Waveguide-mode wireless power transfer in shielded space with aperture plane

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Abstract: This paper introduces a novel method of waveguide-mode wireless power transfer (WPT) in a shielded space with an aperture plane. First, it is shown that the simplified model of the engine compartment behaves as a ridge waveguide. Next, the WPT efficiency at the resonant frequency of the dominant mode in the ridge waveguide is discussed using a monopole probe and a helical probe. The results obtained from these simulations and measurements indicate a possibility that WPT efficiency can be improved by our method. Finally, it is experimentally demonstrated that the line-of-sight and non-line-of-sight wireless sensors can operate using our method.

Keywords: wireless power transfer, waveguide mode, engine compartment, shielded space

Classification: Microwave and millimeter-wave devices, circuits, and modules

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1 Introduction

Reducing vehicle weight is important due to the potential gains in fuel efficiency and safety performance. There are many sensors in a vehicle such as the engine and drive control [1, 2, 3]. The power is transferred to the sensors and the engine control unit using a wire harness. The wire harness in a typical car has a weight of approximately 50 kg. Therefore, wireless power transfer (WPT) using a rectenna has been studied as a possible alternative to the harness [4, 5, 6]. Although power can be transferred to the line-of-sight (LOS) sensor in high efficiency, WPT efficiency is quite low at a non-line-of-sight (NLOS) sensor. It is hard to operate a NLOS sensor using rectennas because the efficiency is dependent on the directionalities of the rectennas. As a novel approach to solve this challenge, WPT using the waveguide mode is proposed in [7]. [7] shows a possibility that LOS and NLOS are non-existent by considering the engine compartment as a ridge waveguide with one aperture plane. In this paper, to verify this possibility, waveguide-mode WPT is demonstrated based on a simplified model of the engine compartment. First, the WPT frequency is determined on the basis of cavity resonant mode. Then, WPT efficiencies at LOS and NLOS receivers are discussed using a monopole probe and a helical probe. Finally, it is experimentally demonstrated that the LOS and NLOS wireless sensors can operate using our method.

2 Determination of WPT frequency

We propose cavity mode wireless power transfer in a fully closed space utilizing frequency selected surfaces [8, 9]. In this case, the shielded space can work as a cavity resonator as shown in Fig. 1(a). The engine compartment has one aperture plane and the compartment must be able to be considered as a rectangular waveguide with one short-circuit end, that is, a quarter-wave resonator as shown in Fig. 1(b). There are two modes of $TE_{mnp}$ and $TM_{mnp}$ as well as the fully shielded space, and both resonant frequencies are

$$f_r = \frac{c}{2} \sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2 + \left(\frac{p}{d}\right)^2}.$$  \hspace{1cm} (1)

When the overall size of the compartment is $1.6 \times 0.90 \times 0.90$ m the resonant frequency of the dominant mode ($TE_{101}$ mode) is $126.1$ MHz from (1). On the other hand, the engine compartment has various conductor and insulator scatterers. Since it works as a ridge waveguide, the resonant frequency shifts to the lower frequency as shown in [6]. The roughly simplified model, as shown in Fig. 2(a) and 2(b), was
designed and the phase characteristics of the simulated S-parameters are shown in Fig. 2(c). It is observed that the first frequency at $\angle S_{11} = 0$ is 69.8 MHz in Fig. 2(c). Thus, we determined 69.8 MHz as a WPT frequency.

![Fig. 1. (a) Fully shielded space. (b) Shielded space with one aperture.](image)

In this section, WPT efficiencies to LOS and NLOS positions are discussed using a monopole probe and a helical probe. The feeding probe is fixed at the top plate and the receiving probes are located in the bottom plate as shown in Fig. 3. P2 is LOS position and others are NLOS positions. The body and probes respectively consist of aluminum and copper. Power from the feeding probe is transferred to the received probes one by one. Other probes, to which power is not transferred, are open ends. First, S-parameters employing a monopole probe in Fig. 4(a) on feeding and receiving probes are calculated by CST Microwave Studio and measured by a vector network analyzer (VNA). The physical length of monopole probe is 0.40 m.

![Fig. 2. Simplified model with scatterers. (a) Perspective view. (b) Side view. (c) Phase characteristics of the simulated $S_{11}$.](image)

3 **WPT efficiencies to LOS and NLOS positions**

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and approximately 1/9 wavelength of 69.8 MHz. From Fig. 4(a), the measurement shows good agreement with the simulation, although there are some differences for the amplitude values due to a fabrication error and deflection. First maximal $|S_{21}|s$ in P1, P2, P3, and P4 around 69.8 MHz were obtained. However, the simulated values are $-33.0$ dB, $-21.8$ dB, $-22.7$ dB, and $-32.0$ dB, respectively. It is difficult to design the matching circuit connecting between each monopole probe and power source or wireless sensor because this monopole has a reactance value that is too large. Therefore, the helical probe is fabricated with consideration for the reactance. The physical length is 0.40 m and the diameter $\phi$ is 20 mm. The probe is fixed by Styrofoam. The electrical length is set to approximately 1/4 wavelength in 69.8 MHz by changing the number $N$ of turns. S-parameters employing a helical probe on feeding and receiving probes in Fig. 4(b) are calculated and measured as well. The $|S_{21}|s$ in P1, P2, P3, and P4 around 69.8 MHz are $-16.2$ dB, $-6.74$ dB, $-6.26$ dB, and $-14.6$ dB, respectively. Since, the transmission characteristics were improved by helical probe, next, the matching circuits connecting the VNA (50 $\Omega$) with the feeding or receiving probes are fabricated and the optimum WPT efficiency of each receiver is measured around 69.8 MHz. The comparison results between these efficiencies and the calculated maximum available efficiency $\eta_{\text{max}}$ [10] are shown in Table I. Although the measured results include the losses of the matching circuits, efficiencies of more than 14% are obtained for all receivers. These results indicate that WPT efficiency can be improved using our method.
4 Driving experiment of sensors

In this section, a driving experiment of the LOS and NLOS wireless sensors was conducted using the prototype in Fig. 3(b). The feeding and receiving probes are helical probes. The output power from RF generator connected to the feeding probe is around 17.5 dBm. Each power receiver at P 1 to 4 is connected to the voltage doubler rectifiers seen in Fig. 5. The DC power from the rectifier is charged in the capacitor \( C_{DC} = 1 \mu F \) and \( C_C = 40 \mu F \). The output of the rectifier is connected to the DC input of a modified circuit of a STRAWBERRY LINUX DC/DC converter module. It is also connected to the enable input through the resistor \( R_T = 100 \text{k} \Omega \) and the capacitor \( C_T = 0.69 \mu F \). \( C_C \) is charged until the voltage of \( C_T \) reaches the wake-up value of the DC/DC converter. When the DC/DC converter is turned on, 3.6 V is output. The capacitor \( C_P = 100 \mu F \) is charged by the output voltage. When the charge voltage exceeds the threshold voltage, RF and sensor module is turned on by Reset IC (BD46235) and MOSFET (SSM3K16FS). The module is TWE-LITE fromMono Wireless Inc. The sensing data transmitted from the RF module with a dipole antenna is received by the master sensor connected to the laptop. The input and output voltages of the DC/DC converters in P2 at the LOS position and P3 at the NLOS position are shown in Fig. 6. It is confirmed that the output voltage is given to the sensor module after the voltage of \( C_C \) increases. Since a large current is consumed waking up the RF module, a voltage drop occurs. The output voltage of 3.6 V is kept and the workable voltage is continuously applied to the sensor. The sensors in P2 and P3 could function, whereas the others could not because WPT efficiency was insufficient. A further improvement of the efficiency at NLOS positions are necessary.

Table I. Wireless power transmission efficiency at each position.

|       | LOS  | NLOS |
|-------|------|------|
| P2    | 37.4%| 19.8%| 35.8%| 19.4%|
| P1    | 19.8%| 35.8%| 32.7%| 14.8%|

Fig. 5. Schematic diagram of the power receiver and sensor module.
5 Conclusion

In this paper, waveguide-mode WPT was demonstrated based on a simplified model of the engine compartment and the possibility was verified. First, for the WPT frequency, 69.8 MHz was determined on the basis of the cavity resonant mode. Then, WPT efficiency was discussed using monopole and helical probes. An efficiency of more than 14% at the NLOS position was achieved by using the helical probe. Finally, it was experimentally demonstrated that the LOS and NLOS sensors could function using our method and that sensing data could be received at a laptop with the master. Our next step is to further improve WPT efficiency at NLOS positions.

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