Development and Verification of Indirect Lightning-Induced Transient Protection Circuit for Avionics System

Sung-Yeon Kim, Jeong-Su Park, and Wang-Sang Lee*

Department of Electronic Engineering, Gyeongsang National University (GNU)
501, Jinju-daero, Jinju, Gyeongnam, 52828, Republic of Korea
*wsang@gnu.ac.kr

Abstract **─** In this paper, an indirect lightning-induced transient protection circuit for avionics system is proposed, and its effectiveness is verified. The proposed circuit consists of a metal oxide varistor (MOV), a transient voltage suppression (TVS) diode, and a resistor. Compared with the conventional circuits (MOV or TVS diode), the improved noise suppression of the proposed circuit against indirect lightning strikes are experimentally verified in accordance with radio technical commission for aeronautics (RTCA) DO-160G Sec. 22. The highest attenuation levels of indirect lightning strike WF5A reference voltage and current signals are approximately 91.0% and approximately 98.4% for the input lightning signals, respectively.

Index Terms **─** Indirect lightning, lightning induced transient, lightning protection, pin injection test, RTCA DO-160G Sec. 22

I. INTRODUCTION

Surge voltages derived from direct lightning strikes cause malfunction or damage to the electronic equipment in aircrafts; this phenomenon is referred to as the indirect effects of direct lightning strikes. The lightning indirect effects are caused by the currents induced by lightning strikes on avionics as well as damage to the aircraft due to direct lightning strikes. There is an increase in the use of miniaturized, solid-state components in aircraft electronics and electric power systems [1],[2]. Moreover, modern aircrafts are increasingly constructed from composite materials, in particular, carbon-fiber composites in place of metal skins, a practice that reduces the electromagnetic shielding previously furnished by the conductive skin as a by-product [3-7]. The application of protection design for indirect lightning strikes on avionics is becoming more important. To establish aircraft airworthiness from lightning-induced effects, the standards and guidelines such as RTCA DO-160G & SAE ARP 5415A and EUROCAE ED-14G are widely used [8]. RTCA DO-160G air-worthiness certification standard for civil aviation aircraft defines the need for flight and safety essential equipment, emphasizing the need for induced lightning protection of aviation electronic equipment. According to this standard, flight essential equipment must verify that the system meets the requirements for lightning protection and electromagnetic environment requirements including it.

This study was conducted based on RTCA DO-160G Sec. 22. The standard is used by the Federal Aviation Administration (FAA) and defines lightning-induced transient susceptibility aircraft test specifications. Lightning-induced transient sets the test standard considering the installation location of the electronic device and the interlocking concept. RTCA DO-160G Sec. 22 consists of pin injection tests and cable bundle tests. The simplified test setup of RTCA DO-160G Sec. 22 pin injection test is shown in Fig. 1.

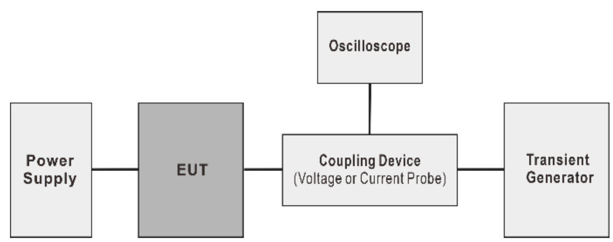

Fig. 1. Simplified test setup of RTCA DO-160G Sec. 22 pin injection test [8].

Table 1. Pin injection test level [9]

Peak Level	Test Waveform No.	
	WF3	WF5A
V_{oc} / I_{sc}*	V_{oc} / I_{sc}	V_{oc} / I_{sc}
1	100/4	50/50
2	250/10	125/125
3	600/24	300/300
4	1500/60	750/750
5	3200/128	1600/1600

*$\boldsymbol{V_{oc}}$: Peak open circuit voltage (Unit: V), $\boldsymbol{I_{sc}}$: Peak short circuit current (Unit: A).

Submitted On: January 25, 2021
Accepted On: July 6, 2021

https://doi.org/10.47037/2020.ACES.J.360608

Table 1 shows the pin injection test level. Pin injection tests level criteria are divided into levels 1 to 5 depending on the installation environment of the equipment. Level 3 applies to equipment and interconnect wiring mounted in environments such as electromagnetically open areas (control rooms) of aircraft, which are made primarily of metal [9]. This study considers the installation and configuration of aviation electronics and applies pin injection tests, Category B (WF3 and WF5A). The WF3 and WF5A voltage/current of RTCA DO-160G Sec. 22 are shown in Fig. 2. Level 3 is the most in demand in aviation electronics development companies.

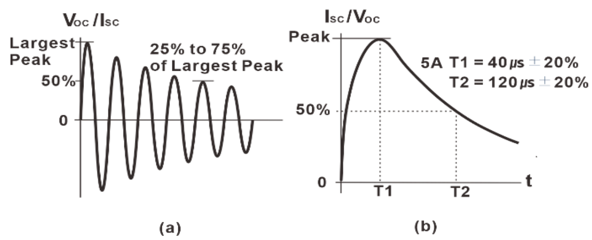

Fig. 2. Voltage/Current waveform of RTCA DO-160G Sec.22: (a)WF3 and (b) WF5A.

II. INDIRECT LIGHTNING PROTECTION CIRCUIT DESIGN

Indirect lightning transient protection and clamping on avionics include series resistors, metal oxide varistors (MOV), gas discharge tubes (GDT), transient voltage suppression (TVS) diodes, and a trace width. The MOV, GDT, and TVS diodes which can be easy to apply to aviation electronics are highly effective for transient suppression without major design changes [10].

Table 2. Comparison of typical MOV, TVS diode, and the proposed circuit

Item	MOV	TVS Diode	Proposed Circuit
Energy capability	High (Hundreds of joules)	Low (Number of joules)	Very high (Hundreds of joules)
Surge current capability	High (Hundreds of amperes)	Low to moderate (Tens of amperes)	Very high (Hundreds of amperes)
Response time	Slow (ns level)	Fast (ps level)	Fast (ps level)
Clamping voltage	High (Hundreds of volts)	Low (Tens of volts)	Low (Tens of volts)
Lifespan	Long (Thousands of times)	Intermediate (Hundreds of times)	Very long (Thousands of times)

Table 2 shows the characteristics of MOV, TVS diode, and proposed circuit. The TVS diode can suppress and protect external instantaneous stress input through external pins by the protection circuit of the input terminal. It can be applied in both directions. The characteristic of the TVS diode can be clamped at lower voltages, low capacitance, low leakage current, and fast response time. However, it is required to use the clamping voltage precisely and is suitable for sensitive circuit parts due to the high price. The peak clamping voltage of the MOV is higher than the TVS diodes. It has greater tolerance for high energy temperatures, long-term life, competitive price (on average, 10 times cheaper than TVS diode), higher capacitance, and bidirectional components. In addition, it can control high currents. Voltage and current characteristics are symmetrical (DC and AC circuits can be applied). However, it is not suitable for sensitive circuits as a high priority. The proposed indirect lightning protection circuit (ILPC) uses the characteristics of the MOV, TVS diode, and series resistor electronic components to create synergy effects. The ILPC is shown in Fig. 3 aiming to maximize benefits and overcome the disadvantages of the individual part. The proposed protection circuit has the structure of first clamping through MOV that withstands a few large surges. A series resistor (R) reduces a residual noise, a shorter-pulse noise, and control current. The value of R was set to 2 Ω and tested due to the impedances (25 Ω or 1 Ω) of the waveforms (WF3 or WF5A). Third clamping is performed through a TVS diode and controls small surges. By using the proposed ILPC, the incoming current noise can be distributed and the lightning long-term stable protection becomes possible [11].

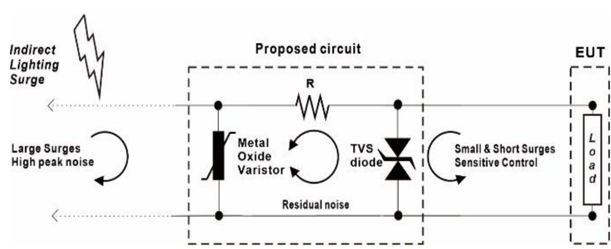

Fig. 3. Proposed indirect lightning protection circuit.

Based on the 28 V power of avionics, the TVS diode applied indirect lightning protection measures applied in positive and negative polarities. Considering the voltage conditions of MIL-STD-704F, a TVS diode with a maximum clamping voltage of ±50 V and higher was selected. The device chosen was 30KPA43CA made by Littelfuse [12],[13] and a maximum clamping voltage (V_C) of 73 V was selected [12]. The allowable peak pulse current ($I_{PP\ @\ WF3\ or\ WF5A}$) at WF3 or WF5A is calculated using:

$$I_{PP@WF3\ or\ WF5A} = \frac{V_{OC} - V_C}{Z_S}, \tag{1}$$

where Z_S is an impedance that can obtain the ratio of V_{OC} and I_{SC}, V_{OC} is a peak open circuit voltage, and V_C is a maximum clamping voltage. The maximum peak pulse currents ($I_{PP\ @\ WF3\ or\ WF5A}$) at WF3 and WF5A are approximately 21.1 A and 227 A, respectively. The peak pulse current ($I_{PP\ @\ TVS}$) at TVS diode is calculated using:

$$I_{PP@TVS} = \frac{P_{PP@T_P}}{P_{PP@10/1000\mu s}} \times I_{PP}, \tag{2}$$

where P_{PP} is a peak pulse power at TVS diode and I_{PP} is a maximum peak pulse current at a datasheet. The allowable current of TVS diode at WF3 and WF5A can obtain approximately 5120 A and 1107 A, respectively. Therefore, the used TVS diode has an enough margin for WF3 and WF5A. It was confirmed that the indirect lightning input current applied to the signal line during the indirect lightning test can be applied within the maximum current of the TVS diode. In case of the MOV circuit application, the MOV can handle the peak pulse current. The peak pulse current is the maximum current at which the MOV voltage does not change by more than 10% [14][15]. The MOV operating DC voltage $V_{M(AC)}$ should be selected to be higher than the maximum allowable DC voltage operating circuit voltage. The ILPC design clamping MOV should be higher than 30.8 V (28 V power of avionics + 10%) and a maximum clamping voltage of over 50 V. The clamping voltage is over 50 V but higher than the TVS diode clamping voltage. This is because MOV is more resistant to indirect lightning strikes than the TVS diode. The maximum current (I_{Surge}) flowing in the MOV during the surge is lower than the indirect lightning surge current (I_{ILS}) [14]. I_{Surge} is calculated using:

$$I_{Surge} = \frac{V_{OC} + V_O\left(1+10\%\right) - V_C}{R}, \tag{3}$$

where R is a value of resistor (2 Ω). The maximum current ($I_{Surge\ @\ WF3\ or\ WF5A}$) at WF3 and WF5A are approximately 268.9 A and 118.9 A, respectively. Using V20E30AUTO (V_C = 93V, V_{DC} = 34V, I_{ILS} = 3000A) as MOV made by Littelfuse [15], it was confirmed that the indirect lightning input current can be applied within the maximum current of MOV. Before the experimental verification, the simulation was performed using the PSPICE program. The waveforms (WF3 and WF5A) of RTCA DO-160G Sec. 22 were applied to each element (MOV and TVS) and the proposed circuit, and the performance was confirmed and compared in Figs. 4 and 5.

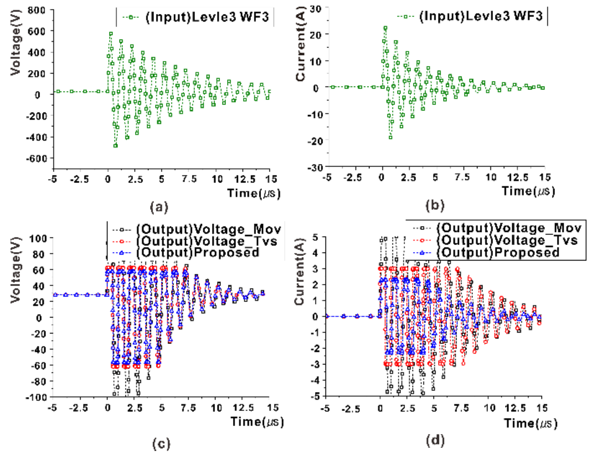

Fig. 4. Simulated comparisons of MOV, TVS diode, and proposed circuits for WF3: (a) and (b) voltage and current WF3, (c) and (d) voltage and current comparisons for WF3, respectively.

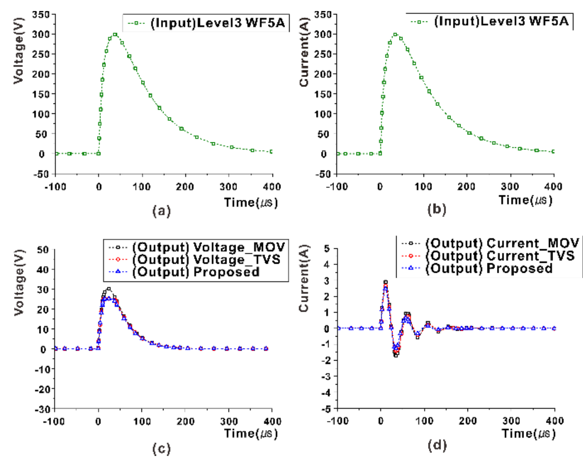

Fig. 5. Simulated comparisons of MOV, TVS diode, and proposed circuits for WF5A: (a) and (b) voltage and current for WF5A, (c) and (d) voltage and current comparisons for WF5A, respectively.

III. RESULTS AND DISCUSSIONS

To experimentally verify the ILPC the proposed circuit, the pin injection test based on RTCA DO-160G Sec. 22 lightning-induced transient susceptibility has been conducted. Pin injection tests are primarily for damage assessment and involve the injection of transients directly into EUT interface circuits [8]. Figure 6 shows the test setup of RTCA DO-160G Sec. 22. The pin injection generators (MIG OS-M and MIG 0600MS by EMC Partner), the injection probe (CN-MIG-BT3 by

EMC partner), the oscilloscope (MSO-X 4154A by Keysight Technologies), the high voltage differential probe (TT-SI9091 by TESTEC), the current clamp probe (Pearson Electronics 3525), and the electric load (PLZ164WA by Kikusui Electric Co.) were used to the test. Waveforms applied to the pin injection test were tested on WF3 and WF5A of level 3. In order to determine the effect of indirect lightning for each of the devices applied by an accredited testing laboratory, a comparative test was conducted by dividing into MOV, TVS diode, and ILPC.

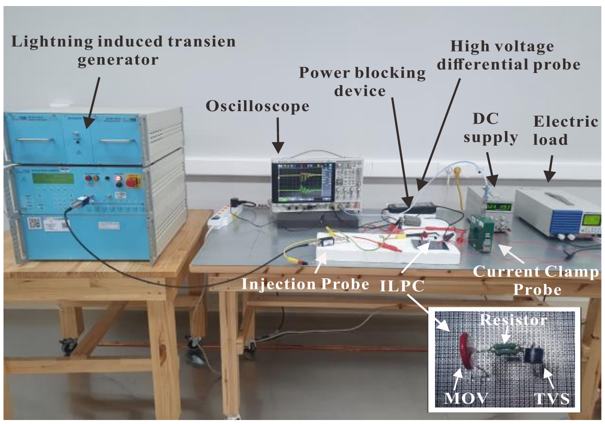

Fig. 6. Proposed indirect lightning protection circuit.

The measured results for WF3 and WF5A are shown in Figs. 7 and 8, respectively. In the WF3 and WF5A tests, it was confirmed that ILPC has the best characteristics of voltage and current reduction. During the test, visual inspection and tolerance items were checked, and no specifics were found. In particular, the characteristics of the indirect lightning filter were confirmed using WF5A, in which a large induced lightning was induced. Table 3 shows the results of pin injection test with regard to WF3 and WF5A by comparison between the MOV, TVS, and the proposed circuits. The calculated measurement uncertainties with 95% confidence level for the pin injection test (voltage and current) in Fig. 6 are 10V and 0.63A, respectively. Compared to the input signals (600 V for WF3 and 300 V for WF5A), the peak voltage of the proposed circuit to which the MOV is applied has attenuation of approximately 74.7% and 87%, and the attenuation of approximately 80.2% and 87.7% when the TVS diode is applied, respectively. The peak current of the circuit to which the MOV is applied has attenuation of approximately 69.2% and 98.2% compared to the input signal (24A for WF3, 300A for WF5A), and approximately 75.4% and 98.2% of attenuation when the TVS diode is applied, respectively. On the other hand, the highest attenuation levels of the proposed circuit in the indirect lightning strike WF5A reference voltage and current signals are approximately 91.0% and approximately 98.4% for the input lightning signals, respectively. As a result, it means that the propose circuit is possible to improve the noise suppression and protect avionics from noised caused by indirect lightning.

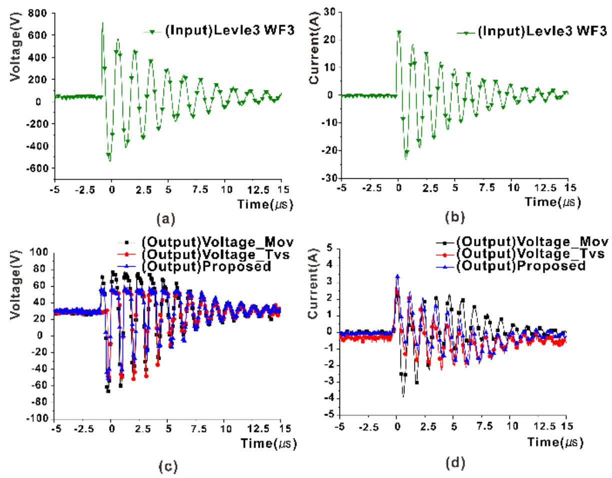

Fig. 7. Measured comparisons of MOV, TVS diode, and proposed circuits for WF3: (a) and (b) voltage and current WF3, (c) and (d) voltage and current comparisons for WF3, respectively.

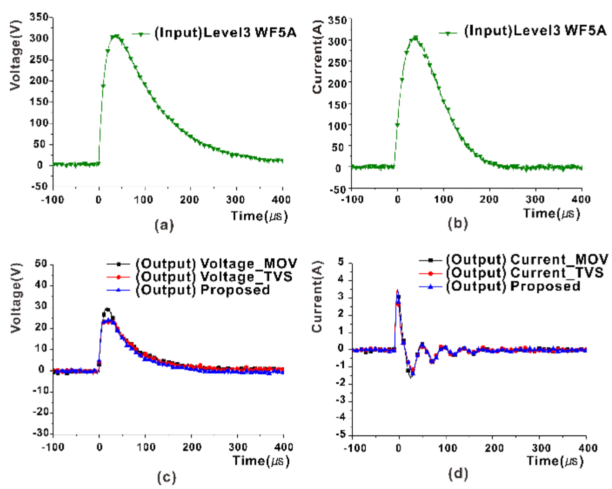

Fig. 8. Measured comparisons of MOV, TVS diode, and proposed circuits for WF5A: (a) and (b) voltage and current for WF5A, (c) and (d) voltage and current comparisons for WF5A, respectively.

Table 3. The results of pin injection test with regard to WF3 and WF5A

Waveforms	V_{Peak} (U = 10 V, 95% Confidence Level)				I_{Peak} (U = 0.63 A, 95% Confidence Level)			
	Input	Reference		Prop. Circuit	Input	Reference		Prop. Circuit
		MOV	TVS Diode			MOV	TVS Diode	
WF3	600 V	152 V	119 V	117 V	24 A	7.4 A	5.9 A	5.4 A
	100%	-74.67%	-80.17%	-80.5%	100%	-69.17%	-75.42%	-77.50%
WF5A	300 V	39 V	37 V	27 V	300 A	5.5 A	5.3 A	4.8 A
	100%	-87.00%	-87.67%	-91.00%	100%	-98.17%	-98.23%	-98.40%

IV. CONCLUSION

In this paper, we proposed an ILPC for indirect avionics filters. Previously, a large protective device had to be attached to the outside of avionics, but the proposed indirect lightning filter can be modified and changed simply by reducing the size and weight. The RTCA DO-160G Sec. 22 test was conducted according to the verified procedure. As a result of the test, ILPC complies with WF3 and WF5A providing lower clamping voltage and current. Owing to its high resistance to noise from indirect lightning strikes, it can be expected to act as a filter for a very long-term protection circuit. The proposed ILPC can be applied to avionics devices that that the aircraft is powered itself, and it can be applied immediately as a power line indirect lightning protection filter for aviation-mounted electronic devices such as aircraft transceivers, communications, navigation, flight recorder, monitoring, control system, the display and management systems etc. This ILPC is an effective way to prevent indirect lightning strikes of avionics systems.

REFERENCES

[1] F. A. Fisher and J. A. Plumer, *Lightning Protection of Aircraft*. Washington D.C., USA: NASA, Oct. 1977.

[2] M. O. Goni, E. Kaneko, and A. Ametani, “Simulation of lightning return stroke currents and its effect to nearby overhead conductor,” *Applied Computational Electromagnetics Society Journal*, vol. 24, no. 5, pp. 469-477, Oct. 2009.

[3] D. Morgan, C. J. Hardwick, S. J. Haigh, and A. J. Meakins, “The interaction of lightning with aircraft and the challenges of lightning testing,” *AerospaceLab*, vol. 5, no. 11, pp. 1-10, Dec. 2012.

[4] C. C. Goodloe, Lightning protection guidelines for aerospace vehicles, *NASA/TM-1999-209734*, Springfield, VA, USA: NASA, pp. 1-48, May 1999.

[5] M. D'Amore and M. Sabrina Sarto, “Time-domain analysis of lightning interaction to aeronautical structures composite materials,” *2017 IEEE EMC Int’l Symp.*, Austin, TX, USA, pp. 397-402, Aug. 1997.

[6] L. Chemartin, P. Lalande, B. Peyrou, A. Chazottes, and P. Q. Elias, “Direct effects of lightning on aircraft structure: analysis of the thermal, electrical and mechanical constraints,” *AerospaceLab*, vol. 5, no. 9, pp. 1-15, Dec. 2012.

[7] J. P. Parmantier, F. Issac, and V. Gobin, “Indirect effects of lightning on aircraft and rotorcraft,” *AerospaceLab*, vol. 5, no. 11, pp. 1-27, Dec. 2012.

[8] Radio Technical Commission for Aeronautics Inc., *RTCA/DO-160G*, “Environmental conditions and test procedures for airborne equipment, Sec. 22 Lightning induced transient susceptibility”, pp. 22-1−22-42, Dec. 2010.

[9] H. P. Rimal and A. Faba, “Lightning indirect effect protection in avionic environment,” *2017 IEEE 3rd Int’l Forum on Research and Technologies for Society and Industry (RTSI)*, Modena, Italy, pp. 1-5, Sep. 2017.

[10] C. A. McCreary and B. A. Lail, “Lightning transient suppression circuit design for avionics equipment,” *2012 IEEE Int’l Symp. on Electromagnetic Compatibility*, Pittsburgh, PA, USA, pp. 93-98, Aug. 2012.

[11] Y. G. Sim, T. S. Ahn, J. H. Park, J. P. Yang, and S. H. Han, “Development and verification of lightning induced transient protection device for avionics computer,” *Journal of Advanced Navigation Technology (JANT)*, vol. 19, no. 5, pp. 395-402, Oct. 2015.

[12] M. Clark, “Lightning protection for aircraft per RTCA/DO-160D and ARINC 429 protocol,” *MicroNote 126*, Microsemi Corporation, Scottsdale, AZ, USA, pp. 1-5, July 2004.

[13] TVS Diode Axial Leaded – 30000W > 30KPA series datasheet, TVS Diode (30KPA43CA), Littelfuse, Inc., Aug. 2020, Littelfuse [Online]. Available: https://www.littelfuse.com/~/media/electronics/datasheets/tvs_diodes/littelfuse_tvs_diode_30kpa_datasheet.pdf

[14] N. Tsukamoto, and M. Ishii, “Repetitive impulse withstand performance of metal–oxide varistors,” *IEEE Trans. on Power Delivery*, vol. 32, no. 4, pp. 1674-1681, Aug. 2017.

[15] Metal-Oxide Varistors (MOVs) Radial Leaded Varistors > AUMOV Varistor Series, MOV (V20E30AUTO), Littelfuse, Oct. 2019. Available: https://www.littelfuse.com/~/media/electronics/datasheets/varistors/littelfuse_aumov_datasheet.pdf

Sung-Yeon Kim received the B.S. degree in Electronic Engineering from Pukyong National University (PKNU), Busan, South Korea, in 2008, received the M.S. degree in Electronic Engineering from Gyeong-sang National University (GNU), Jinju, South Korea, 2017, where he is currently pursuing the Ph.D. degree.

His current research interests include electro-magnetic interference (EMI)/EMC analysis, Modeling, Measurement, Shielding, RF/Microwave Antenna & Circuit. From 2008 to 2014, he was with the Digital Media Communication Division, Samsung Electronics Co., Ltd (SEC), Suwon-si, South Korea. From 2014, he was with the Electromagnetic Compatibility Avionics Center, Digital Industry Division, Korea Testing Laboratory (KTL), Jinju-si, South Korea.

Jeong-Su Park received the B.S. degree in Electronic Engineering from Gyeongsang National University (GNU), Jinju, South Korea, in 2019, where he is currently pursuing the M.S. degree.

His current research interests include wireless communication systems for UAVs, RF-based energy harvesting, RF/Microwave circuit and system, and RFID/IoT sensors.

Wang-Sang Lee received the B.S. degree from Soongsil University, Seoul, South Korea, in 2004, and the M.S. and Ph.D. degrees in Electrical Engineering from the Korea Advanced Institute of Science and Technology (KAIST), Daejeon, South Korea, in 2006 and 2013, respectively.

From 2006 to 2010, he was with the Electromagnetic Compatibility Technology Center, Digital Industry Division, Korea Testing Laboratory (KTL), Ansan-si, South Korea, where he was involved in the international standardization for radio frequency identification (RFID) and photovoltaic systems as well as electromagnetic interference (EMI)/EMC analysis, modeling, and measurements for information technology devices. In 2013, he joined the Korea Railroad Research Institute (KRRI), Uiwang-si, South Korea, as a Senior Researcher, where he was involved in the position detection for high-speed railroad systems and microwave heating for low-vibration rapid tunnel excavation system. Since 2014, he has been an Associate Professor with the Department of Electronic Engineering, Gyeongsang Nat’l University (GNU), Jinju, South Korea. From 2018 to 2019, he was a Visiting Scholar with the ATHENA Group, Georgia Institute of Technology, Atlanta, GA, USA. His current research interests include near- and far-field wireless power and data communications systems, RF/microwave antenna, circuit, and system design, RFID/Internet of Things (IoT) sensors, and EMI/EMC.

Lee is a member of IEC/ISO JTC1/SC31, KIEES, IEIE, and KSR. He was a recipient of the Best Paper Award at IEEE RFID in 2013, the Kim Choong-Ki Award–Electrical Engineering Top Research Achievement Award at the Department of Electrical Engineering, KAIST, in 2013, the Best Ph.D. Dissertation Award at the Department of Electrical Engineering, KAIST, in 2014, the Young Researcher Award at KIEES in 2017, and the Best Paper Awards at IEIE in 2018 and KICS in 2019.