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Modeling of RF Interference Caused by Solid-State Drive Noise

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Abstract— **In this paper, modeling of RFI problem caused by a solid-state drive (SSD) in a laptop is proposed. Two noise sources (one outside and one inside a cavity) in the SSD are reconstructed as dipole moments with magnitude-only near-field scanning data. The dipole moment inside a cavity is then replaced by a Huygens' box covering four side surfaces of the cavity using a numerical simulation. The noise voltage at an RF antenna port is calculated by combining the two reconstructed noise sources with measured transfer functions. The model is successfully validated through a comparison of the calculation with measurement results.**

Keywords—radio frequency interference; solid-state drive; reciprocity theory; Huygens' box; dipole moment

I. Introduction

In modern wireless devices, RF antennas and noise sources are usually placed close to each other for small form factors, which makes them more vulnerable to radio frequency interference (RFI) problems. With the increasing complexities of modern electronic devices, understanding and modeling of RFI is becoming more and more important [1].

In recent studies, dipole moment modeling methods are developed to characterize the RFI problem [2]. With the near-field scanning and least square method (LSQ), the noise source is equivalently modeled as the dipole moment. Then, the coupled voltage on the RF antenna is estimated with the transfer function, which describes a voltage coupling ratio from the dipole moment to the victim RF antenna. However, the dipole moment reconstruction has been applied only when near-field scanning directly over the noise source is feasible.

Solid-state drives (SSDs) have been widely used in many modern electronics due to their compact size and high data rate. Modern SSDs are often mounted on its socket horizontally with the motherboard, such as the M.2 SSD, creating a cavity structure. Existence of noise radiation inside the cavity makes the RFI problem more complex to model. Huygens' box methods were introduced to model the noise sources in complex electronic devices [3-4]. By covering the SSD cavity with a virtual Huygens' box, the radiation from the noise source inside the cavity can be accurately represented. However, phase information is essential for the Huygens' box approach, which is difficult to obtain if not impossible in practical devices.

In this paper, modeling of RFI problems caused by SSD noise, involving a cavity structure, is proposed. The uncorrelated two noise sources are reconstructed by using magnitude-only near-field scanning data. The noise source outside the cavity is reconstructed as a single dipole moment. The noise source inside the cavity is reconstructed as a single dipole moment first, then replaced with Huygens' box covering the four side surfaces of the cavity using a numerical simulation. Transfer functions are measured using a Vector Network Analyzer and combined with the two noise sources to estimate the coupled voltage at an RF antenna port. The model is validated with measurement.

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II. Modeling of RFI Caused by SSD Noise

A. Dipole Moment based RFI Modeling

When voltage potentials or current loops are localized in a compact area, noise sources can be well defined as dipole moments. Combining the forward and reverse problems, an analytical equation to predict the coupled voltage is derived as [2]

$$V^{fwd} = \sum_{i=1}^{N}\left(\frac{Z_L PF_E}{2} S_{21P_i}^{rev} \cdot \vec{P}_i + \frac{Z_L PF_H}{2} S_{21M_i}^{rev} \cdot \vec{M}_i\right) \qquad (1)$$

where PF, S_{21}, $\vec{P}_i$, and $\vec{M}_i$ are the probe factor of electric and magnetic field probes, measured S-parameters, and the electric and magnetic dipole moment, respectively.

The noise source can be reconstructed using the near field scanning data with the least square method as below [5]

$$X_k = [T'_{nk} T_{nk}]^{-1} T_{nk} F_n \qquad (2)$$

where X, T, F are the dipole array, transfer function, and measured field, respectively. When the noise source can be described by a single dipole moment, the phase information is no longer required.

B. Huygens' Box based RFI Modeling

In complex electronic devices with the concealed noise source due to the geometric constraints, the Huygens' box based RFI modeling can be applied. According to [3], the coupled voltage on the victim antenna based on the reciprocity theorem can be expressed by using the field and sources in the forward and reverse problem as

$$V^{fwd} = \frac{-Z_{in}Z_L}{V^{rev}(Z_{in}+Z_L)} \times \sum_{cells} \left(\vec{n}\times\vec{H}^{fwd}\cdot\vec{E}^{rev}\cdot S_{cell} + \vec{n}\times\vec{E}^{fwd}\cdot\vec{H}^{rev}\cdot S_{cell}\right) \tag{3}$$

where Z_{in} is the input impedance of victim antenna in the forward problem, and Z_L is the load impedance in the reverse problem. The S_{cell} denotes the area of each divided unit cell. With the above equation, the coupled voltage on the victim antenna is equivalently calculated using the recorded fields on each surface of the box. In the Huygens's box approach, phase information for all field components needs to be provided.

III. RFI Estimation in Practical Laptop

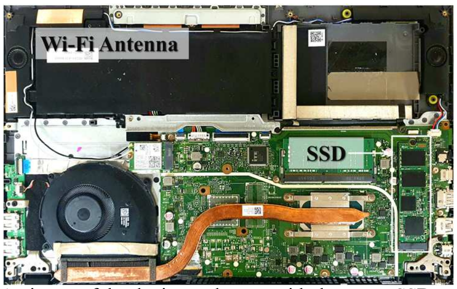

Fig. 1. A picture of the device under test with the target SSD.

The laptop under test is shown in Fig. 1. An SSD is installed at the right corner of the mainboard. An embedded Wi-Fi antenna on the top left corner is considered. The target SSD has two NAND memories, RAM, and controller packages and the size is 25 mm by 78 mm. The controller uses a digital clock of 180 MHz.

A. Cavity Resonance in SSD

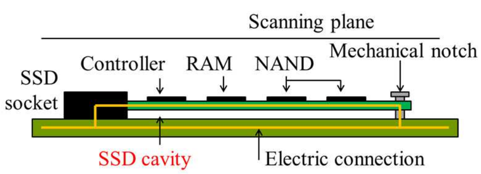

Fig. 2. Configuration of the SSD installed in laptop applications.

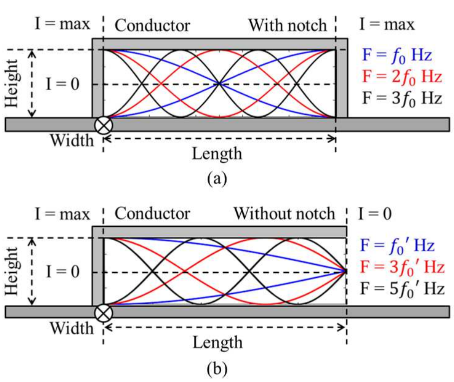

Fig. 3. Cross-sectional view of SSD cavity depending on notch designs. (a) with notch (b) without notch

The configuration of the SSD installed in the laptop is shown in Fig. 2. The pins of the SSD are always connected to the motherboard through the socket. On the other edge, the notch is designed to mechanically fix the SSD on the motherboard. Through this notch design, the local reference of SSD is connected to the motherboard and creates a cavity structure. Due to the cavity structure of the SSD, strong radiations can be generated at the resonance frequencies when a noise source is located inside of the cavity.

The resonance frequencies and current distribution of the SSD cavity depending on the boundary conditions are described in Fig. 3. The area in gray color describes the conductor that creates an electric connection. Dashed lines on the cavity denote the maximum and zero current locations. For instance, the maximum and zero current will be distributed on each edge and the center of the cavity at the first mode resonance frequency which is described in the blue color in Fig. 3(a). When the notch is removed in Fig. 3(b), the current will be the maximum on the shorted socket and zero on opened the other edge. With the mechanical notch design, the half-wave resonance is obtained due to the maximum current on each edge of the SSD. On the other hand, the quarter-wave resonance will be dominant when the notch is removed.

B. Equivalent Dipole Moement Reconstruction

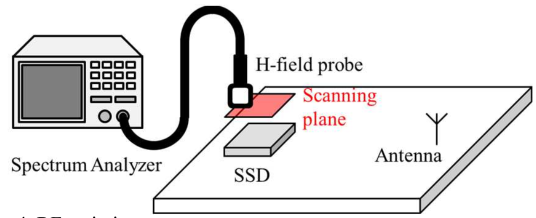

Fig. 4. RF emission measurement setup.

To model the noise radiation sources, the tangential H-fields on the scanning plane are measured. The measurement setup is shown on Fig. 4. An 80*100 mm scanning plane with a 2 mm scanning step is located 7 mm above the SSD. A total of 2091 points of H-fields measured by spectrum analyzer are shown in Fig. 5. From the near-field patterns, we can understand that the field patterns are a combination of fields associated with the cavity resonance formed by the SSD and direct radiation from the SSD top surface (single dipole type). The cavity resonance and single dipole patterns are described in the dotted and dashed line area. It was found that the two noise sources are uncorrelated, thus they are modeled independently and the worst-case noise coupling to an antenna can be estimated by adding noise powers (magnitude) induced by each noise source at the antenna port.

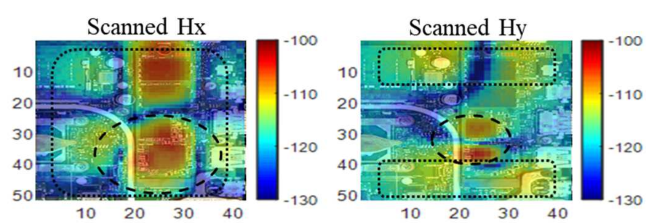

Fig. 5. Measured H-fields at 1.44 GHz with notch

By changing the boundary condition with a notch design, the cavity resonance can be removed, and single dipole patterns can be emphasized as Fig. 6. The measured fields show that the direct radiation from the SSD top surface can be modeled by a single M_Y dipole moment. As a single dipole moment can represent the noise source, the equivalent dipole moment can be reconstructed by following (2) without phase information and validated by comparing the calculated fields shown in Fig. 7.

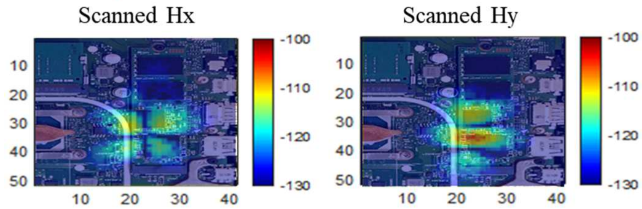

Fig. 6. Measured H-fields at 1.44 GHz without notch

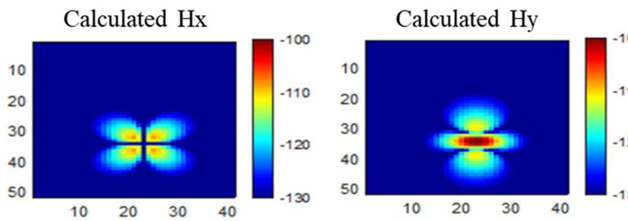

Fig. 7. Calculated H-fields at 1.44 GHz without notch

To reconstruct the noise source inside the cavity, the transfer functions for the source reconstruction were generated by numerical simulations. A cavity structure having the same physical dimension as the actual SSD structure was created and a unit P_Z dipole moment is placed inside the cavity. Based on the field patterns, a P_Z dipole moment is assumed as a dipole type. As the field patterns themselves at the resonance frequencies are not affected by the location of the noise source, the dipole location is irrelevant and can be randomly selected. The simulated fields on the scanning planes are essentially the transfer functions in (2). As a single dipole is used, magnitude-only field data can be used for reconstruction and the phase information is not necessary. The simulated fields patterns are shown in Fig. 8.

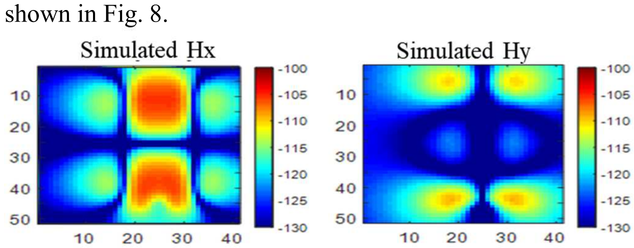

Fig. 8. Simulated H-fields at 1.44 GHz with notch

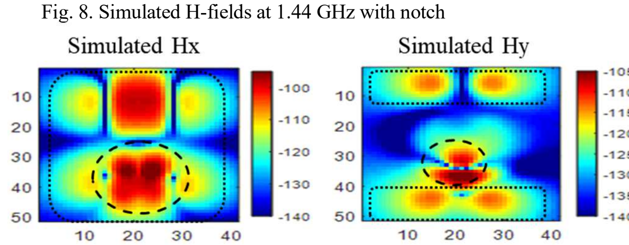

Fig. 9. Simulated SSD radiation at 1.44 GHz with notch

With two uncorrelated single dipole moments, the simulated radiation patterns in SSD are shown on Fig. 9. A good agreement between the measurement in Fig. 4 and Fig. 8 supports that, two single dipole moments in SSD are successfully reconstructed without phase information of measured H-fields. As well as with the notch design, the quarter-wave resonance without notch can be estimated by following the same modeling process.

C. Coupled Voltage Estimation

For the single dipole outside the cavity, the transfer function between the noise source and the Wi-fi antenna was measured using a VNA and combined with the reconstructed M_Y dipole moment using (1) [2]. For the noise source inside the cavity, field data were generated for the four side surfaces, i.e. Huygens' box, using numerical simulations. The reconstructed P_z dipole was used as an excitation. Note that the simulated fields have the phase information. The transfer functions between the four surfaces and the Wi-fi antenna were measured using a VNA and combined with the simulated Huygens' box. As mentioned earlier, two noise sources are uncorrelated, we can add coupled powers at the antenna port for the worst-case estimation.

The coupled voltages at the Wi-Fi antenna were measured directly using the spectrum analyzer. The measured and estimated results are in Table. 1. The measured and calculated power have less than 2dB discrepancies at all resonance frequencies.

TABLE I. RFI PROBLEM SUMMARY

	Frequency	***Measured***	***Calculated***	***Δ***
With notch	1.44 GHz	-90.22 dBm	-90.31 dBm	0.09 dB
	2.88 GHz	-120.82 dBm	-121.86 dBm	1.04 dB
Without notch	720 MHz	-105.81 dBm	-107.77 dBm	1.96 dB
	2.16 GHz	-112.61 dBm	-111.40 dBm	1.21 dB

IV. CONCLUSION

In this paper, the estimation method for the RFI caused by SSD noise is proposed. The noise sources are reconstructed based on the dipole moment and Huygens' box with magnitude-only near-field scanning data. With two uncorrelated noise sources, the coupled voltage on the RF antenna is calculated and successfully validated with measurement.

REFERENCES

[1] K. Slattery and H. Skinner, *Platform Interference in Wireless Systems: Models, Measurement, and Mitigation.* Burlington, MA, USA: Newnes, 2008, pp. 5–6.

[2] Q. Huang, T. Enomoto, S. Seto, K. Araki, J Fan, and C. Hwang, "A Transfer Function Based Calculation Method for Radio Frequency Interference," *IEEE Trans. Electromagn. Compat.*, vol. 61, no. 4, pp. 1280-1288, Aug. 2019.

[3] Q. Huang, Y. Zhong, Z. Sun, T. Enomoto, S. Seto, K, Araki, J. Fan, and C. Hwang, "Reciprocity theorem based RFI estimation for heatsink emission," *in Proc. IEEE Int. Symp. Electromagn. Compat.*, New Orleans, LA, USA, 2019, pp. 590–594.

[4] L. Zhang, H. Yang, X. Su, Q, Huang, J. Rajagopalan, D. Pai, C. Hwang, "Radio-Frequency Interference Estimation for Multiple Random Noise Sources," *IEEE Trans. Electromagn. Compat.*, Nov. 2021.

[5] P.Wilson, "On correlating TEM cell and OATS emission measurements," *IEEE Trans. Electromagn. Compat.*, vol. 37, no. 1, pp. 1–16, Feb. 1995