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Design of a Miniaturized High-Isolation Diversity Antenna for Wearable WBAN Applications

Seongjin Kim · Kyeol Kwon · Jaehoon Choi

Abstract

This paper proposes a miniaturized high-isolation diversity antenna for wearable wireless body area network (W-BAN) applications. An inverted-F type radiating element is used to reduce the overall dimension of the proposed antenna to 30 mm×30 mm×2.5 mm. The antenna performance on the human body phantom is analyzed through simulation and the performance of the fabricated antenna is verified by comparing the measured data with that of the simulation when the antenna is placed on a semi-solid flat phantom with equivalent electrical properties of a human body. The fabricated antenna has a 10 dB return loss bandwidth over the Industrial Scientific Medical (ISM) band from 2.35 GHz to 2.71 GHz and isolation is higher than 28 dB at 2.45 GHz. The measured peak gain of antenna elements # 1 and # 2 is −0.43 dBi and −0.54 dBi, respectively. Performance parameters are analyzed, including envelope correlation coefficient (ECC), mean effective gain (MEG), and the MEG ratio. In addition, the specific absorption ratio (SAR) distributions of the proposed antenna are measured for consideration in use.

Key words: WBAN, Planar Inverted-F Antenna (PIFA), Diversity, ECC, MEG, SAR.

Ⅰ. Introduction

The rapid advances in communication technologies have led to the use of the wearable wireless body area network (WBAN) for various applications such as medical devices, police and military agencies, sports training, entertainment, and wearable computing etc. [1]. The antennas used for WBAN require a small size, a low human body effect, and a low specific absorption ratio (SAR) [2]. The human body has a high dielectric constant with a high loss tangent and low conductivity at the microwave frequency band. Therefore, the gain and radiation efficiency of an antenna can be reduced when an antenna is operated on or within the human body.

Recently, much work has been done to investigate the on-body communication channel at the Industrial Scientific Medical (ISM) band [3]～[5]. In a WBAN system, multipath propagation can occur due to reflections from the surrounding environment and the body parts. In addition, multipath fading can occur in response to the large relative movements of body parts, shadowing, polarization mismatch, and scattering by the body and the surrounding environment [3]. This harsh WBAN communication environment has been addressed by the recent proposal of various diversity techniques [6]. The placement of two antennas close to each other requires an isolation between the antennas that is sufficiently high to minimize the mutual effects.

This paper proposes a miniaturized high isolation diversity antenna for wearable WBAN applications in the ISM band (2.4～2.485 GHz). A planar inverted-F antenna (PIFA) is used to achieve a compact size of an antenna for on-body communication. Two antenna elements are placed on the same substrate with a small ground element in order to improve the performance and overcome multipath fading. The performance parameters of the proposed diversity antenna placed on the human body tissues, including the S-parameter characteristics, radiation patterns and mean effective gain (MEG), MEG ratio, envelope correlation coefficient (ECC), and specific absorption ratio (SAR), are analyzed through a simulation and measurements by using a semi-solid flat phantom that has electrical properties equivalent to those of a whole human body. The proposed diversity antenna was designed and analyzed using the Ansys HFSS v14 software [7]. The details of the antenna design and the

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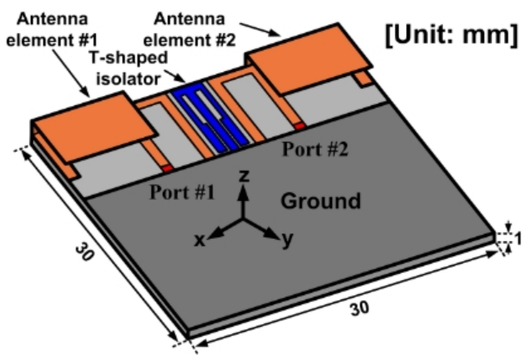
Department of Electronics and Computer Engineering, Hanyang University, Seoul, Korea.
Corresponding Author : Jaehoon Choi (e-mail : choijh@hanyang.ac.kr)

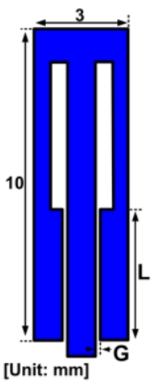
experimental results are presented and discussed in the following sections.

Ⅱ. Antenna Design and Performance

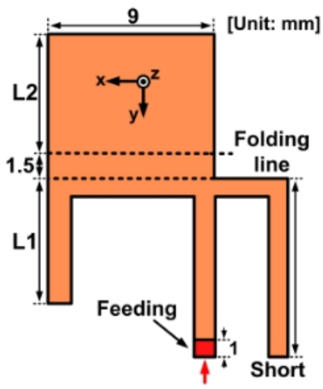
The configuration of the proposed diversity antenna is shown in Fig. 1(a). The proposed diversity antenna consists of PIFAs, which are placed near the corners of the top edge of the ground plane. A T-shaped isolator is then placed between the two antenna elements. The two antenna elements of the diversity antenna are symmetrically placed with respect to the y-axis. Each antenna element has a dimension of 13 mm×10 mm×1.5 mm and is fed by a 50 Ω coaxial cable. Fig. 1(b) shows the



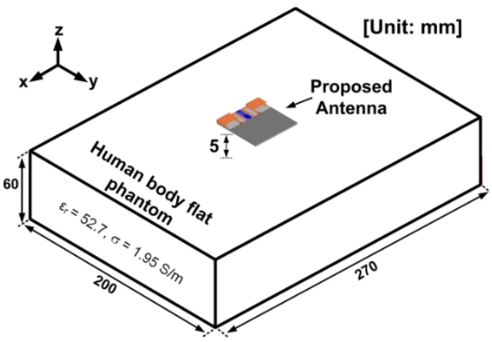
(a) Perspective view of the proposed diversity antenna



(b) T-shaped isolator

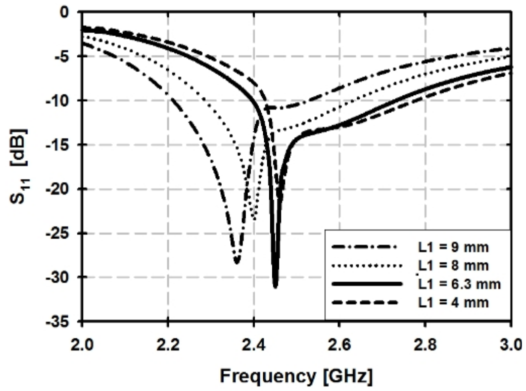


(c) Antenna element #1

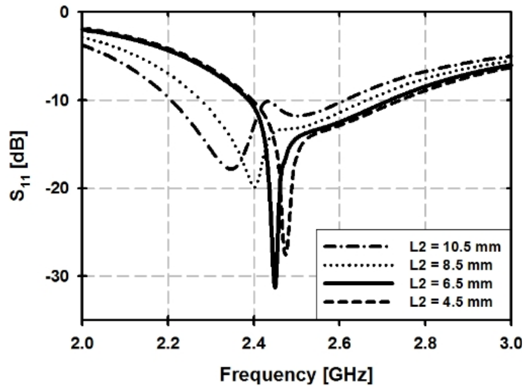


(d) Human body flat phantom model for numerical analysis

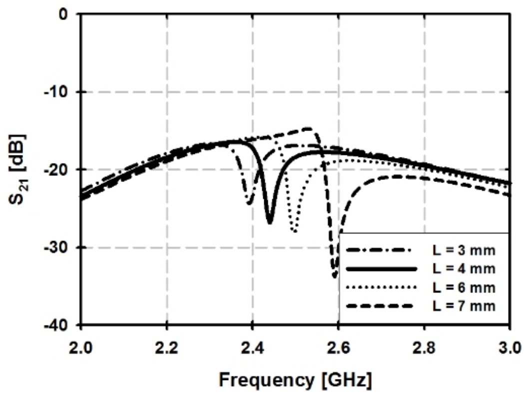
Fig. 1. Configuration of the diversity antenna.



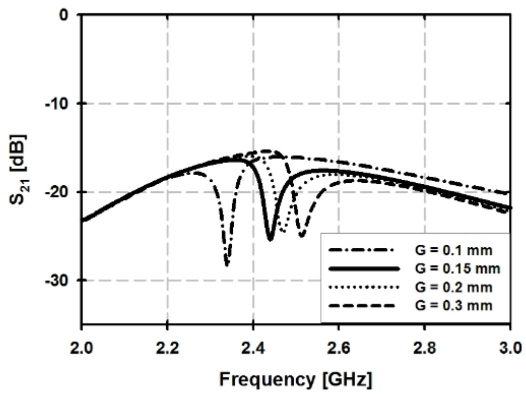
(a) S_{11} for variation in L_1



(b) S_{11} for variation in L_2



(c) S_{21} for variation in L



(d) S_{21} for variation in G

Fig. 2. Simulated S_{11} and S_{21} characteristics.

structure of a T-shaped isolator that is used to enhance the isolation characteristic at the ISM band. The ground plane is composed of a 1-mm-thick FR-4 substrate with a relative dielectric constant of 4.4 and a size of 30 mm×30 mm.

Antenna performance when the antenna is placed on a human body is analyzed by running simulations using a human body flat phantom (200 mm×270 mm×60 mm) with ε_r=52.7 and σ=1.95 S/m, as shown in Fig. 1(d).

A parametric study of the proposed antenna is shown in Fig. 2. Figs. 2(a) and (b) show the simulated S_{11} characteristics of the proposed diversity antenna for various values of L_1 and L_2 when the antenna is placed on a human body flat phantom. As L_1 decreases, the resonant frequency is shifted toward the higher frequency side. Likewise, as L_2 decreases, the resonant frequencies are shifted toward the higher frequency side. The values of L_1 and L_2 are chosen as 6.3 mm and 6.5 mm, respectively. Figs. 2(c) and (*d*) show the effects of the length (*L*) and gap distance (*G*) of the T-shaped isolator. The T-shaped isolator acts as a parallel resonator between the two antenna elements. This isolator effectively prevents current flow from port # 1 to port # 2 and vice versa. As the length of T-shaped isolator (*L*) increases, the stop-band frequency is shifted toward the higher frequency band, owing to the increasing inductive component. Adjusting the length (*L*) of T-shaped isolator allows control of the inductance of the parallel resonator. As the gap distance of T-shaped isolator (*G*) increases, the capacitance decreases. In turn, the stop band frequency is shifted toward the higher frequency side. Consequently, good isolation performance in the desired frequency band can be achieved by controlling the inductances and capacitances of the T-shaped parallel resonator. The T-shaped isolator length (*L*) is chosen to be 4 mm, and gap distance (*G*) is chosen to be 0.15 mm.

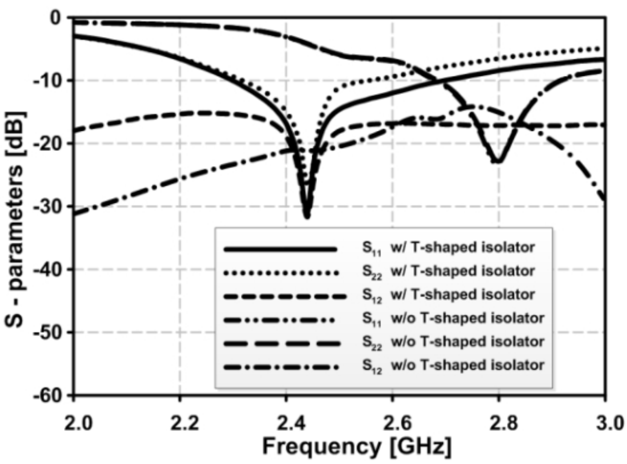
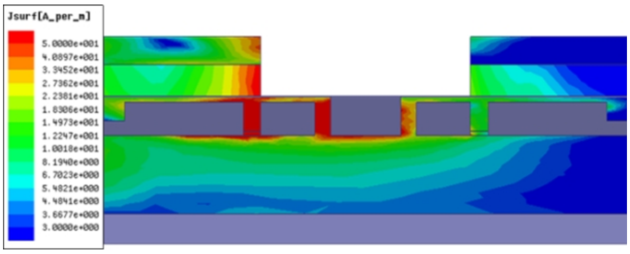
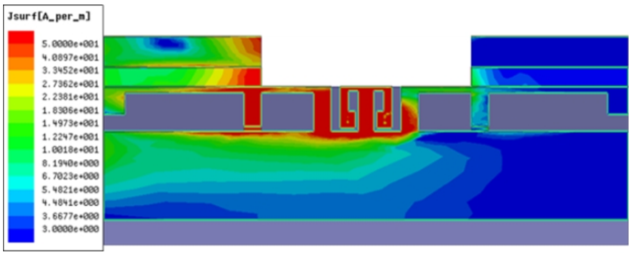


Fig. 3. The simulated *S*-parameter characteristics.



(a) Without T-shaped isolator



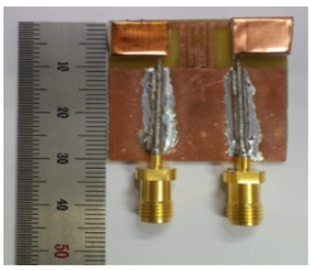
(b) With T-shaped isolator

Fig. 4. Current distributions of the proposed diversity antenna at 2.45 GHz.

The simulated *S*-parameter characteristics obtained with the T-shaped isolator are shown in Fig. 3. The effect of the T-shaped isolator on the isolation characteristic is investigated by analyzing the current distributions at 2.45 GHz with and without the T-shaped isolator, as shown in Fig. 4. When one of the two elements is excited, a strong current is induced in the other element in the absence of the T-shaped isolator. After the T-shaped isolator is embedded, the induced current in the non-excited element weakens.

Ⅲ. Experimental Results

The fabricated antenna and the semi-solid flat phantom are shown in Figs. 5(a) and (b), respectively. The relative dielectric constant and conductivity of the fabricated semi-solid phantom [8], measured using an Agilent 8570E dielectric probe kit and an 8719ES network analyzer, are shown in Fig. 6. The phantom with a dimension of 200 mm×270 mm×60 mm is used to



(a) Fabricated antenna

(b) Fabricated phantom

Fig. 5. Fabricated antenna and the semi-solid flat phantom.

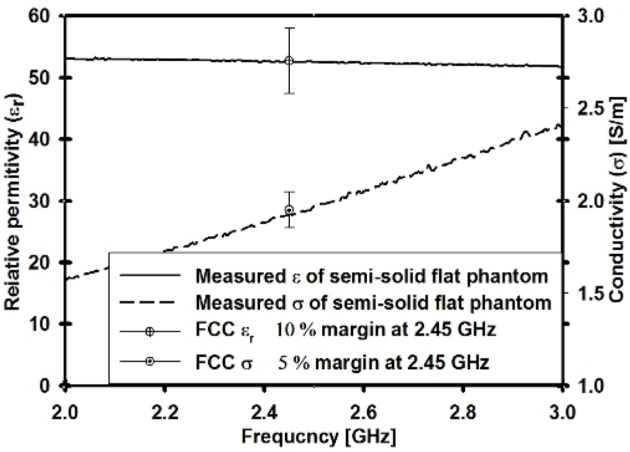


Fig. 6. The measured performance of the fabricated phantom.

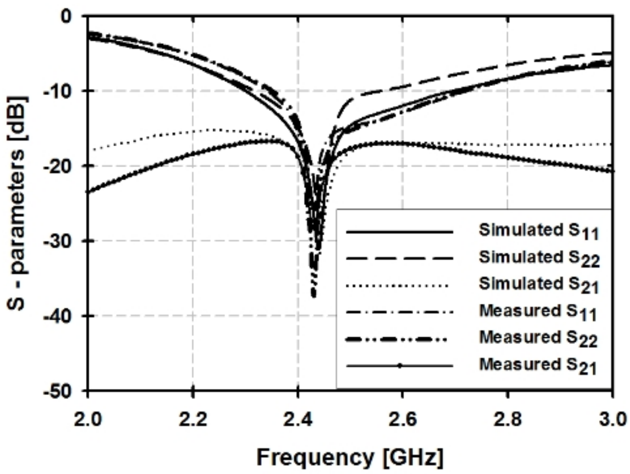
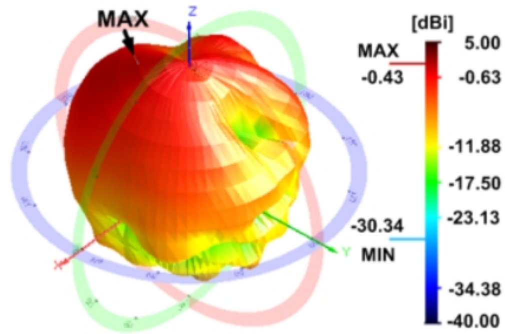


Fig. 7. The measured and simulated *S*-parameter characteristics.

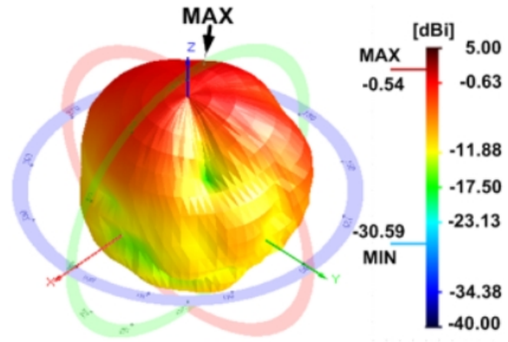
measure the *S*-parameter characteristics and 3D radiation patterns, as shown in Fig. 7 and Figs. 8(a) and (b). Fig. 7 shows the measured S-parameter characteristics of the proposed diversity antenna. When the antenna is placed 5 mm above the semi-solid phantom surface, the proposed antenna achieves a 10 dB return loss bandwidth over the ISM band (2.4～2.485 GHz) from 2.35 GHz to 2.71 GHz. Also, the isolation is higher than 28 dB at 2.45 GHz. The simulated and measured *S*-parameter resonant frequencies are in good agreement, as shown in Fig. 7.

Fig. 8(a) and (b) show the measured 3D radiation patterns of the proposed antenna placed on the semi-solid flat phantom. The measured peak gain of the antenna elements # 1 and # 2 is −0.43 dBi and −0.54 dBi at 2.45 GHz, respectively.

The performance of the proposed diversity antenna is evaluated by analyzing the key performance parameters such as the ECC, MEG, and MEG ratio. For diversity



(a) The measured 3-D pattern of Ant. #1 at 2.45 GHz



(b) The measured 3-D pattern of Ant. #2 at 2.45 GHz

Fig. 8. The measured 3-D radiation patterns of the fabricated antenna.

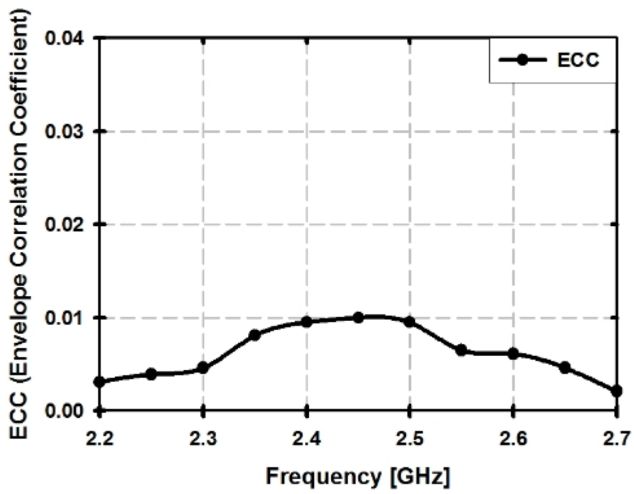


Fig. 9. The measured ECC characteristics.

and multiple-input multiple-output (MIMO) applications, the correlation between the signals, received at the same side of a wireless link by the involved antenna, is an important figure of merit for the whole system. The ECC is normally used to evaluate the diversity capability of multi antenna system. This parameter should preferably be computed from 3-D radiation patterns [9]. A good diversity gain can be obtained when the ECC is less than 0.5. Fig. 9 shows the ECC characteristics computed from the measured radiation pattern. The ECC

Table 1. ECC, MEG, and MEG ratio, and actual diversity gain of the proposed diversity antenna.

Freq. [GHz]	ECC	Ant. #1 MEG [dBi]	Ant. #2 MEG [dBi]	MEG ratio [dB]	Actual diversity gain[dB]
2.45	0.01	−11.015	−11.385	0.27	4.55

of the two antennas is maintained below 0.1 over the whole frequency band. This leads us to expect good performance in terms of diversity.

The performance of the proposed diversity antenna, including the ECC, MEG, and MEG ratio, and actual diversity gain, is summarized in Table 1. The information in Table 1 shows that the received signals satisfy the conditions suggested in [9], such that:

$$ECC < 0.5 \text{ and } 10 \log | MEG_1/MEG_2 | < 3 \text{ dB} \quad (1)$$

When a uniform propagation environment is assumed, the MEG ratio is almost unity, indicating that the mean power delivered from the two ports are almost the same.

The SAR is an essential factor for consideration when the antenna is operated on or inside the human body. The SAR is measured using the ESSAY system [10] at the Radio Research Agency of Korea, as shown in Fig. 10. The proposed antenna is excited by a signal generator. Fig. 10 shows the measured SAR distributions of the proposed diversity antenna placed 5 mm outside of the liquid flat phantom, which has a dimension of 300 mm×200 mm×200 mm. It is filled with a liquid having electrical properties equivalent to those of the human body tissue (ε_r=52.7, σ=1.95 S/m) at 2.45 GHz.

The FCC of the United States requires that the SAR values should be below 1.6 W/kg over a volume of 1 gram of tissue. Delivery of an input power of 250 mW, which is the input power normally used for the SAR

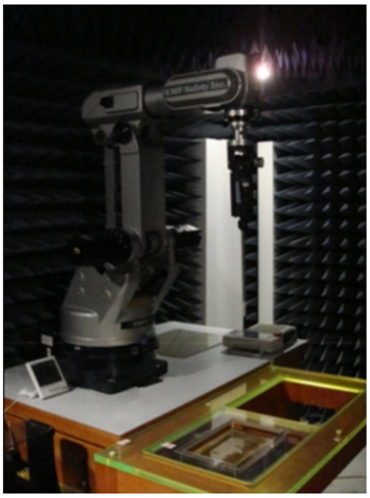
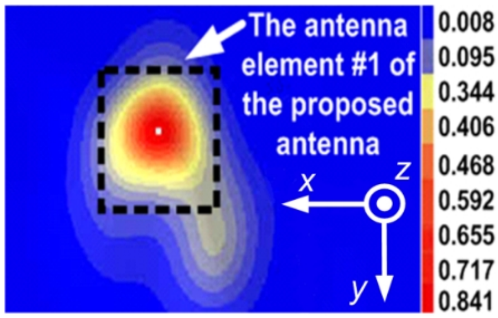
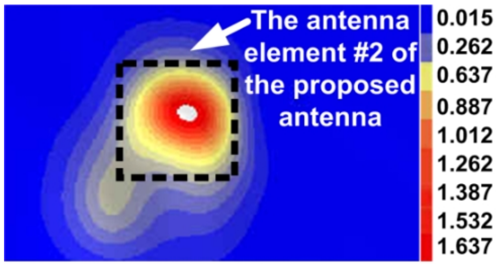


Fig. 10. SAR measurement by ESSAY system [10].



(a) Measured SAR distributions by element #1



(b) Measured SAR distributions by element #2

Fig. 11. The measured SAR distributions of the fabricated antenna(input power : 250 mW).

measurement of mobile application devices, results in the maximum SAR values obtained for the antenna elements #1 and #2, at 1.801 W/kg and 1.637 W/kg (1 g tissue), as shown in Figs. 11(a) and (b), respectively. Portable devices using 2.45 GHz applications, such as Bluetooth and Zigbee, operate below 100 mW (0.7204 W/kg for antenna element #1 and 0.6548 W/kg for antenna element #2 when the input power is 100 mW), so the maximum SAR values of the antenna are sufficiently low to satisfy the SAR limitation (1.6 W/kg for partial-body exposure) in practical use [8].

Ⅳ. Conclusion

This paper proposes a miniaturized diversity antenna with high isolation for wearable WBAN applications that overcomes the multipath fading caused by large relative movements of the body parts. The proposed diversity antenna has a dimension of 30 mm×30 mm×2.5 mm. The isolation performance is improved by using a T-shaped isolator, which is placed between the two antenna elements. The performance of the proposed diversity antenna, including bandwidth, MEG ratio, ECC, and SAR distribution, is sufficient for use in WBAN applications. In addition, the antenna is well suited for on-body applications, owing to its compact size.

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Seongjin Kim

received a B.S. degree in Information and Communication Engineering from Seokyeong University, Seoul, Korea, in 2011, and is currently working toward his M.S. degree in the Department of Electronics and Computer Engineering at Hanyang University, Seoul, Korea. His current research interests include RF devices, antennas, WBAN and wireless communication systems.

Kyeol Kwon

received a B.S. degree in Electronics Engineering from Konkuk University, Seoul, Republic of Korea, in 2010. He is currently working toward the unified course of the M.S. and the Ph.D. degrees in Electronics and Computer Engineering at Hanyang University. His research is mainly focused on the design of compact antennas for wireless body area network system.

Jaehoon Choi

received the B.S. degree from Hanyang University, Korea, the M.S. degree and the Ph.D. degree from Ohio State University, Ohio, in 1980, 1986, and 1989, respectively. From 1989～1991, he was a research analyst with the Telecommunication Research Center at Arizona State University, Tempe, Arizona. He worked for Korea Telecom as a team leader of the Satellite Communication Division from 1991 to 1995. Since 1995, he has been a professor in the Department of Electronics and Communication Engineering at Hanyang University, Korea. He has published more than 100 refereed journal articles and numerous conference proceedings. He also holds over 20 patents. His research interests include antennas, microwave circuit design, and EMC. Currently, his research is mainly focused on the design of compact, multi-band antennas for mobile wireless communication, software defined radio (SDR) systems, and ultra-wideband (UWB) systems.