01 Jan 2023

Modeling And Mitigation Of Radio Frequency Interference For Wireless Devices

Chulsoon Hwang
Missouri University of Science and Technology, hwangc@mst.edu

Jun Fan
Missouri University of Science and Technology, jfan@mst.edu

Recommended Citation

C. Hwang and J. Fan, "Modeling And Mitigation Of Radio Frequency Interference For Wireless Devices," *IEEE Electromagnetic Compatibility Magazine*, vol. 12, no. 1, pp. 87 - 92, Institute of Electrical and Electronics Engineers, Jan 2023.
The definitive version is available at https://doi.org/10.1109/MEMC.2023.10136454

Modeling and Mitigation of Radio Frequency Interference for Wireless Devices

Chulsoon Hwang and Jun Fan

Department of Electrical and Computer Engineering, Missouri University of Science and Technology, Rolla, MO

Email: hwangc@mst.edu, jfan@mst.edu

Abstract— This article reviews the electromagnetic framework used to model radio frequency interference (RFI) and the resulting development of mitigation methods. With the rise of IoT devices, wireless devices in which RF antennas are integrated with high-performance digital systems in small form factors suffer from electromagnetic interference, known as RF interference or RF desensitization. The simple yet rigorous framework can be used for a systematic RFI-aware design, saving time and effort for trial-and-error troubleshooting.

Index Terms —RF interference, RF desensitization, electromagnetic interference (EMI), interference mitigation.

I. Introduction

A fundamental requirement of wireless devices is a long radio frequency (RF) range. Radio range is a function of multiple factors, including transmitter power, antenna gain, path loss, and receiver sensitivity. Transmitter power and antenna gain are typically regulated by federal law. Transmitters with higher power also consume more energy, whereas low power is critical for portable devices. Therefore, increasing the RF ranges of wireless devices by increasing transmitter power or antenna gain is not advisable. Furthermore, path loss is an environmental feature that is usually unmanageable. Accordingly, the only practical and feasible approach to increasing RF range is improving receiver sensitivity. Increasing receiver sensitivity can increase radio range as much as increasing transmitter power without increasing power consumption or causing harm to the human body.

Modern technology has enabled extreme levels of amplification to be easily achieved within a receiver; thus, receiver amplification is not a factor limiting receiver sensitivity. Instead, the limiting factor in modern receiving antennas or receiver systems is noise: a weak signal is not limited by the actual strength of the signal but rather by the noise that masks it out. This noise can come from a variety of sources. The main type of noise that limits receiver sensitivity is internally generated by digital integrated circuits (ICs) and their interconnects. This is called RF interference (RFI), also known as RF desensitization.

Typical solutions to this problem involve adding shielding or absorbing components (usually later in the development cycle) that can alter RF antenna performance (detuning its resonant frequency) when placed in its proximity. However, such additions increase product cost. An alternative mitigation solution is damping signal edges (intentionally degrading signal quality) to decrease the energy of the noise radiation source. However, this approach decreases data rate and is thus not desirable for modern high-speed digital systems.

Departing from the conventional mitigation approaches, a new paradigm of RFI mitigation without adding extra components or compromising signal integrity was introduced in [1]-[3]. The concept is based on and derived from an electromagnetic (EM) framework and demonstrated with real product examples [4]-[6]. This article reviews the EM framework and mitigation methods.

II. RFI Model

A. EM Framework

This section introduces the EM framework used to model noise coupling to RF antennas. The reciprocity theorem, also known as the Lorentz reciprocity theorem, is the cornerstone of the coupling model. Consider two sources, (J_1, K_1) and (J_2, K_2), and their associated fields within a medium that is enclosed by a sphere of infinite radius. From the RFI perspective, the infinite radius implies that every noise source, not just a specific noise of interest, contributing to the noise presented at the antenna terminals should be considered. The reciprocity theorem is then expressed by (1) [7], where J and K are the densities of the electric- and magnetic-source currents. Subscripts indicate the source of the field. For example, E_1 represents the electric field intensity set up by source 1.

$$\iiint_V (E_1 \cdot J_2 - H_1 \cdot K_2)dv = \iiint_V (E_2 \cdot J_1 - H_2 \cdot K_1)dv \qquad (1)$$

The interaction between a set of fields and a set of sources that produces another set of fields has been defined as Reaction [8]. <1,2> presents the reaction of fields E_1 and H_1 on source J_2 and K_2, and <2,1> represents the reaction of fields E_2 and H_2 on source J_1 and K_1. The reactions in (2) and (3) are equal, i.e., <1,2>=<2,1>

$$<1,2> = \iiint_V (E_1 \cdot J_2 - H_1 \cdot K_2) dv \tag{2}$$

$$<2,1> = \iiint_V (E_2 \cdot J_1 - H_2 \cdot K_1) dv \tag{3}$$

Consider the situation shown in Fig. 1 in which the noise source (source 1) is radiating, setting up the field (E_1, H_1), and inducing voltage V_1 at the terminals of the receiving antenna (source 2), called the forward problem. Similarly, we can define the reverse problem, as shown in Fig. 2, in which the antenna is transmitting.

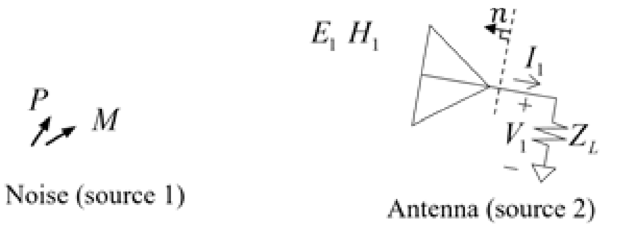


Fig. 1. Forward problem: Noise radiates, and the antenna receives.

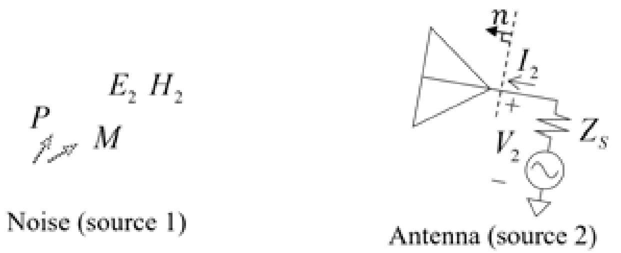


Fig. 2. Reverse problem: The antenna transmits.

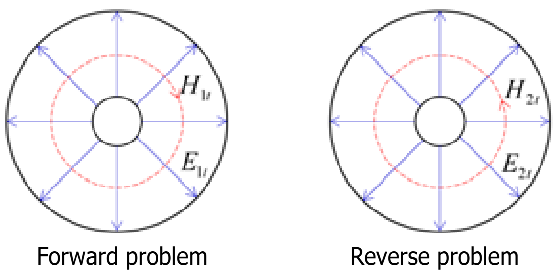


Fig. 3. E and H fields on the antenna feed (transmission line).

It is assumed that the feed system of the antenna has a section of a transmission line, and only a TEM mode exists at some point on the feed. The antenna terminals are chosen for such a point, and the E and H fields at that point are shown in Fig. 3. A normal vector coming out of the page in Fig. 3 corresponds to the direction toward the antenna, as denoted as n, in Fig. 1 and Fig. 2. The E and H fields in the transmission line in the forward problem are denoted as E_{1t} and H_{1t}. In the reverse problem, the fields inside the transmission line at the point (E_{2t}, H_{2t} in Fig. 3) are considered as source 2 generating the fields outside the transmission line (E_2, H_2). According to the equivalence principle, $J_{2t} = n \times H_{2t}$ and $K_{2t} = -n \times E_{2t}$. J_{2t} and K_{2t} are surface currents (A/m and V/m, respectively). The volume integral in (2) is reduced to the surface integral because source 2 (J_{2t}, K_{2t}) only exists at the terminal surface. The right-hand side of (2) can then be converted to terminal voltage and current as shown below. The reaction <1,2> is now linked to the terminal voltage and current.

$$\iiint E_1 \cdot J_2 dv = \iint E_{1t} \cdot J_{2t} ds = -I_2 V_1 \tag{4}$$

$$-\iiint H_1 \cdot K_2 dv = -\iint H_{1t} \cdot K_{2t} ds = -I_1 V_2 \tag{5}$$

$$<1,2> = -I_2 V_1 - I_1 V_2 \tag{6}$$

Based on network theory, we can simplify (6) as below. It is assumed that $Z_L = Z_S$, which is valid for most systems. V_2^+ is the incident voltage wave propagating toward the antenna.

$$<1,2> = -\frac{V_2}{Z_{in}} V_1 - \frac{V_1}{Z_L} V_2 = -\frac{Z_{in} + Z_L}{Z_{in} Z_L} V_1 V_2 \tag{7}$$

$$V_2 = V_2^+ + V_2^- = V_2^+ \frac{2Z_{in}}{Z_{in} + Z_S} \tag{8}$$

$$<1,2> = -\frac{2}{Z_L} V_1 V_2^+ \tag{9}$$

When source 1 is localized in a small volume, the volume integration of the electric- and magnetic-current densities are essentially the same as the electric and magnetic dipole moments. The use of equivalent dipole moments for a noise source is well established and dipole reconstruction methods will be discussed in the next section. Assuming that E_2 and H_2 are constant across source 1, the reaction <2,1> can be represented as (11).

$$\iiint J dv = P, \quad \iiint K dv = M \tag{10}$$

$$<2,1> = E_2 \cdot P - H_2 \cdot M \tag{11}$$

The physical unit of the electric- and magnetic- dipole moment is Am and Vm, respectively. In the EMC community, the magnetic-dipole moment is often defined using a current loop with its physical unit of Am^2 [9]. In such cases, the unit must be converted properly using the duality $M[Vm] = j\omega\mu M[Am^2]$ [10]. Note that although (11) is based on single electric and magnetic dipoles, it can be easily extended for distributed sources that are modeled by multiple dipoles, as in [6].Combining (9) and (11),

$$V_1 = \frac{Z_L}{2V_2^+}\left[-E_2 \cdot P + H_2 \cdot M\right] \tag{12}$$

As discussed in [8], Friis' transmission formula applies only in the far-field case (when the antennas are far apart), the reciprocity-based method, including (12), does not have this restriction. As the fields (E_2, H_2) are related to the terminal voltage at the antenna feed in the reverse problem, it is both meaningful and convenient to rewrite (12) as below

$$V_1 = \frac{Z_L}{2}\left[-\frac{E_2}{V_2^+} \cdot P + \frac{H_2}{V_2^+} \cdot M\right] \tag{13}$$

Equation (13) is simple yet insightful. The first term of the inner products represents the transfer function between the noise source and antenna (remember that we are using reciprocity). This can also be called antenna susceptibility. The coupling can then be interpreted as a combination of the noise source, antenna susceptibility, and their interaction (the inner product relationship). It should be emphasized that the electric-dipole moment only reacts to the electric field intensity of the antenna, and the magnetic-dipole moment to the magnetic field intensity. Moreover, when the antenna fields (E_2, H_2) and noise sources are orthogonal, even though their magnitudes are nonzero, the coupling could be zero. This is particularly interesting and important, leading to a new mitigation concept, as will be shown.

B. Validation

We need to know two parameters to model the coupling: the dipole moments in the forward problem and the transfer function, i.e., fields (E_2, H_2) with respect to the antenna terminal voltage, in the reverse problem.

Various methods are used to reconstruct the dipole moments, two popular ones being 1) using a TEM cell and 2) using a near-field scanner. A TEM cell can typically provide higher sensitivity owing to its guided structure, but it requires a specially designed board for EMI testing. A near-field scanner is suitable when it is difficult to fabricate a specific evaluation board for EMI testing.

The transfer function in the reverse problem can be obtained in two ways: simulation or measurement. Simulation is straightforward. We can set up a port at the antenna feed and monitor the electric and/or magnetic fields at the noise source location. Which field to monitor depends on the dipole moment type. Note that different tools may have different types of excitations, and (13) is based on incident voltage. Having total voltage as excitation, the expression in (7) should be used instead of (9). Because the reverse problem is of concern, we do not need the layout of the digital part or detailed information, which is related to the noise source. As long as the antennas are not detuned by the simplification (e.g. removing digital signal traces) and the same EM environment (boundaries) is kept, simplified 3D models can be used for the reverse problem.

When 3D models are not available, we can extract the transfer function through measurement. The measurement setup is illustrated in Fig. 4. As the scattering parameters (S-parameters) are defined using the incident and reflected waves, measured insertion loss can be readily converted to the transfer function as in (14).

$$\frac{H_2}{V_2^+} = PF_H S_{21}, \quad PF_H = \frac{E}{V} \tag{14}$$

The probe factor, *PF*, is defined as the ratio of electric field intensity for electric probes (or magnetic field intensity for magnetic probes) to the voltage measured at the instrument. The probe factor measurement is done with a 50-Ohm system, such as a spectrum analyzer. Thus, V in (14) is equal to the b_2 term in S-parameter.

The RFI model using (13) has been used in many studies to estimate the coupled noise at the antenna terminals, and some of them are shown here. The first example is from [6], where two dipoles (one electric dipole and one magnetic dipole) are placed near a patch antenna (Fig. 4 in [6]). The Hertzian dipole sources (built-in source type in HFSS) were used in the forward problem, and the fields (E_2, H_2) in the reverse problem were obtained when the antenna is transmitting without the dipole moments. A comparison with direct simulation results is shown in Fig. 5, and the error is smaller than 0.3 dB. The second example is from [3] where the CPU-memory interface is radiating interfering with embedded Wi-Fi antennas. The dipole moments were extracted using near-field scanning data and the least-square method. We can apply the least-square method and extract dipole moment without any problems using magnitude-only data only when there is a single dipole moment. Interestingly, we have observed that noise radiation from practical wireless devices can often be reasonably modeled as a single magnetic dipole moment. The devices investigated include smart speakers [2], cell phones [6], laptops [10], and streaming devices [11]. This is presumably because the distributed structures, e.g., long microstrip lines, are effective (unintentional) antennas and have already been removed in the design stage considering RFI. In addition, the frequency of interest for RFI is typically from 500 MHz to 5 GHz where ICs, short interconnects, and connectors are considered electrically short antennas. It should also be noted that the observation cannot be generalized for every wireless device, and one may still find distributed radiation sources in practical devices.

The fields in the reverse problem were measured using the procedure explained above. The comparison between direct measurement using the SA and estimation using (13) is shown in Fig. 6. The noise is broadband because it is related to data transmission between the CPU and DRAM.

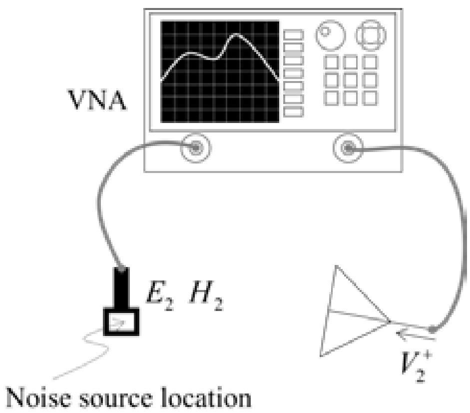


Fig. 4. VNA measurement setup for the reverse problem.

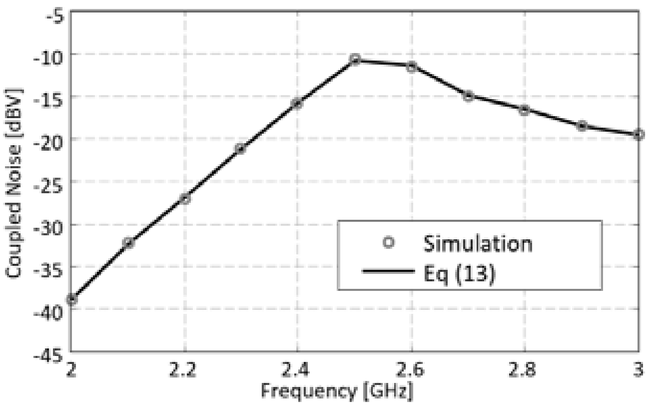


Fig. 5. Validation example using a full-wave simulation.

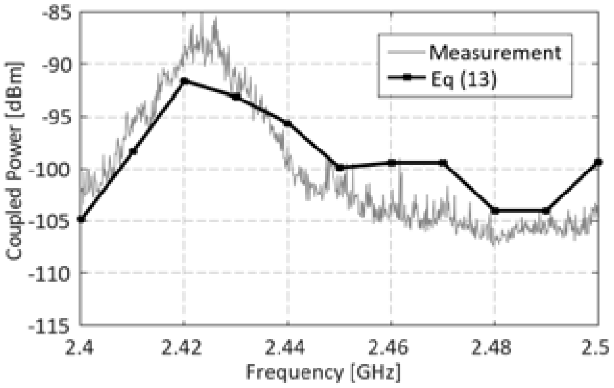


Fig. 6. Validation example using a real smart speaker.

III. RFI Mitigation

From (13), we can tackle the RFI issues from three perspectives: 1) reducing the magnitude of the noise source, 2) reducing the coupling, i.e., the transfer function, between the noise source and antenna, and 3) reducing their interaction. Methods 1 and 2 are well-known and common practices in the field. Reducing the noise can be done by changing the layout, e.g., changing the microstrips to strip lines, or by adding shielding cans. Reducing the transfer function can be done by adding absorbers in the coupling path or moving the noise source away from the victim antenna (however, this does not necessarily always help). Identifying the dominant noise coupling path in a complex system is not a trivial task, and noise coupling path visualization techniques can be used [13][14].

In this article, we will focus on the newer third approach – reducing the interaction between the noise source and antenna. There are two ways to reduce this interaction: 1) moving the noise source to the point where the antenna becomes less susceptible to the noise, and 2) rotating the noise source such that the inner product in (13) decreases.

A. Noise Source Displacement

The noise coupling is directly related to the transfer function, which represents the susceptibility of antennas. Here, the smaller the transfer function, the less susceptible an antenna becomes to noise. For a P-type noise source, the transfer function is just a ratio of electric field intensity to the incident voltage in the reverse problem, and the electric field map directly indicates the susceptibility of the victim antenna. For an M-type noise source, we need a magnetic field map.

For example, suppose there is a single My dipole moment (a magnetic dipole pointing in the y-direction). Owing to the inner product relationship in (13), we need to consider only Hy (the magnetic field in the y-direction. Other fields such as Hx and Hz or any electric field do not play any role in noise coupling. Fig. 7 shows an example of measured |Hy|. The DUT was a real product with an embedded Wi-Fi antenna, and the setup described in Fig. 4 was used. As discussed before, the H-field magnitude is directly related to the noise coupling, and moving the noise source to the smallest Hy location possible can decrease the coupling. In this example, the original ICs were located around the center, and we can obtain about 10 dB mitigation by moving the source to the left-bottom corner of the device.

Although it is straightforward to implement, moving a noisy component to the minimum transfer function may not always be feasible in practical designs due to many restrictions such as space, layout, etc.

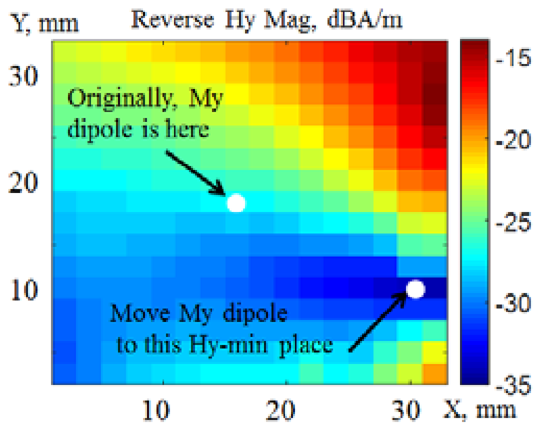


Fig. 7. Measured |Hy| field map.

B. Noise Source Rotation

We can minimize the inner product in (13) by making one vector orthogonal to the other. It may be easier to understand this concept by connecting it to the cross-polarization between antennas, as illustrated in Fig. 8 (a). When two antennas communicate, they must be similarly polarized to ensure optimal performance. Antennas operating with orthogonal polarization will not perform well due to substantial losses. Orthogonality, therefore, allows an antenna with a given polarization to avoid interference created by energy from an antenna with an orthogonal polarization. In an ideal case, two orthogonally polarized antennas have infinite isolation (i.e., zero interference). Isolation using orthogonality is a well-known concept in the antenna community, but the orthogonality in RFI problems is different in the sense that the interaction occurs in the near-field region and the polarization is not defined.

Assuming that the antenna design is complete, we can obtain the antenna fields for the reverse problem by either simulation or measurement, as discussed earlier. Based on the known noise source type, we can choose either an electric or magnetic field and set the rotation angle to 90° with respect to the antenna field at the noise source location. We should rotate the entire circuit (that is related to the noise radiation) so that the noise radiation property can be kept the same. Because the entire circuit is rotated, a substantial redesign of the layout is unnecessary.

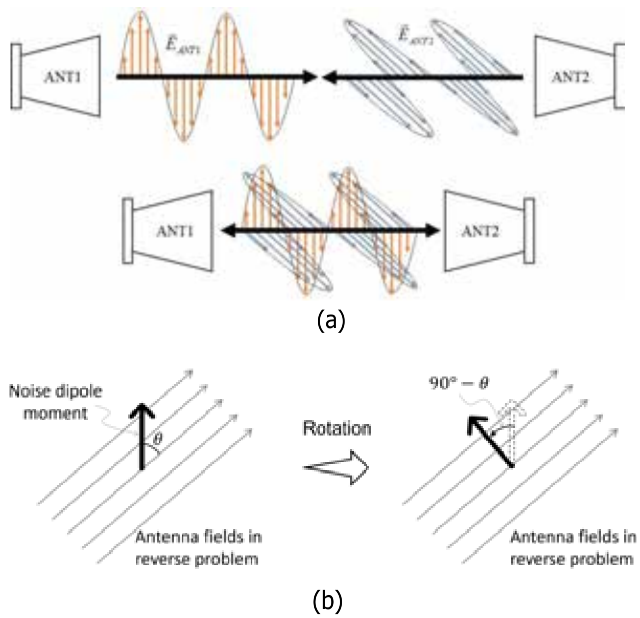


Fig. 8. The concept of orthogonality to avoid interference: a) in two linearly polarized antennas and b) in RFI problems.

As an example, let us revisit the case introduced in [2] where there is a noise source presented by an My dipole moment, and the antenna H vector in the reverse problem has an angle of approximately 63° at the noise location. Then, the rotation angle is determined to be 27°. A device with the new placement was fabricated and tested in collaboration with Amazon Lab126 Wireless Technology Group. Compared with the original design, an 8–12 dB improvement was achieved. As the entire layout for the CPU and memory was rotated, there was no signal integrity performance compromise and no need to rerun the signal integrity simulation.

If moving or rotating the circuit is not feasible, or if we are allowed to change the antenna design, it is very helpful if we can take RFI in the design stage of an antenna such that the antenna is less susceptible to the given noise source location and type. Characteristic mode analysis (CMA) has been used in the analysis of antenna radiation [15]. By combing the CMA with the reciprocity theorem, we can change the radiation problem to a susceptibility problem, and use it for noise-immune antenna design. The details of this idea will be introduced in a future publication.

IV. Conclusion

RFI problems are becoming more common and increasingly critical in wireless device design. The RF range can change substantially depending on RFI performance. The theoretical background for the electromagnetic framework and corresponding mitigation methods are discussed. They can be used to establish a systematic approach for RFI-aware design and troubleshooting.

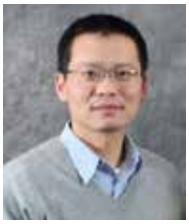
References

[1] C. Hwang and Q. Huang, “IC Placement Optimization for RF Interference based on Dipole Moment Sources and Reciprocity” Asia-Pacific Int. Sym. Electromag. Compat. (AP-EMC), Seoul, Korea, 20-23 June 2017, pp. 331-333.
[2] Q. Huang, L. Zhang, J. Rajagopalan, D. Pai, C. Chen, A. Gaikwad, C. Hwang, and J. Fan, “A Novel RFI Mitigation Method Using Source Rotation” IEEE Trans. Electromag. Compat., vol. 63, no.1, pp.11-18, Feb. 2021.
[3] Q. Huang, L. Zhang, Y. Zhong, J. Rajagopalan, D. Pai, C. Chen, A. Gaikwad, C. Hwang, and J. Fan, “A Fast and Simple RFI Mitigation Method without Compromising Signal Integrity” DesignCon 2019, Santa Clara, CA, Jan. 28-30, 2019.
[4] S. Lee, Y. Zhong, Q. Huang, T. Enomoto, S. Seto, K. Araki, J. Fan, and C. Hwang, “Analytical Intra-System EMI Model using Dipole Moments and Reciprocity” 2018 IEEE Electromagnetic Compatibility and Asia-Pacific Symp. Electromag. Compat. (EMC/APEMC), Singapore, 2018, pp. 1169-1173.
[5] Q. Huang, T. Enomoto, S. Seto, K. Araki, J. Fan, and C. Hwang, “Accurate and Fast RFI Prediction based on Dipole Moment Sources and Reciprocity” DesignCon 2018, Santa Clara, CA, Jan. 30-Feb. 1, 2018.
[6] 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. Electromag. Compat., vol. 61, no. 4, pp. 1280-1288, Aug. 2019.
[7] C. A. Balanis, Antenna Theory: Analysis and Design, Hoboken, NJ, Wiley-Interscience, pp. 144-146, 2005
[8] J. Richmond, "A reaction theorem and its application to antenna impedance calculations," IRE Trans. Antennas Propag., vol. 9, no. 6, pp. 515-520, November 1961.
[9] P. Wilson, “On correlating TEM cell and OATS emission measurements,” IEEE Trans. Electromag. Compat., vol. 37, no. 1, pp. 1–16, Feb. 1995.
[10] C. A. Balanis, Antenna Theory: Analysis and Design, Hoboken, NJ, Wiley-Interscience, pp. 233-237, 2005
[11] Y. Sun, H. Lin, B. Tseng, D. Pommerenke, and C. Hwang, “Mechanism and Validation of USB 3.0 Connector Caused Radio Frequency Interference,” IEEE Trans. Electromag. Compat., vol. 62. no.4, pp.1169-1178, Aug. 2020.
[12] L. Zhang, H. Yang, Q. Huang, J. Rajagopalan, D. Pai, C. Hwang, and J. Fan, “Radio-Frequency Interference Estimation for Multiple Random Noise Sources,” IEEE Trans. Electromag. Compat., vol. 64, no. 2, pp. 358-366, April 2022.
[13] J. Lundgren, J. Malmström, J. -M. Hannula and B. L. G. Jonsson, “Visualization and Reduction of Mutual Coupling Between Antennas Installed on a Platform,” Trans. Electromag. Compat., vol. 64, no. 1, pp. 92-101, Feb. 2022.
[14] S. Jeong, J. Kwon, D. Pai, J. Rajagopalan, and C. Hwang, “Visualization of Noise Coupling Paths based on Reciprocity Theorem,” submitted to Trans. Electromag. Compat.
[15] R. Harrington and J. Mautz, "Theory of characteristic modes for conducting bodies," IEEE Trans. Antennas Propag., vol. 19, no. 5, pp. 622-628, September 1971.

Biographies

***Chulsoon Hwang** (S'08-M'13-SM'18) received a Ph.D. degree in electrical engineering from the KAIST, Daejeon, South Korea, in 2012. He was a Senior Engineer with Samsung Electronics, Suwon, South Korea, from 2012 to 2015. In July 2015, he joined the Missouri University of Science and Technology (formerly University of Missouri-Rolla), Rolla, MO, USA, where he is currently an Associate Professor. His research interests include RF desensitization, signal/power integrity in high-speed digital systems, EMI/EMC, hardware security, and machine learning.*

Dr. Hwang serves as an associated editor for the IEEE Transactions on Signal and Power Integrity. Dr. Hwang was a recipient of the AP-EMC Young Scientist Award, the Google Faculty Research Award, and Missouri S&T's Faculty Research Award. He has also been a co-recipient of eight Best/Best Student Paper Awards from various conferences.



Jun Fan *(S'97-M'00-SM'06-F'16) received his B.S. and M.S. degrees in Electronic Engineering from Tsinghua University, Beijing, China, in 1994 and 1997, respectively. He received his Ph.D. degree in Electrical Engineering from the University of Missouri-Rolla in 2000. From 2000 to 2007, he worked for NCR Corporation, San Diego, CA, as a Consultant Engineer. In July 2007, he joined the Missouri University of Science and Technology (formerly University of Missouri-Rolla), and became tenured Professor in 2016. From October 2018 to August 2020, he was the Cynthia Tang Missouri Distinguished Professor in Computer Engineering. He served as the Director of the Missouri S&T EMC Laboratory, and the Director of the National Science Foundation (NSF) Industry/University Cooperative Research Center (I/UCRC) for Electromagnetic Compatibility (EMC) from 2013 to 2020. He was a Senior Investigator of Missouri S&T Material Research Center as well. His research focuses on hardware design and fundamental research for electromagnetic compatibility (including signal and power integrity) at the levels of integrated circuit, package, PCB and system, and development of specialized design tools and innovative measurement technologies. In the IEEE EMC Society, Dr. Fan served as a member of the Board of Directors, the Chair of the Technical Advisory Committee, the chair of the TC-9 Computational Electromagnetics Committee, and a Distinguished Lecturer. He currently is the inaugural Editor in Chief for the IEEE Transactions on Signal and Power Integrity, and an associate editor for the IEEE Transactions on Electromagnetic Compatibility. He was Technical Paper Chair and Technical Program Chair for a few IEEE International Symposia on EMC, General Chair for IEEE International Conference on Signal and Power Integrity, founding chair for the SC-4 EMC for Emerging Wireless Technologies Special Committee, and so on. Dr. Fan received an IEEE EMC Society Technical Achievement Award in August 2009 and the Richard R. Stoddart Award for Outstanding Performance in 2022.*

EMC