configurations described above were calculated using full wave simulations [6]. The input impedance at 315.2 MHz was also obtained in order to calculate the quality factor as [7]:

$$Q(\omega_0) \approx \frac{\omega_0}{2R(\omega_0)}\left|\frac{Z_{in2} - Z_{in1}}{\Delta\omega}\right|. \quad (1)$$

Results for the antenna and PCB structures without the rim (Case 1) are shown in Table I. In this case, the loop antenna has a very low efficiency and a small Q-factor. The whip antenna has a relatively high efficiency but a larger Q-factor. Results for the antenna structures above a rim (Case 2) are listed in Table II. When the metal rim is included in the simulation, the efficiencies for the loop antenna are greatly enhanced and the Q-factors are slightly decreased no matter what the rim dimensions are. The whip antennas exhibit reduced efficiencies and higher Q-factors. Connecting the PCB ground plane to the rim (Case 3) yields the results in Table III. When the conducting rim is electrically connected to the PCB ground, both Q-factors and efficiencies are slightly improved for the whip antenna, while remaining relatively unchanged for the loop antenna.

TABLE I. CALCULATED PARAMETERS FOR LOOP AND WHIP ANTENNAS

Antenna Type	Z_{in1} (ohms)	Z_{in2} (ohms)	Q	ε_{cd} (%)
Loop	0.07864 + j62.9475	0.07868 + j62.9901	427	5.2
Whip	0.22717 - j806.619	0.22745 - j806.084	1854	87.7

Compared to the loop antenna, the much higher efficiency of the whip antenna makes it more attractive for TPMS applications, if its Q-factor can be controlled. When the Q-factor is too high, minor changes in the resonant frequency of the antenna can have a significant effect on the antenna performance.

TABLE II. CALCULATED PARAMETERS FOR LOOP AND WHIP ANTENNAS NEAR RIMS OF VARIOUS SIZES

Antenna Type	W/D (mm/inch)	Z_{in1} (ohms)	Z_{in2} (ohms)	Q	ε_{cd} (%)
Loop antenna	245/17	0.08580 + j62.2653	0.08586 + j62.3074	386	13.0
	245/14	0.08790 + j62.2902	0.08797 + j62.3324	378	15.1
	245/18	0.08536 + j62.2592	0.08542 + j62.3014	389	12.6
	315/18	0.08885 + j62.2602	0.08892 + j62.3023	373	16.0
	175/14	0.08388 + j62.3009	0.08393 + j62.3431	396	11.0
	175/18	0.08247 + j62.2696	0.08252 + j62.3118	403	9.5
	315/14	0.09118 + j62.2884	0.09125 + j62.3306	365	18.1
Whip antenna	245/17	0.11392 - j783.909	0.11398 - j783.389	3595	75.0
	245/14	0.14635 - j784.672	0.14627 - j784.151	2803	80.6
	245/18	0.11388 - j783.748	0.11400 - j783.229	3589	75.0
	315/18	0.11621 - j783.659	0.11633 - j783.14	3517	75.5
	175/14	0.15453 - j784.298	0.15437 - j783.779	2645	81.6
	175/18	0.10296 - j783.383	0.10307 - j782.864	3970	72.4
	315/14	0.13614 - j784.584	0.13612 - j784.064	3008	79.1

TABLE III. CALCULATED PARAMETERS FOR LOOP AND WHIP ANTENNAS CONNECTED TO RIMS OF VARIOUS SIZES

Antenna Type	W/D (mm/inch)	Z_{in1} (ohms)	Z_{in2} (ohms)	Q	ε_{cd} (%)
Loop antenna	245/17	0.08623 + j62.4463	0.08629 + j62.4887	387	13.2
	245/14	0.08843 + j62.4908	0.08850 + j62.5332	378	15.4
	245/18	0.08584 + j62.4364	0.08590 + j62.4787	388	12.8
	315/18	0.08952 + j62.4360	0.08960 + j62.4783	372	16.4
	175/14	0.08424 + j62.4922	0.08430 + j62.5346	396	11.2
	175/18	0.08278 + j62.4403	0.08283 + j62.4826	402	9.6
	315/14	0.09184 + j62.4884	0.09191 + j62.5307	363	18.5
Whip antenna	245/17	0.16163 - j763.382	0.16173 - j762.872	2485	78.9
	245/14	0.21098 - j763.992	0.21086 - j763.481	1907	83.9
	245/18	0.15972 - j763.278	0.15990 - j762.767	2519	78.6
	315/18	0.16549 - j763.167	0.16568 - j762.657	2427	79.3
	175/14	0.22189 - j763.271	0.22164 - j762.761	1810	84.7
	175/18	0.14489 - j762.531	0.14505 - j762.021	2772	76.4
	315/14	0.19780 - j763.905	0.19779 - j763.395	2030	82.8

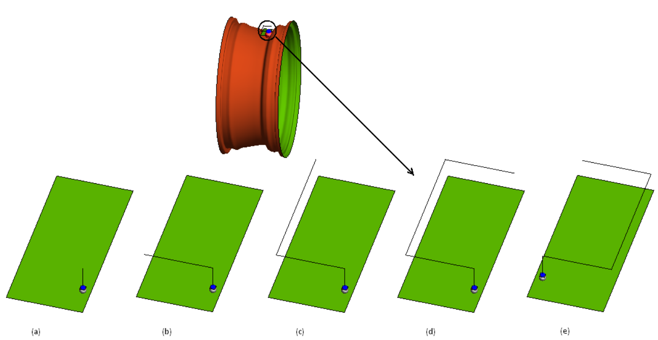


Figure 4. Geometries of different whip antennas.

III. CONTROLLING THE Q-FACTOR OF A WHIP ANTENNA

Considering its higher efficiency, the whip antenna is the more attractive alternative if its Q-factor can be controlled. This section discusses two approaches for controlling the Q-factor of a whip antenna without increasing the volume of the TPMS module. Since the Q-factor and radiation efficiency are worse when the antenna is located near the metal rim, it is better to discuss the proposed approaches when the effect of the rim is accounted for. For the results presented here, the rim has a width of 245 mm and a diameter of 17 inches. Figure 4 shows five whip antennas with geometries that vary from a single straight monopole to an antenna with several bent arms extending to fill the entire volume. The radius of the antenna wire is 0.5 mm.

The calculated radiation efficiency and Q-factors of these 5 antennas are listed in Table IV. It is evident that the Q-factor can be significantly decreased when the antenna structure fills a larger volume. However, when the bent arm is close to the rim edge, the radiation resistance decreases excessively, which makes both the radiation efficiency and the Q-factor worse.

TABLE IV. CALCULATED PARAMETERS FOR DIFFERENT WHIP ANTENNAS

Ant.	Z_{in1} (ohms)	Z_{in2} (ohms)	Q	ε_{cd} (%)
(a)	0.0349829 - j1850.44	0.035 - j1849.26	26563	45.6
(b)	0.120836 - j767.215	0.120917 - j766.706	3317.2	73.7
(c)	0.194157 - j341.603	0.194296 - j341.331	1103.2	68.5
(d)	0.21716 - j258.339	0.217312 - j258.102	859.4	64.7
(e)	0.15512 - j247.468	0.155197 - j247.237	1172.7	49.8

For the antennas above, antenna configuration (d) exhibits the best overall performance regarding Q-factor and radiation efficiency. Without sacrificing much radiation efficiency, the Q-factor of antenna (d) is four times lower than that of antenna configuration (b), the antenna evaluated in the previous section. Based on the results of many simulations, the Q-factor cannot be improved much more than this value without increasing the volume of the TPMS module. Thus other approaches are needed to further reduce the Q-factor. One possible method is electrically connecting the ground plane of the PCB to the metal rim as discussed in the previous section. Another method is to apply a lossy coating to increase the input resistance. Table V lists the computed parameters of antenna configuration (d) employing these methods. Compared to the traditional whip antenna (b), the new antenna (d) electrically connected to the rim and coated with a 0.5-mm thick lossy material (dielectric constant = 2.1, loss factor = 0.01) has a Q-factor 10 times lower, while the radiation efficiency is reduced by less than a factor of 2.

TABLE V. COMPUTED PARAMETERS FOR VARIOUS ANTENNA CONFIGURATIONS

Approaches	Z_{in1} (ohms)	Z_{in2} (ohms)	Q	ε_{cd} (%)
Antenna (b)	0.12084 - j767.22	0.120917 - j766.706	3317	73.7
Antenna (d)	0.21716 - j258.34	0.217312 - j258.102	859	64.7
Connecting rim	0.29588 - j226.96	0.296106 - j226.737	601	70.0
Connecting rim and coating	0.55248 - j199.62	0.55256 - j199.41	299	37.9

Table VI lists the computed parameters for antenna configuration (d) for various rim dimensions when the rim is electrically connected to the PCB ground and the lossy coating material is applied. It is important to note that the lossy coating reduces the Q-factor by reducing the transmitted power at the resonant frequency. Lossy materials do not increase the power transmitted at any frequency, but can be used to provide a more stable input impedance.

TABLE VI. COMPUTED PARAMETERS FOR ANTENNA (D) WHEN THE RIM IS ELECTRICALLY CONNECTED AND COATING IS APPLIED FOR VARIOUS RIM DIMENSIONS

W/D (mm/inch)	Z_{in1} (ohms)	Z_{in2} (ohms)	Q	ε_{cd} (%)
245/17	0.552479 - j199.62	0.55256 - j199.41	299	37.9
245/14	0.632894 - j200.009	0.63266 - j199.798	263	45.8
245/18	0.551881 - j199.459	0.55209 - j199.248	301	37.8
315/18	0.584032 - j199.477	0.58435 - j199.267	283	41.3
175/14	0.617142 - j197.89	0.61670 - j197.681	267	44.4
175/18	0.504637 - j197.448	0.50475 - j197.238	328	32.0
315/14	0.635245 - j199.964	0.63524 - j199.753	262	46.0

IV. MATCHING NETWORK

The radiation resistance of extremely small antennas is very low, even for whip antennas where the efficiency can be as high as 90 percent. Matching the antenna input impedance to the transmitter output in order to minimize the mismatch losses is a significant challenge. The complexity is increased when the dissipative losses from all matching components are taken into account. For TPMS applications, the simplest matching network is the L-section, which employs two reactive elements to match an antenna impedance to a transmission line impedance [8]. For an electrically small antenna, the normalized impedance is usually outside the $1 + jX$ circle on the Smith chart due to the small input resistance and relatively large characteristic impedance of the feed line. Therefore, the L-section circuit shown in Figure 5 is employed, where the reactive elements X_1 and X_2 may be either capacitors or inductors, depending on the antenna's input impedance $R_A + jX_A$.

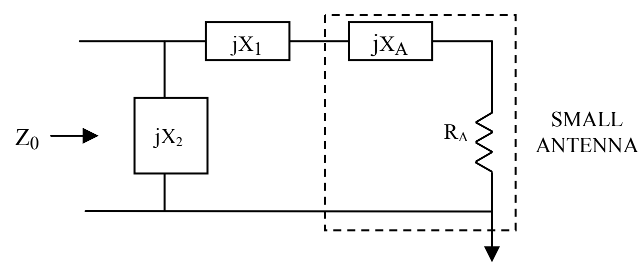


Figure 5. L-section matching network

The admittance seen looking into the matching network should equal the desired characteristic impedance of the feed line, Z_0.

$$\frac{1}{Z_0} = \frac{1}{jX_2} + \frac{1}{R_A + j\left(X_A + X_1\right)} . \tag{2}$$

By equating the real and imaginary parts respectively, X_1 and X_2 can be determined,

$$X_1 = \pm\sqrt{R_A\left(Z_0 - R_A\right)} - X_A \tag{3}$$

$$X_2 = \mp\frac{R_A Z_0}{\sqrt{R_A\left(Z_0 - R_A\right)}} . \tag{4}$$

Therefore, the capacitance or inductance of the lumped element matching network can be determined based on the values of X_1 and X_2 and the operating frequency.

Matching circuits for the loop and whip antennas in Section II and the whip antenna (d) in Section III are discussed in this section. Two sets of parameters for each model are derived. One set is derived based on the antenna structure itself. The other set is derived based on the antenna is its working environment including the rim. For this comparison, the rim dimensions are 245/17. The calculated input impedances and the total radiation efficiencies ε_{tot} after taking the reflection loss into account for these antennas under different matching conditions are listed in Table VII. Considering the large differences in the total radiation efficiencies, it is evident that the antennas should be tuned in their intended working environment. The 3-dB bandwidths for these antennas after matching with the rim are listed in the last column of Table VII. It can be seen that whip antenna in Section II has the narrowest bandwidths due to its high Q-factor. The whip antenna configuration (d) has a better radiation efficiency and 3-dB bandwidth compared to the antennas in Section II.

TABLE VII. THE INPUT IMPEDANCE, RADIATION EFFICIENCIES, AND 3-DB BANDWIDTH FOR SELECTED ANTENNAS WITH OR WITHOUT MATCHING

Model	Matching	Matching Parameters	Z_{in1} (ohm)	ε_{tot}(%)	3-dB bandwidth
Loop antenna with rim in Section II	No matching	*	0.0858 + j62.2653	0.035	*
	Matching with rim	C1 = 8.3935 pF C2 = 243.73 pF	49.9967 + j0.0138	13.0	314.6 MHz - 315.4 MHz
	Matching without rim	C1 = 8.2875 pF C2 = 254.60 pF	0.7090 + j3.6759	0.713	*
Whip antenna with rim in Section II	No matching	*	0.1139 - j783.909	0.003	*
	Matching with rim	L1 = 397.28 nH C2 = 211.46 pF	50.112 - j2.1784	75.0	314.95 MHz - 315.05 MHz
	Matching without rim	L1 = 409.25 nH C2 = 149.58 pF	0.0025 - j3.8804	0.015	*
Whip antenna (d) after improving the Q-factor as described in Section III	No matching	*	0.5525 - j199.62	0.099	*
	Matching with rim	L1 = 103.50 nH C2 = 95.599 pF	50.0069 - j0.0317	37.9	314.4 MHz - 315.6 MHz
	Matching without rim	L1 = 131.76 nH C2 = 103.90 pF	0.0041 - j5.2829	0.012	*
	Matching with rim	C1 = 21.133 pF L2 = 6.4903 nH	49.9984 - j0.0044	52.1	313.8 MHz - 316.2 MHz
	Matching without rim	L1 = 35.304 nH C2 = 41.908 pF	0.0925 - j14.1383	0.356	*

V. CONCLUSIONS

By comparing the radiation efficiencies and Q-factors of the antennas evaluated above, it can be seen that different types of antennas perform very differently. The loop antenna has the lowest efficiency and also the lowest Q-factor. The whip antenna has the largest efficiency but the Q-factor is also the largest. By extending the whip antenna around the perimeter of the PCB and keeping the bent arm away from the rim edge, the Q-factor of the whip antenna can be significantly improved. Additionally, after electrically connecting the PCB ground to the rim and applying a lossy coating material to the antenna structure, the Q-factor is reduced to below 300 while the radiation efficiency is still as high as about 40 percent for various rim diameters from 14 inches to 18 inches and widths from 175 mm to 315 mm. The high radiation efficiency makes the whip antenna a better choice for most TPMS applications, though care must be taken to control the Q-factor. Other electrically small antenna designs (e.g. the inverted-F antenna) combine the properties of whip and loop antennas, but exhibit a similar trade-off between radiation efficiency and bandwidth. Based on the simulation results for different matching configurations presented here, it is clear that high efficiencies are only achievable when the matching network is configured for the antenna's intended environment.

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