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Identifying Interference From Multiple Noise Sources Using Only Magnetic Near Fields

Jingnan Pan, *Member, IEEE*, Xu Gao, *Member, IEEE*, and Jun Fan, *Fellow, IEEE*

***Abstract*—As electronic products become increasingly more complicated, multiple noise sources are likely to simultaneously interfere with the radio frequency (RF) receiver. It will be very helpful if the dominant noise source can be identified when solving the RF interference issue in a complex system. This article proposes a method to separately calculate the contributions from multiple noise sources at their overlapped frequencies so that the worse noise source could be identified even when multiple sources radiate simultaneously. The proposed method creatively employs the decomposition method based on the reciprocity theory to calculate the interference contribution from different sources. Furthermore, in the interest of reducing the near-field scanning time and complexity, the magnetic field only scanning method is developed by using the finite-element method (FEM). In the proposed method, Huygens's surface is established for each source. The tangential magnetic near fields on each Huygens's surface were then applied to solve the corresponding tangential electric fields by the FEM. Subsequently, the sources are removed while the corresponding Huygens's surfaces are maintained. The victim structure is excited under these conditions to obtain the tangential magnetic fields on Huygens's surfaces, and a novel FEM procedure is applied to obtain the tangential electric fields. Finally, based on the electric and magnetic fields, the interference from each noise source can be separately estimated based on the reciprocity theory. This method is validated by a numerical example and measurement. This approach can assist engineers in identifying the contribution of coupling from different sources and in efficiently resolving electromagnetic interference issues.**

***Index Terms*—Electromagnetic interference, finite-element method (FEM), radiated emission, reciprocity theory.**

I. Introduction

MOST electronic systems encounter radio frequency interference (RFI) problems. The most common sources of interference include components such as switching power supplies, displays, high-speed I/O traces, and processing components. As the overall size of electronic products continues to decrease, RFI has become an increasingly considerable problem. Moreover, there is generally more than one radiation source in a typical system with several sources radiating simultaneously. All of these sources will contribute to the victim structure. In this situation, identifying the corresponding contribution from each interference source is critical, in order to enable engineers to easily and rapidly find the dominant such that the RFI issues can be efficiently resolved.

Previously, engineers primarily identified electromagnetic noise source based on their experience or by using a spectrum analyzer to differentiate operating frequencies. For about a decade, artificial neural networks (ANN) have also been widely applied to identify electromagnetic radiated noise source types based on their different frequencies [1]–[3]. Weng *et al*. [1] utilized a multiple layer perception architecture neural network to identify different types of source devices. The shielding effectiveness of an enclosure was also investigated by the ANN method in [2]. Shieh and Lin [3] further evaluated the direction of arrival based on the phase difference. However, none of the above applications can handle sources that are radiating simultaneously or at similar frequencies. In modern electronic products, multiple sources often have overlapping radiation frequencies; thus, a method for discriminating interference from different sources at the same frequency is in high demand.

Recently, several interesting works have been reported in the field of RFI estimation using the reciprocity theory [4], [5], [12]–[17]. Wang *et al.* [4] proposed a decomposition method based on reciprocity and obtained good estimation results for numerical cases. In [5], this method was further developed and predicted the coupling from a single source to the victim antenna in different locations, enabling an evaluation of the victim antenna placement. Essentially, this method is based on tangential fields on Huygens's surface covering the victim antenna in "Forward Problem" and "Reverse Problem" of the article presented in [4]. In [13], a similar method has been used for IC placement optimization to reduce RFI. In [14], one analytical intrasystem electromagnetic interference model has been proposed. However, the method in [5], [13] and [14] may not be suitable for identifying RFI for multiple sources mainly because of two reasons. First, Huygens's surface is defined at the victim antenna side. Thus, it cannot be used when multiple noise sources radiate at the same time because the near-field scanning on Huygens's surface cannot separate different sources. Second, it uses the dipole element to model the noise source, which takes efforts for establishing the accurate dipole element model. The number and location of dipole elements have a large effect on the

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quality of the modeling for representing the noise source. And also the near-field scanning area for dipole element modeling needs to be large enough that may make the scanning planes for different noise sources overlapping.

In this article, Huygens's surfaces used to estimate the coupling are proposed to move to the locations of the sources. In this manner, the fundamental theory still applies, and the coupling from multiple sources to the same antenna can be obtained separately. This method not only makes it possible to discriminate the coupling contribution from each source at the same frequency but also overcomes the difficulty when the setup of the antenna is not suitable to place Huygens's surface. Due to the moving of Huygens's surface to the noise source location, Huygens's surface can be small and close to the noise source, as long as it can enclose the source. This means that the near-field scanning can be implemented as close as possible to the specific radiator, and thus, the radiation from other sources will not be involved or can be neglected.

Moreover, as discussed in [6], for a radiator positioned close to the ground plane of a printed circuit board (PCB), its five-faced Huygens's surface can be further simplified as a top plane and four sidelines. The effectiveness of the five-faced Huygens's surface and one-faced Huygens's surface was also compared in [12], where simplified Huygens's surfaces were utilized instead of those reported in [4]. Moreover, because the simplified Huygens's surface is smaller than the five-faced one, the scanning procedure is less likely to be interrupted by nearby structures in a complex system. Based on the analysis in [6], the vertical components on the sidelines can be neglected; thus, all of the measurements can be performed by one magnetic probe, ensuring that the measurements are consistent.

Another contribution of this article is using magnetic fields only in the measurements. The corresponding electric fields will be converted from scanned magnetic fields by finite-element method (FEM), as first introduced in [7]. Article [8] improved this procedure to make it usable for the "Forward Problem" in the decomposition method of the article presented in [5]. In this article, a novel and creative FEM processing procedure is proposed for the first time to solve the electric fields from the magnetic fields in the "Reverse Problem" of the article presented in [5]. Thus, the decomposition method can be applied by using only magnetic fields from measurements. The magnetic field only measurement can reduce the scanning time and complexity of the measurement. In this article, the magnetic field is used because designing the electric field probe is more difficult than designing the magnetic field probes with the same sensitivity and bandwidth [7]. Although the magnetic field only algorithm is used in this article, a similar method and principle can be applied for the electric field only algorithm if for some reason electric near-field measurement is preferred.

In sum, this article proposed a novel method based on the reciprocity theory to identify the interference contributions from multiple sources at their overlapped frequencies. Compared with the methods in [1]–[3] and [9], the proposed method is more practical for the intersystem sources of complex products. By using a simplified Huygens's surface and the conversion of electric fields from magnetic fields, the time and cost of the measurements are decreased, while the accuracy increases.

II. Decomposition Method With Huygens's Surface on the Source

In this section, the decomposition method based on reciprocity will be introduced. In modern complex electronic products, it is sometimes more difficult to set Huygens's surface above the victim antenna. In this situation, Huygens's surface is set up above the radiation source. The validation of this method is also given in Section II-B.

A. Methodology

As described in [4] and [5], the decomposition method has three steps, "Forward Problem," "Reverse Problem," and "Interference Estimation" to estimate the coupling from the radiation source to the victim antenna. Choosing Huygens's surface of the radiation source, the method is illustrated in Fig. 1.

One typical RFI problem is described in Fig. 1(a); the radiation source and the victim antenna are located on the ground of the PCB. When the radiation source is excited, its radiation will be coupled to the nearby victim antenna.

In "Forward Problem," as shown in Fig. 1(b), Huygens's surface is set up to enclose the radiation source. This Huygens's surface can be divided into many cells on which the tangential electromagnetic fields are denoted as E_c^{fwd} and H_c^{fwd}. The coupling induces electromagnetic fields on the port of victim antenna, which is in the receiving mode, named as E_a^{fwd} and H_a^{fwd}.

In "Reverse Problem," as shown in Fig. 1(c), the source is removed and the victim antenna is excited with a known voltage, U_a^{rev}. The tangential electromagnetic induced by this excitation on the antenna port is E_a^{rev} and H_a^{rev}. Thus, the tangential fields on the same Huygens's surface with "Forward Problem" are from the radiation of the victim antenna. They are recorded as E_c^{rev} and H_c^{rev}.

Furthermore, similar with the article presented in [6], when the five-faced Huygens's surface is very close to the PCB ground, the four sidewalls can be simplified as the four sidelines and the vertical components of the magnetic fields, the horizontal components of the electric fields can be neglected, as shown in Fig. 1(d). This simplification is based on the perfect electrical conductor (PEC) boundary condition. For PCB application, usually, there will be a solid ground plane under radiation sources, which can be taken as the PEC boundary. Thus, when the height of Huygens's surface is small (relative to the wavelength of interested frequency), the tangential electric fields and the vertical magnetic fields should be much smaller than the vertical electric fields and the tangential magnetic fields. The theory fundamentals and validation results in both simulation and measurements for the accuracy of this simplified Huygens's surface in PCB application are illustrated in [6] with detail.

Based on the reciprocity theorem, the electric current J and the magnetic current M in "Forward Problem" and "Reverse

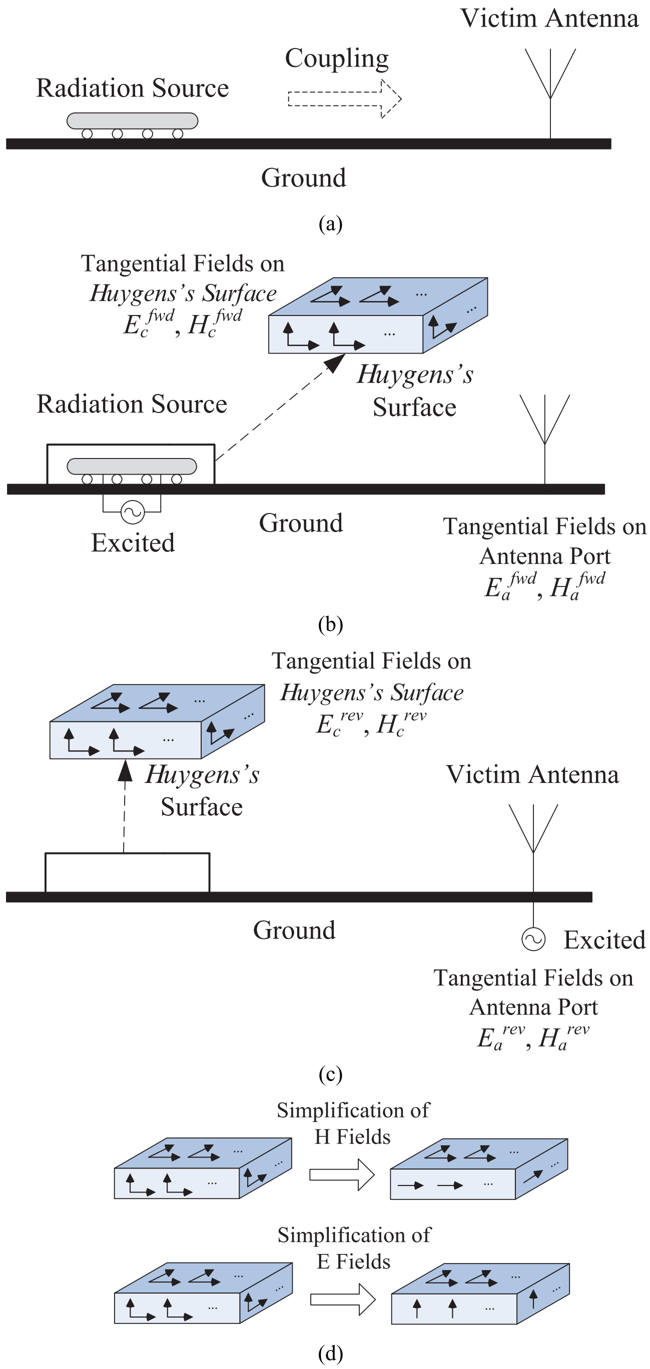

Fig. 1. Decomposition method based on reciprocity. (a) Original RFI problem. (b) "Forward Problem." (c) "Reverse Problem." (d) Simplification of Huygens's surface and the fields on it.

Problem" satisfy

$$\int_V \left(E_c^{\mathrm{rev}} \cdot J_c^{\mathrm{fwd}} - H_c^{\mathrm{rev}} \cdot M_c^{\mathrm{fwd}}\right) dv = \int_V \left(E_a^{\mathrm{fwd}} \cdot J_a^{\mathrm{rev}} - H_a^{\mathrm{fwd}} \cdot M_a^{\mathrm{rev}}\right) dv \quad (1)$$

where "fwd" and "rev" denote the problem type, the subscript c means the corresponding fields or currents located on Huygens's box, and similarly, a means the antenna port.

The current sources J_c^{fwd} and M_c^{fwd} are the equivalent sources resulting from the tangential electromagnetic fields on Huygens's surface, which can be replaced by the tangential fields on the box. On the other hand, following the procedure in [10], the two terms on the right side of (1) can be expressed by the current and voltage on the antenna port. Thus, (1) becomes

$$\sum_{\mathrm{cells}} \hat{n} \times H_c^{\mathrm{fwd}} \cdot E_c^{\mathrm{rev}} S_{\mathrm{cell}} + \sum_{\mathrm{cells}} \hat{n} \times E_c^{\mathrm{fwd}} \cdot H_c^{\mathrm{rev}} S_{\mathrm{cell}} = -I_a^{\mathrm{rev}} U_a^{\mathrm{fwd}} - I_a^{\mathrm{fwd}} U_a^{\mathrm{rev}} = -\left(\frac{1}{Z_{\mathrm{in}}} + \frac{1}{Z_L}\right) U_a^{\mathrm{fwd}} U_a^{\mathrm{rev}} \quad (2)$$

where Huygens's surface is equally meshed into small square cells with the area of S_{cell}; Z_{in} is the input impedance of the antenna and Z_L is the load impedance at the antenna port in "Forward Problem," 50 Ω in common usage; and U_a^{rev} is the exciting voltage of antenna in "Reverse Problem."

By solving (2), the coupling voltage is obtained as follows:

$$U_a^{\mathrm{fwd}} = -\frac{Z_{\mathrm{in}} Z_L}{U_a^{\mathrm{rev}} (Z_{\mathrm{in}} + Z_L)} \times \left(\sum_{\mathrm{cells}} \hat{n} \times H_c^{\mathrm{fwd}} \cdot E_c^{\mathrm{rev}} S_{\mathrm{cell}} + \sum_{\mathrm{cells}} \hat{n} \times E_c^{\mathrm{fwd}} \cdot H_c^{\mathrm{rev}} S_{\mathrm{cell}}\right). \quad (3)$$

B. Validation

To validate the decomposition method based on reciprocity, one simple passive structure is taken as an example in Fig. 2.

Structure 1 is a patch antenna working at 2.5 GHz as well as a curved 50 Ω trace; and structure 3 plays the role of a radiation source. The trace is shorted at one end and excited at the other one. Huygens's surface is the blue box above the trace. It is a 40 × 40 mm box with a height of 5 mm. Four lines just below the edges of the top plane with a height of 3 mm are taken as the sidelines of Huygens's surface. These validation structures are also fabricated on a PCB. This PCB has the same geometries and materials to the simulation model. So, the validation structures are modeled both in simulation, as shown in Fig. 2(a), and measurements Fig. 2(b). For this simple case, the simulation model could predict the radiation and coupling of the PCB structures very well.

Applying the decomposition method based on reciprocity, the S-parameters between the victim antenna and the source can be estimated. The results are compared with direct simulation in HFSS (one commercial electromagnetic simulation software) and the measurements in Fig. 3.

Good agreement of the comparison validates that the decomposition method based on the reciprocity can predict the interference between the victim antenna and the noise source well.

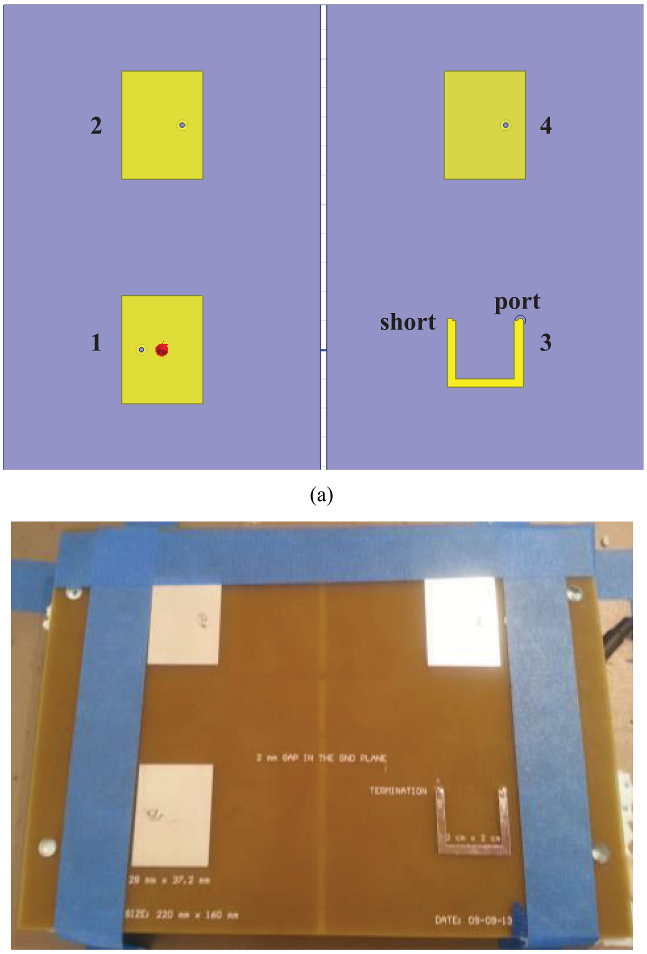

Fig. 2. Passive structure model for validation, 1 is the victim antenna and 3 is the radiation source. (a) HFSS model in the simulation. (b) PCB of the model in measurement.

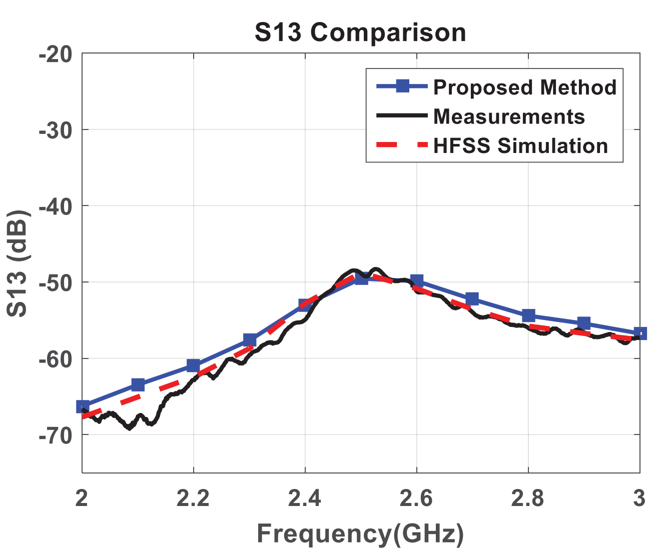

Fig. 3. Estimation of the S-parameters between the victim antenna and the radiation source, compared with direct simulation in HFSS and measurements.

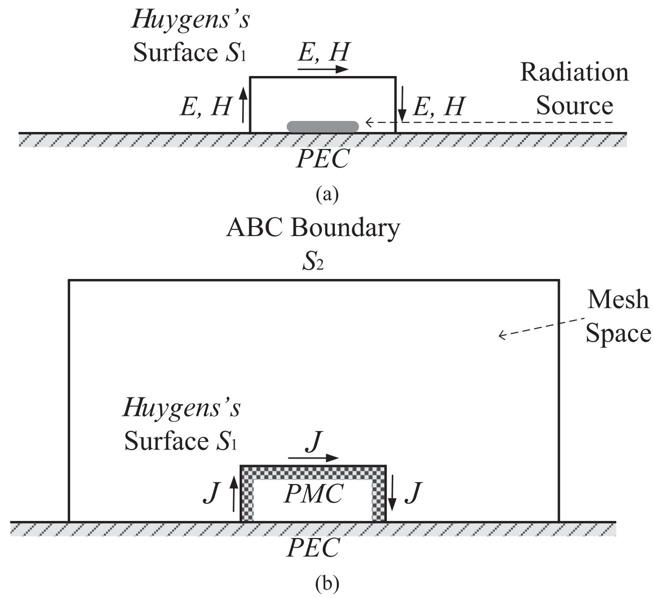

Fig. 4. Convert H-fields to E-fields in "Forward Problem." (a) Original situation. (b) FEM processing to solve the E-fields by the equivalent electric current sources from H-fields.

III. *H*-Fields to *E*-Fields Conversion in Forward Problem

In Section II, the procedure of how to estimate the interference between the radiation source and the victim antenna by a decomposition method is demonstrated. In both "Forward Problem" and "Reverse Problem," the tangential electromagnetic fields are employed to do the calculation. However, in practical applications, the electric field probe is much more difficult to design and calibrate. It is very propitious to obtain the E-fields from the measured H-fields instead of direct measurement. This section will introduce a method to convert H-fields to E-fields in "Forward Problem" by Huygens's principle and FEM.

A. Methodology

In "Forward Problem," the tangential electromagnetic fields on Huygens's surface are from the radiation source inside the surface. Thus, some specific boundaries are set up based on Huygens's principle [11] and the FEM process is applied to solve E-fields from H-fields, as in [8]. This procedure is illustrated in Fig. 4.

The original situation in "Forward Problem" is described in Fig. 4(a). The ground plane of the PCB is assumed as the PEC boundary. Based on Huygens's principle, the fields outside Huygens's surface S_1 can be reproduced by the equivalent current sources converted from the tangential electromagnetic fields on S_1. By filling the perfect magnetic conductor (PMC) boundary inside S_1, the radiation outside is all coming from the equivalent electric current sources [J in Fig. 4(b)] [8]. Therefore, the E-fields on S_1 can be solved by the FEM processing setup in Fig. 4(b). The absorbing boundary condition is applied to the five-faced box S_2, which is located at a proper distance

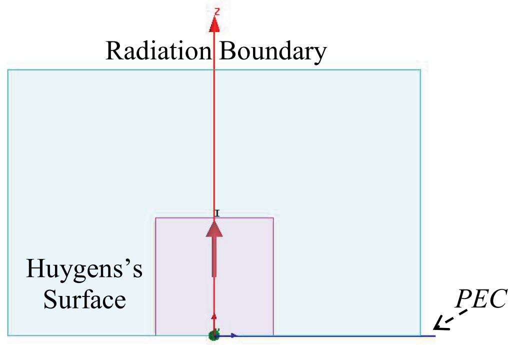

Fig. 5. HFSS model of one dipole to validate the *H*-fields to *E*-fields conversion method in "Forward Problem."

away from Huygens's surface. Meshing the area between S_2 and S_1, the electric fields everywhere in the mesh space can be calculated by

$$\nabla \times \left(\frac{1}{\mu_r}\nabla \times \bar{E}\right) - k_0^2\varepsilon_r\bar{E} = -jk_0Z_0\bar{J}. \quad (4)$$

Consequently, the tangential electromagnetic fields E_c^{fwd} and H_c^{fwd} on Huygens's surface in "Forward Problem" are obtained. This approach prevents using problematic electric probes to improve the accuracy of the measurements.

B. Validation

A dipole is taken as the radiation source inside Huygens's surface in this part to validate the above-mentioned *H*-fields to the *E*-fields conversion method. Its full-wave model in HFSS is plotted in Fig. 5.

An electric dipole directing to the *z*-axis is located in the center of Huygens's surface with the size of 60 × 60 mm × 60 mm. The bottom of Huygens's surface is an infinitely large PEC boundary. The excitation of the dipole is 1 μA·m at 1 GHz. The solved electric fields by the method in Section III-A are compared with the simulation on the top plane of Huygens's surface in Fig. 6.

From Fig. 6, it is observed that the average field distribution and strength are reconstructed by the proposed method.

IV. *H*-Fields to *E*-Fields Conversion in Reverse Problem

On the other hand, in "Reverse Problem," electric fields are also preferred to be solved from the measured magnetic fields. However, different from "Forward Problem," the excited source is the victim antenna, which is located outside Huygens's surface in this case. For this situation, an innovative FEM processing procedure is proposed to fulfill *H*-fields to *E*-fields conversion in this section.

A. Methodology

As described in Fig. 7(a), the radiation source is removed and the victim antenna is excited by a known voltage. Under this circumstance, the electromagnetic fields on the same Huygens's

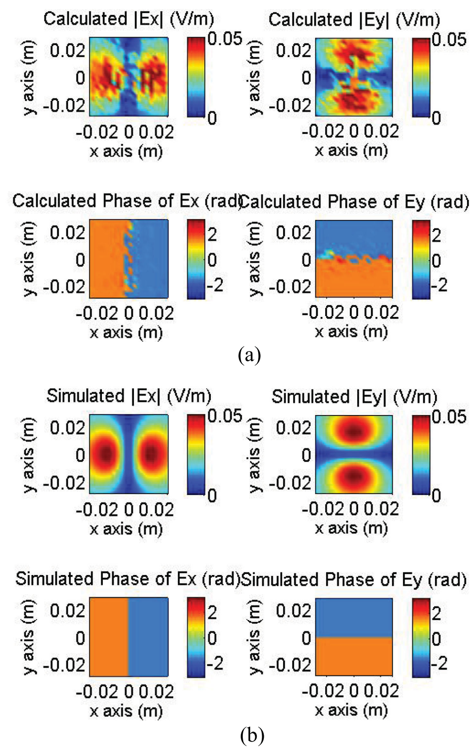

Fig. 6. *E*-fields comparison on the top plane of Huygens's surface in "Forward Problem." (a) *E*-fields converted from *H*-fields by the proposed method. (b) Simulated *E*-fields.

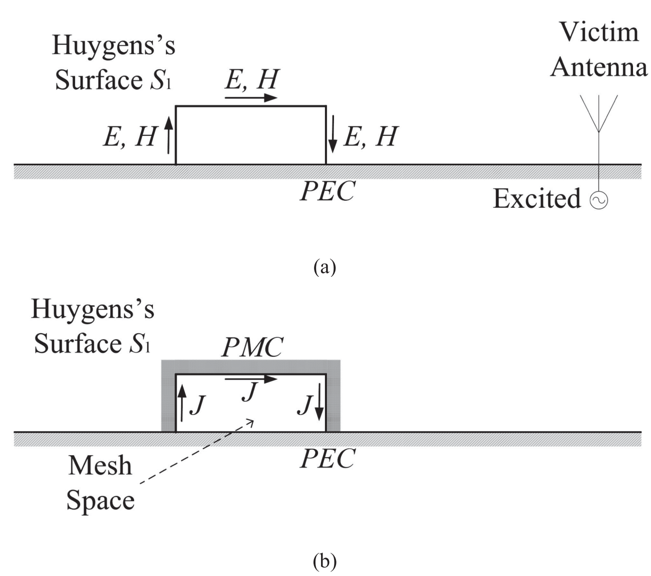

Fig. 7. Convert *H*-fields to *E*-fields in "Reverse Problem." (a) Original situation. (b) FEM processing to solve the *E*-fields by the equivalent electric current sources from *H*-fields.

surface with the "Forward Problem" are all from the radiation of the victim antenna. The difference between "Reverse Problem" and "Forward Problem" is in "Reverse Problem" because the fields is generated by the antenna outside Huygens's Surface [*S*1 in Fig. 7(b)], the computational region will be the space inside *S*1. Then, filling the PMC boundary on and outside Huygens's

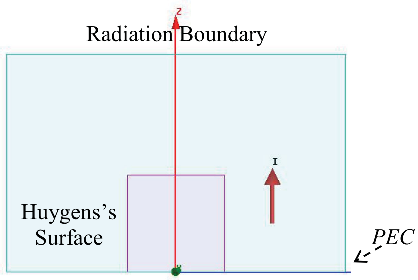

Fig. 8. HFSS model of one dipole to validate the H-fields to E-fields conversion method in "Forward Problem."

surface, the fields inside it can be reproduced by the equivalent electric current sources, converted from magnetic fields, on the surface. It is a similar FEM procedure but uses the interior of Huygens's box as the mesh and calculation region, as shown in Fig. 7(b). The region for FEM processing has five faces of PMC boundary and one face of PEC boundary so that the fields in it can be solved by (4). Thus, E_c^{rev} on Huygens's surface is obtained from the measured H_c^{rev} in the "Reverse Problem."

B. Validation

The validation of H-fields to E-fields conversion in "Reverse Problem" also uses a 1 μA·m electric dipole at 1 GHz. But this time, the dipole is outside Huygens's surface, drawn in Fig. 8. The distance between the dipole and the center of the side-length box is 60 mm. The simulated magnetic fields on Huygens's surface are exported and the proposed method is applied to get the electric fields. The solved electric fields are compared with the simulated fields in Fig. 9.

The comparison in Fig. 9 indicates similar results with Section III. The H-fields to E-fields conversion method for "Reverse Problem" also has good performance to solve the electric fields. Both the pattern and the strength are well predicted.

V. Identify Multiple Noise Sources

Previous sections have illustrated three algorithms. A decomposition method based on reciprocity gives how to predict the interference between the radiation source and the victim antenna; and in both "Forward Problem" and "Reverse Problem," the electric fields on Huygens's surface can be obtained from magnetic fields, which are more accurate in measurement. Combining the three methods above, the interference can be estimated by the magnetic fields only.

Furthermore, in the situation of multiple sources, it is likely that at the very close region of each source, the radiation is mainly from this specific source itself. Thus, although the radiation from multiple sources cannot be distinguished from each other at the victim antenna, the radiation at the close region to the source is noninterfering. Hence, when Huygens's surface is set above one of the radiation sources, the decomposition method could give the interference from this specific source and not related to any other one. By calculating the interference using different Huygens's surfaces on different sources, the interference contribution from different sources is identified, even though they radiate simultaneously and have overlapped frequencies.

The diagram for identifying the interference from different sources is plotted in Figs. 10 and 11.

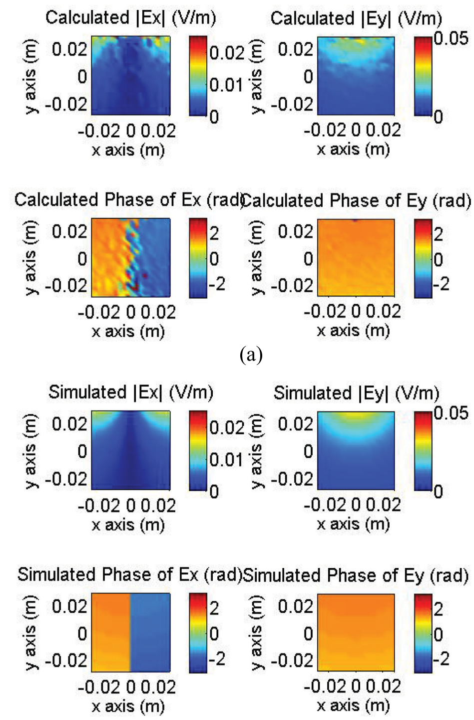

Fig. 9. E-fields comparison on the top plane of Huygens's surface in "Reverse Problem." (a) E-fields converted from H-fields by the proposed method. (b) Simulated E-fields.

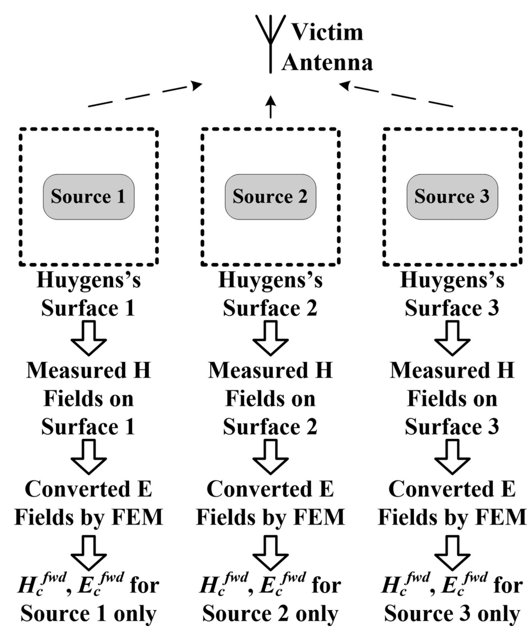

Fig. 10. Flowchart of "Forward Problem" to identify the interference from different sources.

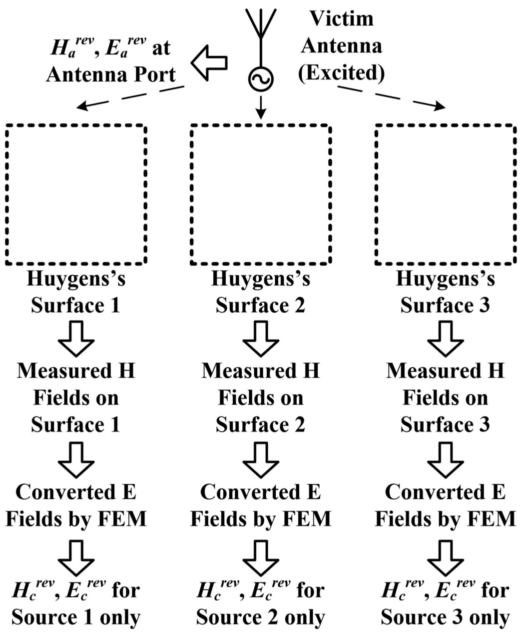

Fig. 11. Flowchart of "Reverse Problem" to identify the interference from different sources.

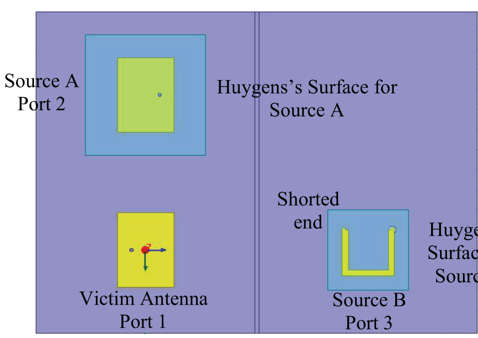

Fig. 12. Passive structures model in HFSS for identifying different sources.

Fig. 10 explains the procedure to get E_c^{fwd} and H_c^{fwd} on different Huygens's surfaces for the corresponding source in the "Forward Problem" of decomposition method based on reciprocity. H_c^{fwd} comes from measurements or simulation and E_c^{fwd} is converted from H_c^{fwd}. Fig. 11 shows the procedure to get E_a^{fwd} and H_a^{fwd} from the excited antenna on the same Huygens's surfaces in "Reverse Problem." Based on the article presented in [10], with the excitation, the input impedance and load impedance of the antenna, applying the obtained fields on each Huygens's surface in (4), the interference from each source can be estimated separately.

A simple PCB with several passive structures is taken to present the procedure and the performance of the proposed method to identify the coupling from different sources. Fig. 12 gives the full-wave model of this PCB.

On this PCB, a patch antenna with a size of 28 × 37.2 mm is the victim antenna. Its excitation port is numbered as 1. There are two sources. source A is also a patch antenna with the same size and located 77.2 mm away from the victim. The port of source A is numbered as 2. The other source, source B, is a curved trace shorted at one end and excited by port 3 at the other end. The two blue squares on two sources are their Huygens's surfaces. One is 60 × 60 × 5 mm for source A and the other one is 40 × 40 × 5 mm for source B.

In "Forward Problem," the excitation for source A is 0.1 V and the excitation for source B is 0.3162 V. The two sources are excited simultaneously. The victim antenna is not excited. The magnetic fields on two Huygens's surfaces are exported from the simulation. And the electric fields are calculated from magnetic fields by the methods in Section III.

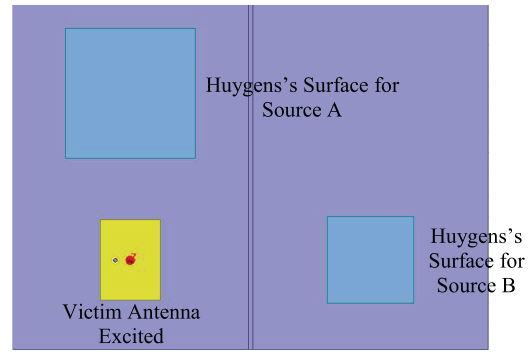

Fig. 13. Passive structures model in HFSS for identifying different sources.

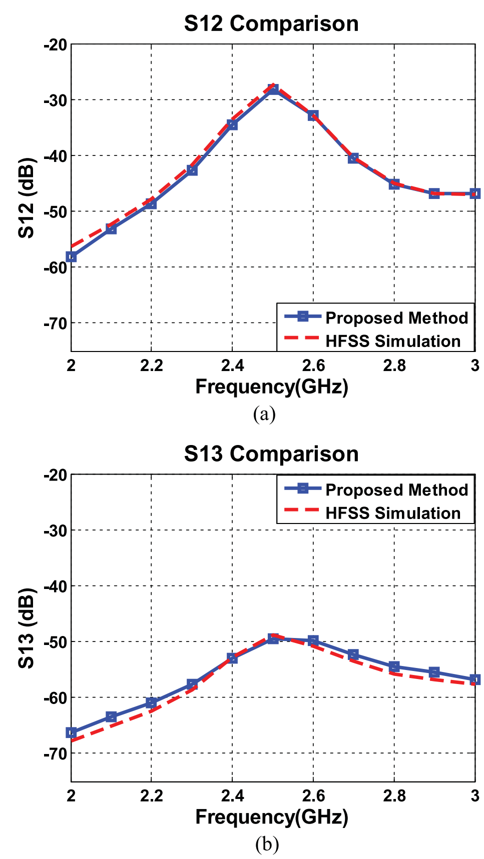

Fig. 14. Estimation of the *S*-parameters between the victim antenna and (a) source A (*S*12), (b) source B (*S*13).

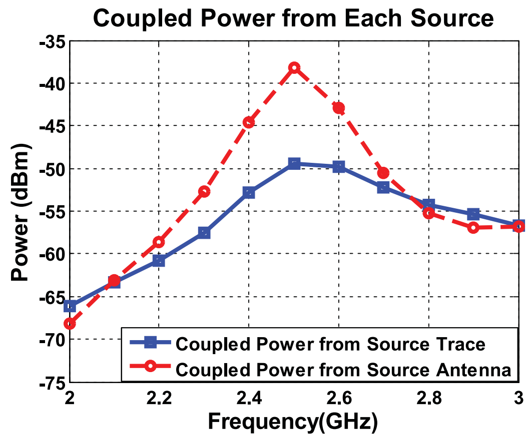

Fig. 15. Estimation of the coupled power from each source.

For “Reverse Problem,” the model is changed as Fig. 13. The sources are removed as well as an excitation of 1 V is applied on the victim antenna. Similarly, the magnetic fields on two Huygens’s surfaces are simulated and the electric fields can be converted by the method in Section IV.

With the fields obtained in “Forward Problem” and “Reverse Problem” and the load impedance and the input impedance of the victim antenna, the coupled voltages from different sources are given by (4) separately. Since all the ports are designed as 50 Ω, the *S*-parameters, the coupled power between each source and the victim antenna can be easily calculated from the coupled voltages. Fig. 14 plots these two *S*-parameters.Good agreement of the *S*-parameters of both sources validates that the proposed method can estimate the coupled voltage from different sources separately over a frequency band well. Thus, the coupled power from each source at different frequencies can also be predicted, as shown in Fig. 15.

From the estimation in Fig. 15, although two sources are radiating in the overlapped frequencies at the same time, the coupled power from each source can still be predicted, respectively, by putting Huygens’s surface on each source in the proposed method. It makes the evaluation of the interference problem easier. Engineers can conveniently find out the major noise source at different frequencies and observe the interference trend of different sources by reading the estimation in Fig. 15.

VI. Conclusion

In this article, a method to identify the interference from multiple noise sources using only magnetic near fields is proposed. There are two main novelties in this article. The first one is that this method sets Huygens’s surfaces on each noise source in the decomposition method based on the reciprocity theory. By doing this, the coupled power from each source to the victim antenna can be separately identified, even if the sources are radiating simultaneously at the overlapping frequencies. Another novelty of the proposed method is that two FEM processing procedures are introduced to solve the electric fields from the magnetic fields on Huygens’s surfaces so that the proposed method can be achieved by magnetic only near-field scanning in practical. This approach allows reducing the scanning time by half at least. The computation time of this algorithm is negligible compared with the near-field scanning time. The proposed method was validated step-by-step in this article and can assist engineers better evaluating the RFI problems in the presence of multiple sources.

Compared with the previously proposed RFI estimation method in [5], the proposed method has lowered the complexity in practical implementation for the case with multiple sources in one system. At first, only one near-field scanning area for one noise source is needed, which is Huygens’s surface enclosing the noise source instead of two areas, the source area and the victim antenna area. Furthermore, Huygens’s surface for the noise source is simplified so that it is usually can be done with the 2-D scanning instead of the 3-D scanning. Last but not the least, the magnetic only near-field scanning makes the practical implementation better in terms of scanning time, setup, and calibration of the testing.

In real applications, whether this proposed method can be applied to the product mainly depends on if the near-field scanning on Huygens’s surface of the noise source is achievable. It is usually can be done for the general PCB structures, for example, the noise source is one IC, or some traces on the PCB. However, for some complex system, the techniques to precisely locate the radiation sources, accurately measure *H*-field for the 3-D structure, will be needed to expand the application of the proposed method.

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References

[1] H. Weng, X. Dong, X. Hu, D. G. Beetner, T. Hubing, and D. Wunsch, “Neural network detection and identification of electronic devices based on their unintended emissions,” in *Proc. Int. Symp. Electromagn. Compat.*, 2005, vol. 1, pp. 245–249.

[2] F. T. Belkacem *et al.*, “The analytical, numerical and neural network evaluation versus experimental of electromagnetic shielding effectiveness of a rectangular enclosure with apertures,” in *Proc. IEEE 9th Int. Conf. Cybern. Intell. Syst.*, 2010, pp. 1–6.

[3] C.-S. Shieh and C.-T. Lin, “Direction of arrival estimation based on phase differences using neural fuzzy network,” *IEEE Trans. Antennas Propag.*, vol. 48, no. 7, pp. 1115–1124, Jul. 2000.

[4] H. Wang, V. Khilkevich, Y.-J. Zhang, and J. Fan, “Estimating radio-frequency interference to an antenna due to near-field coupling using decomposition method based on reciprocity,” *IEEE Trans. Electromagn. Compat.*, vol. 55, no. 6, pp. 1125–1131, Dec. 2013.

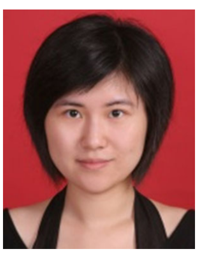
[5] J. Pan *et al.*, “Radio-frequency interference estimation using equivalent dipole-moment models and decomposition method based on reciprocity,” *IEEE Trans. Electromagn. Compat.*, vol. 58, no. 1, pp. 75–84, Feb. 2016.

[6] J. Pan, X. Gao, Y. Zhang, and J. Fan, “Far-field radiation estimation from near-field measurements and image theory,” in *Proc. IEEE Int. Symp. Electromagn. Compat.*, 2014, vol. 1, pp. 609–614.

[7] X. Gao, J. Fan, Y. Zhang, H. Kajbaf, and D. Pommerenke, “Far-field prediction using only magnetic near-field scanning for EMI test,” *IEEE Trans. Electromagn. Compat.*, vol. 56, no. 6, pp. 1335–1343, Dec. 2014.

[8] J. Pan, X. Gao, and J. Fan, “Far-field prediction by only magnetic near fields on a simplified Huygens’s surface,” *IEEE Trans. Electromagn. Compat.*, vol. 57, no. 4, pp. 693–701, Aug. 2015.

[9] D. Shi and Y. Gao, "A new method for identifying electromagnetic radiation sources using backpropagation neural network," *IEEE Trans. Electromagn. Compat.*, vol. 55, no. 5, pp. 842–848, Oct. 2013.
[10] J. Richmond, "A reaction theorem and its applications to antenna impedance calculations," *IRE Trans. Antennas Propag.*, vol. 9, no. 6, pp. 515–520, Nov. 1961.
[11] C. A. Balanis, *Advanced Engineering Electromagnetics*. New York, NY, USA: Wiley, 1999.
[12] Y. Sun, B.-C. Tseng, H. Lin, and C. Hwang, "RFI noise source quantification based on reciprocity," in *Proc. IEEE Symp. Electromagn. Compat., Signal Integrity Power Integrity*, 2018, pp. 548–553.
[13] C. Hwang and Q. Huang, "IC placement optimization for RF interference based on dipole moment sources and reciprocity," in *Proc. Asia-Pac. Int. Symp. Electromagn. Compat.*, Seoul, South Korea, 2017, pp. 331–333.
[14] S. Lee *et al.*, "Analytical intra-system EMI model using dipole moments and reciprocity," in *Proc. IEEE Int. Symp. Electromagn. Compat. IEEE Asia-Pac. Symp. Electromagn. Compat.*, Singapore, 2018, pp. 1169–1173.
[15] Y. Zhong, W. Song, C. Kim, C. Park, and C. Hwang, "Efficient automotive simulation using reciprocity for intentional electromagnetic interference," in *Proc. IEEE Int. Symp. Electromagn. Compat., Signal Power Integrity*, New Orleans, LA, USA, 2019, pp. 600–604.
[16] Y.-F. Shu and X.-C. Wei, "PCB electromagnetic interference modelling based on reciprocity theorem," in *Proc. IEEE Elect. Des. Adv. Packag. Syst. Symp.*, Haining, China, 2017, pp. 1–3.
[17] Q. Huang *et al.*, "Reciprocity theorem based RFI estimation for heatsink emission," in *Proc. IEEE Int. Symp. Electromagn. Compat., Signal Power Integrity*, New Orleans, LA, USA, 2019, pp. 590–594.



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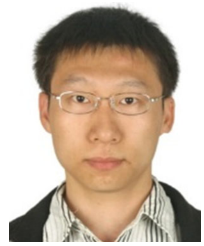

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