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Investigation of Antennas used in Tire Pressure Monitoring Systems

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Abstract

Due to the restrictive size requirements for Tire Pressure Monitoring System (TPMS) modules that are mounted in tires, their antennas are typically much smaller than a wavelength at the frequency of operation. Therefore, antenna performance is a key issue for TPMS applications. The objective of this paper is to investigate the performance of loop antenna and whip antenna designs commonly used in TPMS applications. The paper also explores possible improvements to existing designs to decrease the Q factor and/or increase the radiation efficiency. Moreover, the importance of matching the antenna in its intended environment is evaluated. For common TPMS antennas, the metal rim of the wheel plays an important role in the overall performance whether or not it is directly connected to the PCB. Therefore, the impedance, radiation efficiency, and Q factor of various antennas are evaluated for three different configurations: without rim, above rim with no electrical contact, and electrically connected to a metal rim. A full-wave moment method is employed to simulate the antenna performance. The results show that whip antennas will generally be a better choice for TPMS applications if the Q value can be controlled. Suggested improvements are proposed based on simulation results. Additionally, after electrically connecting the PCB ground to the conducting rim and applying a lossy coating material to the antenna structure, the Q value can be made lower than 300, while the radiation efficiency is still as high as about 40 percent for various rims with diameters from 14 inches to 18 inches and widths from 175mm to 315 mm which covers most passenger car tires. Considering the possibility that the antenna signals may be attenuated by the lossy tire material for common antennas installed entirely within the wheel, a helical valve antenna that wraps around the valve stem outside the rim is proposed. The results show that this design has the best overall performance compared to loop, whip, and improved whip antennas and would be a better choice if the complexity and cost were not a problem. However, no matter what kind of antenna is used, the matching of the antenna in its intended environment needs to be addressed.

1. Introduction

Automatic tire pressure monitoring has been required on all new vehicles sold in the U.S. since September 2007. Most of the Tire Pressure Monitoring Systems (TPMS) in vehicles today employ battery powered sensors that are mounted in each of the tires 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 wavelength of interest. 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 the matching network can help reduce the mismatch loss, any loss in the antenna structure itself, or in the matching network can significantly reduce the overall efficiency. Since the total power transmitted from the TPMS module will be limited by the antenna radiation efficiency, an antenna with a high radiation efficiency is preferred. 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 susceptible to surrounding objects. Therefore, for a good antenna design, high radiation efficiencies and low quality factors are required.

In addition, the effect of the rim has not been given enough attention in previous studies. Metal rims can play an important role in an antenna's radiation efficiency. In order to evaluate the performance of antennas more accurately, different connecting conditions between the antenna and the rim need be investigated.

This paper first investigates the performance of different 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. Considering the impact that a lossy tire material may have on an antenna's signal, a new valve stem antenna employing a helix structure is proposed and its performance is analyzed. 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 matching network with lumped elements is briefly described, and its influence on an antenna's total radiation efficiency is evaluated.

2. Evaluation of Common Antennas used in TPMS Applications

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

2.1 Case 1. Antenna structure without rim

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 Fig. 1. They are 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.

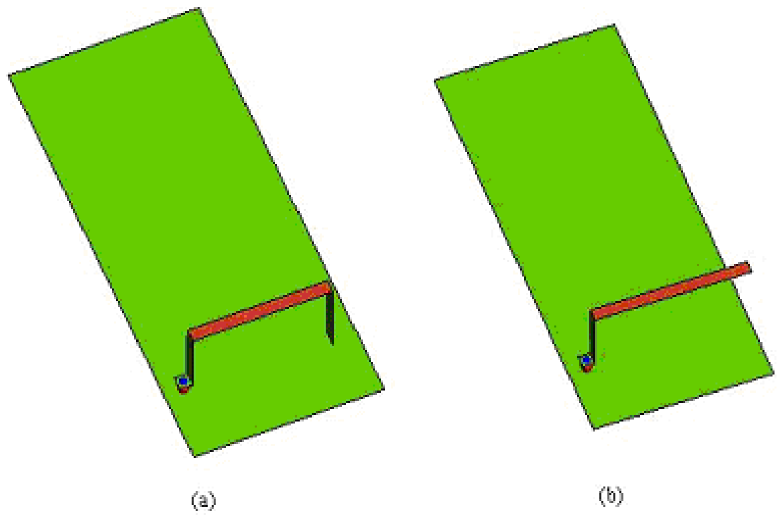

Fig.1. a) loop antenna, and b) whip antenna.

2.2 Case 2. Antenna above rim with no electrical contact

In order to analyze these two types of antennas in their intended environments, a metal rim is included in the model. In this case, as shown in Fig 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.

Fig. 2. Model for loop antenna above a metal rim

2.3 Case 3: Antenna electrically connected to a metal rim

Fig. 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 length of 6 mm and diameter of 0.4 mm, makes electrical contact between the rim and the PCB ground plane.

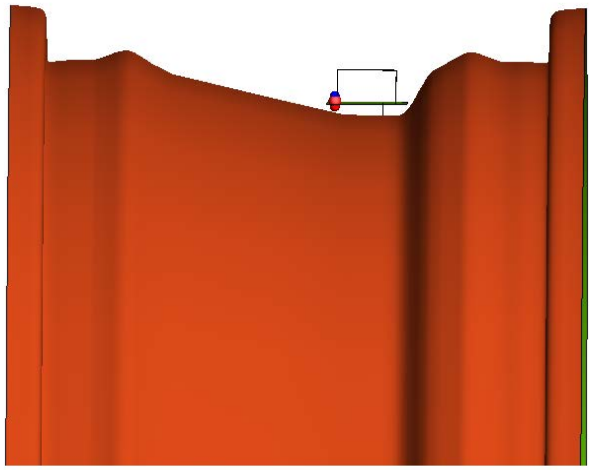

Fig. 3. Model for loop antenna electrically connected to metal rim.

2.4 Evaluation of overall performance of loop and whip antennas

The input impedances and radiation efficiencies at 315.0 MHz for both the loop antenna and whip antennas in each of the three cases 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]:

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

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

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

Table 1: Calculated parameters for loop and whip antennas in free space

Antenna type	Z_{in1} (ohms)	Z_{in2} (ohms)	Q	ε_{cd} (%)
Loop antenna	0.07864+j*62.9475	0.07868+j*62.9901	426.6	5.2
Whip antenna	0.22717-j*806.619	0.22745-j*806.084	1854.6	87.7

Table 2: 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+j*62.2653	0.08586+j*62.3074	386.4	13.0
	245/14	0.08790+j*62.2902	0.08797+j*62.3324	378.1	15.1
	245/18	0.08536+j*62.2592	0.08542+j*62.3014	389.3	12.6
	315/18	0.08885+j*62.2602	0.08892+j*62.3023	373.1	16.0
	175/14	0.08388+j*62.3009	0.08393+j*62.3431	396.2	11.0
	175/18	0.08247+j*62.2696	0.08252+j*62.3118	403.0	9.5
	315/14	0.09118+j*62.2884	0.09125+j*62.3306	364.5	18.1
Whip antenna	245/17	0.11392-j*783.909	0.11398-j*783.389	3594.6	75.0
	245/14	0.14635-j*784.672	0.14627-j*784.151	2803.4	80.6
	245/18	0.11388-j*783.748	0.11400-j*783.229	3588.9	75.0
	315/18	0.11621-j*783.659	0.11633-j*783.14	3516.9	75.5
	175/14	0.15453-j*784.298	0.15437-j*783.779	2644.8	81.6
	175/18	0.10296-j*783.383	0.10307-j*782.864	3969.5	72.4
	315/14	0.13614-j*784.584	0.13612-j*784.064	3008.0	79.1

Table 3: 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+j*62.4463	0.08629+j*62.4887	387.2	13.2
	245/14	0.08843+j*62.4908	0.08850+j*62.5332	377.6	15.4
	245/18	0.08584+j*62.4364	0.08590+j*62.4787	388.1	12.8
	315/18	0.08952+j*62.4360	0.08960+j*62.4783	372.1	16.4
	175/14	0.08424+j*62.4922	0.08430+j*62.5346	396.4	11.2
	175/18	0.08278+j*62.4403	0.08283+j*62.4826	402.4	9.6
	315/14	0.09184+j*62.4884	0.09191+j*62.5307	362.7	18.5
Whip antenna	245/17	0.16163-j*763.382	0.16173-j*762.872	2484.8	78.9
	245/14	0.21098-j*763.992	0.21086-j*763.481	1907.3	83.9
	245/18	0.15972-j*763.278	0.15990-j*762.767	2519.4	78.6
	315/18	0.16549-j*763.167	0.16568-j*762.657	2426.9	79.3
	175/14	0.22189-j*763.271	0.22164-j*762.761	1810.0	84.7
	175/18	0.14489-j*762.531	0.14505-j*762.021	2771.9	76.4
	315/14	0.19780-j*763.905	0.19779-j*763.395	2030.4	82.8

3. Improving the Q Value of a Whip Antenna

Considering its higher efficiency, the whip antenna is the more attractive alternative if its Q value can be decreased. This section will discuss possible approaches for controlling the Q value of a whip antenna without increasing the volume of the TPMS module. Since the Q value 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 this comparison, the rim has a width of 245 mm and a diameter of 17 inches. Fig. 4 shows 5 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.

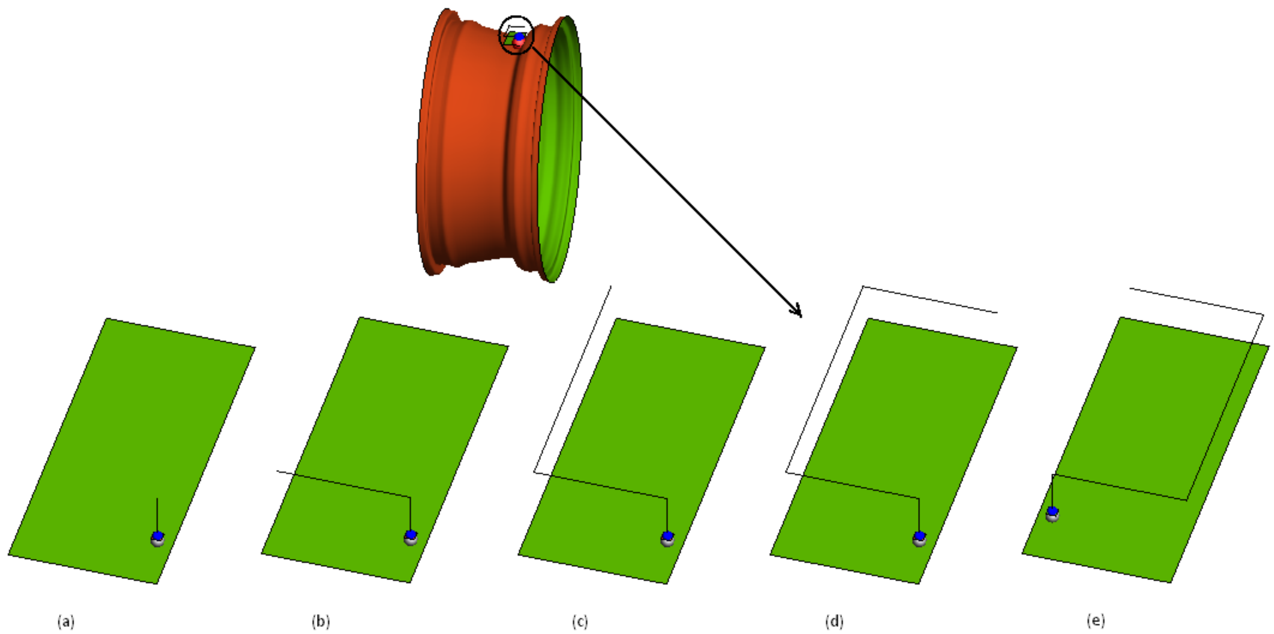

Fig. 4. Geometries of different whip antennas.

The calculated radiation efficiency and Q values of these 5 antennas are listed in Table 4. It is evident that the Q value can be significantly decreased when the antenna structure fills a larger volume. However, when the bent arm is too close to the rim edge, the radiation resistance decreases excessively, which makes both the radiation efficiency and the Q value worse.

Table 4: Calculated parameters for different whip antennas

Antenna	Z_{in1} (ohms)	Z_{in2} (ohms)	Q	ε_{cd} (%)
(a)	0.0349829-j*1850.44	0.035-j*1849.26	26563	45.6
(b)	0.120836-j*767.215	0.120917-j*766.706	3317.2	73.7
(c)	0.194157-j*341.603	0.194296-j*341.331	1103.2	68.5
(d)	0.21716-j*258.339	0.217312-j*258.102	859.4	64.7
(e)	0.15512-j*247.468	0.155197-j*247.237	1172.7	49.8

Among the antennas above, antenna (d) exhibits the best overall performance regarding Q value and radiation efficiency. Without sacrificing much radiation efficiency, the Q value of antenna (d) is four times less than antenna (b), the antenna evaluated in the previous section. Based on the results of many simulations, the Q value 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 value. 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 5 lists the computed parameters of antenna (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 value 10 times lower, while the radiation efficiency is reduced by less than a factor of 2.

Table 6 lists computed parameters for antenna (d) when the rim is electrically connected to the PCB ground and the lossy coating material is applied for various rim dimensions. In spite of more volume space required by the antenna (d), it exhibits a better overall performance with high radiation efficiency and low Q value. Additionally, the actual space for the components on the PCB does not decrease much because antenna (d) is arranged along the edge of the PCB.

Table 5: Computed parameters for various antenna configurations

Approaches	Z_{in1} (ohms)	Z_{in2} (ohms)	Q	ε_{cd} (%)
Antenna (b)	0.120836-j*767.215	0.120917-j*766.706	3317.2	73.7
Antenna (d)	0.21716-j*258.339	0.217312-j*258.102	859.4	64.7
Connecting rim	0.29588-j*226.963	0.296106-j*226.737	601.5	70.0
Connecting rim and coating	0.552479-j*199.62	0.55256-j*199.41	299.3	37.9

Table 6: 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-j*199.62	0.55256-j*199.41	299.3	37.9
245/14	0.632894-j*200.009	0.632656-j*199.798	262.5	45.8
245/18	0.551881-j*199.459	0.552086-j*199.248	301.1	37.8
315/18	0.584032-j*199.477	0.584348-j*199.267	283.2	41.3
175/14	0.617142-j*197.89	0.616703-j*197.681	266.7	44.4
175/18	0.504637-j*197.448	0.50475-j*197.238	327.7	32.0
315/14	0.635245-j*199.964	0.635236-j*199.753	261.6	46.0

4. Antenna Employing Valve Stem

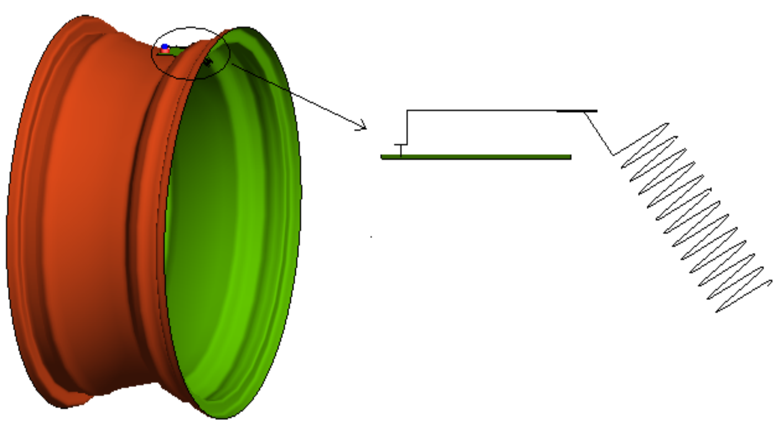

Fig. 5. Geometry of helix valve antenna

The above antennas were installed entirely within the wheel, where their signals could be attenuated by the lossy tire material. Therefore, it is worth investigating an antenna design which would be installed outside the rim to avoid or decrease the impact of tire material. The most intuitive and convenient approach is to use the valve stem as an antenna platform. In this section, a helix antenna structure with the dimensions of a valve stem is evaluated. The helix structure can be wrapped around an existing valve stem. The geometry of this antenna is shown in Fig. 5. The helix has a radius of 5 mm, a height of 30 mm, and 12.6 turns. The wire radius is 0.4 mm. The helix is pointed 45 degrees from horizontal. For the antenna part inside the tire, the raised height is 5 mm and the length of the antenna along the short edge of the PCB is 20 mm. The board has the same dimensions as those in Section II, and the three simulation cases are also the same as discussed in Section 2.

Table 7: Computed parameters for valve helix antenna

Antenna Type	W/D (mm/inch)	Z_{in1} (ohms)	Z_{in2} (ohms)	Q	ε_{cd} (%)
Case 1	*	1.92495-j*79.9996	1.93436-j*79.1902	331.1	70.9
Case 2	245/17	2.00077-j*14.8728	2.01301-j*13.9652	357.3	67.0
	245/14	1.4377-j*16.6116	1.44611-j*15.7061	496.0	54.2
	245/18	2.16467-j*14.611	2.17789-j*13.7037	330.1	69.5
	315/18	1.79757-j*14.174	1.80924-j*13.2643	398.6	63.2
	175/14	2.12551-j*19.4257	2.13781-j*18.5284	332.5	69.3
	175/18	2.70497-j*18.1236	2.71978-j*17.2268	261.1	75.9
	315/14	1.11527-j*16.3163	1.1217-j*15.4095	640.3	40.9
Case 3	245/17	2.5873+j*75.6128	2.60297+j*76.6513	316.1	69.0
	245/14	1.99219+j*76.038	2.00358+j*77.0777	411.0	59.7
	245/18	2.76012+j*75.5217	2.77693+j*76.5593	296.1	71.0
	315/18	2.304+j*76.0943	2.31896+j*77.1355	355.9	65.1
	175/14	2.96569+j*74.8898	2.98231+j*75.9233	274.5	73.1
	175/18	3.47413+j*73.5274	3.4932+j*74.5561	233.2	77.1
	315/14	1.51129+j*76.4674	1.51991+j*77.5067	541.6	46.8

Table 8: Computed parameters for valve helix antenna with a lossy coating

Antenna Type	W/D (mm/inch)	Z_{in1} (ohms)	Z_{in2} (ohms)	Q	ε_{cd} (%)
Case 1	*	2.74739-j*58.48	2.76234-j*57.56	263.7	56.4
Case 2	245/17	3.09582+j*11.8583	3.11702+j*12.9285	272.3	52.1
	245/14	2.41711+j*10.0226	2.43317+j*11.0901	347.8	38.8
	245/18	3.29249+j*12.1202	3.31501+j*13.1898	255.9	54.9
	315/18	2.85598+j*12.6536	2.87635+j*13.7265	295.9	47.9
	175/14	3.22929+j*6.87336	3.25052+j*7.92953	257.6	54.8
	175/18	3.92079+j*8.15987	3.9455+j*9.21509	212.0	62.7
	315/14	2.03042+j*10.3719	2.04379+j*11.4408	414.6	27.1
Case 3	245/17	4.13111+j*126.781	4.16+j*128.083	248.3	54.7
	245/14	3.39533+j*127.314	3.41826+j*128.618	302.5	44.8
	245/18	4.33988+j*126.67	4.37031+j*127.971	236.1	56.9
	315/18	3.78572+j*127.426	3.81352+j*128.733	271.9	50.4
	175/14	4.62472+j*125.793	4.65518+j*127.088	220.6	59.8
	175/18	5.18768+j*124.188	5.22138+j*125.475	195.4	64.4
	315/14	2.78221+j*127.83	2.80107+j*129.137	370.0	32.5

The parameters of the helical valve antenna calculated for each of the three cases are listed in Table 7. As the rim’s width becomes larger and the diameter becomes smaller, the antenna performance gets worse. Both radiation efficiency and Q value can be improved by electrically connecting the antenna ground to the rim. Table 8 shows the computed parameters for the valve helix antenna when a lossy coating is applied to the antenna. The coating material has permittivity of 2.1, a loss factor of 0.025, and thickness of 0.5 mm. It can be seen that some loss on the antenna improves the Q factor while sacrificing the radiation efficiency.

Compared to the loop and whip antennas discussed above, the helical valve antenna shows the best performance considering both Q factor and radiation efficiency. The shortcoming for this antenna is its potential increased cost.

5. 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 Fig. 6 is used, 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.

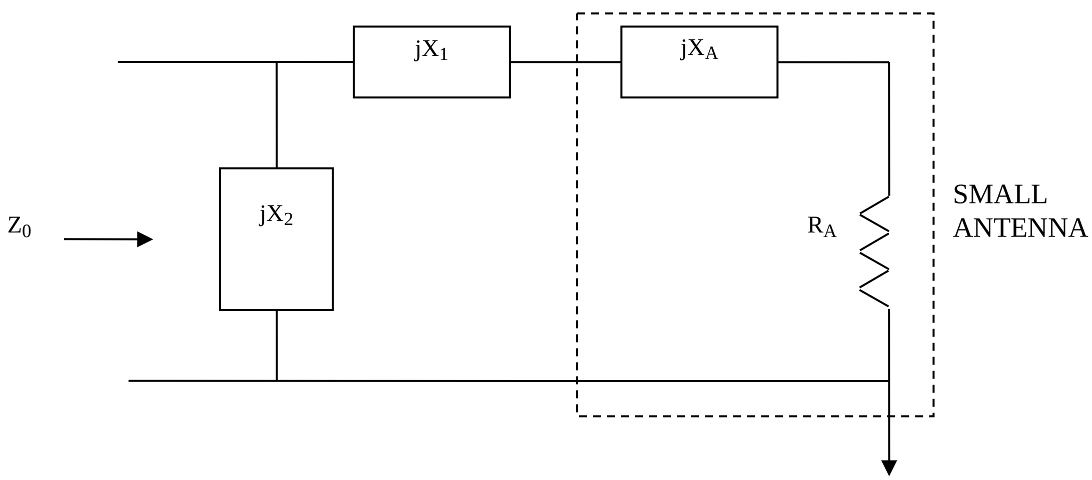

Fig.6. L-section matching network

The admittance seen looking into the matching network must 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.

The loop antenna and whip antenna in Section 2, the whip antenna (d) in Section 3, and the helical antenna in Section 4 are discussed here to investigate how the matching should be performed in order to achieve optimum system efficiency. Two sets of parameters for each model are derived. One set is derived based on the antenna structure itself. The other set is derived in the antenna's working environment after the rim is included. To simplify the comparison, the rim dimension is selected to be 245/17. The input impedances and the total radiation efficiencies ε_{tot} after taking the reflection loss into account for these antennas under different matching conditions are calculated and listed in Table 9. Considering the big differences for 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 9. It can be seen that whip antenna in Section 2 has the narrowest bandwidths due to its high Q value. The whip antenna (d) has improved total radiation efficiency and 3-dB bandwidth compared to the antennas in Section 2. The helical valve antenna has a bandwidth greater than 1 MHz and a total radiation efficiency larger than 50 percent, which gives it the best overall performance.

Table 9: 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}(%)	3dB bandwidth
Loop antenna with rim in Section II	No matching	*	0.0858+j*62.2653	0.035	*
	Matching with rim	C1=8.3935pF C2=243.73pF	49.9967+j*0.0138	13.0	314.6 MHz-315.4 MHz
	Matching without rim	C1=8.2875pF C2=254.60pF	0.7090+j*3.6759	0.713	*
Whip antenna with rim in Section II	No matching	*	0.1139-j*783.909	0.003	*
	Matching with rim	L1=397.28nH C2=211.46pF	50.112-j*2.1784	75.0	314.95 MHz-315.05 MHz
	Matching without rim	L1=409.25nH C2=149.58pF	0.0025-j*3.8804	0.015	*
Whip antenna (d) after improving Q in Section III	No matching	*	0.5525-j*199.62	0.099	*
	Matching with rim	L1=103.50nH C2=95.599pF	50.0069-j*0.0317	37.9	314.4 MHz-315.6 MHz
	Matching without rim	L1=131.76nH C2=103.90pF	0.0041-j*5.2829	0.012	*
Helical valve antenna after coating in Section IV	No matching	*	3.0958+j*11.8583	10.9	*
	Matching with rim	C1=21.133pF L2=6.4903nH	49.9984-j*0.0044	52.1	313.8 MHz-316.2 MHz
	Matching without rim	L1=35.304nH C2=41.908pF	0.0925-j*14.1383	0.356	*

6. Conclusions

By comparing the radiation efficiencies and Q values 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 value. The whip antenna has the largest efficiency but the Q value is also the largest. By extending the whip antenna around the entire box volume and keeping the bent arm away from the rim edge, the Q value of the whip antenna can be greatly improved. Additionally, after electrically connecting the PCB ground to the rim and applying the lossy coating material to the antenna structure, the Q value 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 and improved Q value make the whip antenna a better choice for TPMS applications. A helical valve antenna wrapped around valve outside the rim exhibits the best overall performance in terms of the radiation efficiency and Q value, and would be a good choice if the complexity and cost were not a problem. Based on the simulation results for different matching configurations for TPMS antennas, it is clear that no matter what type of antenna is used, the antenna should be matched in its intended environment.

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