Design and Implementation of Dual Band Microstrip Patch Antenna for WLAN Energy Harvesting System

Osama Amjad [1], Syeda W. Munir [1], Şehabeddin T. İmeci [2], and Ali Ö. Ercan [1]

[1] Department of Electrical and Electronics Engineering
Ozyegin University, Istanbul 34794, Turkey
osama.amjad@ozu.edu.tr, wajiha.munir@ozu.edu.tr, ali.ercan@ozyegin.edu.tr

[2] Department of Electrical and Electronics Engineering
International University of Sarajevo, 71210, Bosnia and Herzegovina
simeci@ius.edu.ba

Abstract ─ Since the demand for self-sustained wireless systems is increasing, there is a trend towards RF energy harvesting. It is a key solution to energize the low power systems such as the Internet of Things (IoT) devices without replacing the batteries periodically. This paper presents the design and analysis of RF energy harvesting system that consists of dual-band microstrip patch antenna operating at 2.4 GHz and 5.8 GHz, an impedance matching network, 4-stage voltage doubler and a storing circuit. The antenna is designed using ADS Agilent and sonnet suites software that provides a directivity of 5.5 dBi and 6.3 dBi at 2.4 GHz and 5.8 GHz respectively. The measured results of the fabricated antenna are well agreement with the simulated results. Simulated results show that for an input received power of 10 mW, the proposed system can provide 4.5 mW power at the output of 4-stage voltage rectifier with an overall efficiency of 45%.

Index Terms ─ Dual-band, impedance matching, microstrip patch antenna, RF energy harvesting and voltage rectifier.

I. INTRODUCTION

With the rapid growth of low power wireless devices, the last few years have witnessed enhanced research trends towards energy efficient wireless systems. Conventionally, these devices were powered by batteries, which have limited life time and were needed to be replaced/recharged manually once the energy is consumed. This challenge leads to an upsurge of research interests in wireless energy harvesting technique from ambient green sources (e.g., solar, thermal, vibrational, RF). Among other sources, RF source is a potential candidate for energy harvesting due to continuous availability of RF signals irrespective of geographical area and weather conditions. Moreover, RF energy harvesting is considered as a revolutionary technology that helps to develop the energy efficient wireless networks. It converts the received RF ambient signals into usable form i.e. electricity and enables the efficient use of available spectrum and provides an efficient solution to empower low-power wireless devices [1], [2]. Energy can be harvested from several digital and analog RF sources such as analog/digital TV broadcasting stations, FM/AM radio towers, WLAN access points, and cellular base stations [3]. Although a limited amount of energy can be harvested from these RF sources, it can still be used to energize the low power devices, which may solve the problem of replacing the batteries [1], [2]. Despite certain critical challenges in design and implementation of RF energy harvesting system, it is still preferred due to the high availability of free RF signals.

The concept of RF energy harvesting is shown in Fig. 1. It constitutes of receiving antenna that captures the RF signal of a certain frequency from the transmitter, matching network, RF-DC converter, and load circuitry [4]. The proposed work details the design, implementation, and analysis of energy harvesting system with dual-band microstrip patch antenna operating at WLAN frequencies. The designed antenna is integrated with the energy harvester and DC voltage has been measured at the output.

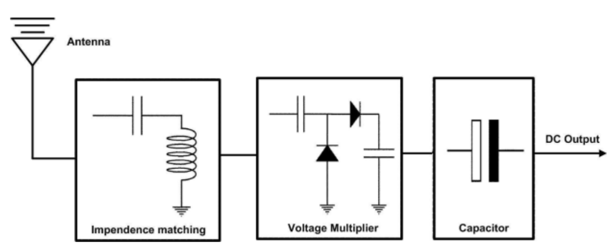


Fig. 1. General architecture of RF energy harvesting system.

This work has been partially supported by the Scientific and Technological Research Council of Turkey (TÜBİTAK) under BIDEB-2215 graduate scholarship programme for international students and under Grant No. 114E739.

Submitted On: January 7, 2017
Accepted On: June 21, 2018

The amount of harvested energy depends on the type of source, transmitted power, environment, path loss exponent and distance between the source and receiving antenna, etc. [2]. Moreover, it is significantly affected by the characteristics of the antenna; therefore suitable receiving antenna is very important in this regard. In past few years, different types of antennas have been proposed for RF energy harvesting, for example, dipoles, Yagi-Uda, microstrip, monopole, loop, spiral, and coplanar patch antennas [5]. The design of RF energy harvesting system generally utilized microstrip patch antennas because of their low profile, lightweight and planar structure.

In today's wireless communication systems, development of multiple frequency bands has provided the multi-band antennas structures for RF energy harvesting, which is quite useful. The design and implementation of energy harvesting antennas from 3G/4G cellular base stations and WLAN RF sources are presented in [6]. In [7], a 2.45/5.8 GHz simultaneously operating dual-band rectenna for an integrated wireless energy harvesting system has been implemented and analyzed. A dual-frequency circular patch antenna with a gain of 8.3 and 7.8 dBi at 1.95 and 2.45 GHz, respectively has been shown in [8]. A microstrip patch antenna with novel slot resonator for compact RF energy harvesting modules operating at 2.4 GHz is proposed in [9]. The energy harvesting system presented in [10], has been integrated with dual-core wireless multimedia sensor networks to enhance the capability of the system. Within short distances, limited amount of energy can be harvested from a typical WLAN router with transmitting power of 50-100 mW. It is an omnipresent source of renewable energy in an indoor environment and size of resonating antennas is in the order of 10-50 cm^2 [11].

In comparison to the past research that only considered the single band for RF energy harvesting this paper focuses on dual-band RF energy harvesting system that operates at Wi-Fi frequencies of 2.4 GHz and 5.8 GHz. In the simulation setup, we have used our designed dual-band microstrip patch antenna published in [3]. Moreover, the antenna is fabricated on FR4 substrate and the measured and simulated results are compared. In Section II, the design consideration of energy harvesting systems is explained including antenna design, impedance matching, and voltage rectification. Section III presents the results of the designed antenna and overall RF energy harvesting system. Section IV concludes our findings and analysis.

II. DESIGN CONSIDERATION IN RF ENERGY HARVESTING

In RF energy harvesting the most important component is the receiving antenna, which captures the ambient RF signals of a particular frequency band from transmitting source via wireless channel and converts these signals to AC voltages. The matching network, composed of capacitive and inductive elements ensures the maximum power delivery from receiving antenna to the voltage rectifier by reducing the transmission loss. The matching network has AC type voltage at the output; therefore the voltage rectifier is used to convert this voltage into usable DC power. The obtained power is either directly supplied to energize the low power device or stored in the energy storage unit. The storage circuit allows uninterrupted power delivery to the load and serves as a backup reserve when external energy is not available.

A. Proposed antenna design

The antenna can be designed to operate on either single frequency or multiple frequency bands, in which the device can simultaneously harvest from single or multiple sources. Previously, research motivation on RF energy harvesting was restricted to a single band which was not much efficient. However, recently there has been more focus towards design and implementation of dual-band and antenna arrays for RF energy scavenging. In this regard, the design of high directive dual-band microstrip patch antennas for wireless applications also received much importance [5], [6].

The proposed antenna in this paper is microstrip-fed patch antenna with a rectangular slot to operate at WLAN dual frequencies, i.e., 2.4 GHz and 5.8 GHz. The antenna has been designed on ADS Agilent software and Sonnet Suites. An FR4 epoxy substrate with a thickness of 1.6 mm and dielectric constant $\varepsilon_r = 4.4$ is used. Figure 2 shows the front and back view of the designed antenna. The dimensions of the antenna are given in Table 1. A prototype of the fabricated antenna is shown in Fig. 3. The feed line for excitation is provided having an impedance of 50 Ω. The slot dimensions are optimized such that maximum efficiency can be achieved in terms of return loss.

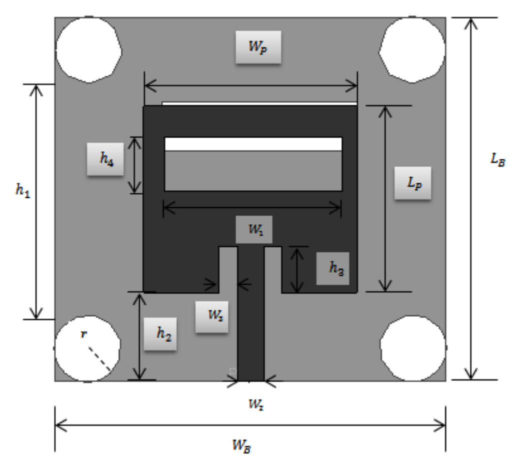
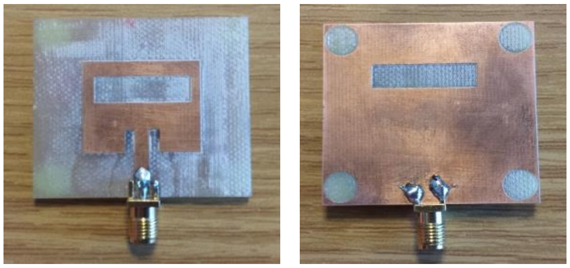


Fig. 2. Front and back view of the proposed dual-band antenna.



(a) (b)

Fig. 3. Prototype of the designed antenna: (a) front view and (b) back view.

B. Impedance matching network

Impedance matching decreases the transmission loss and ensures the maximum power transfer from antenna to the rectifier circuit such that the output voltage of rectifier circuit is increased [12]. The input impedance of the rectifier at each frequency is calculated using the modular block provided in the ADS schematic design. Further, ADS Smith chart utility has been used to match the input impedance of the rectifier to the antenna impedance of 50 Ω. Two separate LC matching networks with a capacitor C1 = 6.8 pF and an inductor L1 = 5.35 nH for 2.4 GHz and a capacitor C1 =1.3 pF and an inductor L1= 0.68 nH for 5.8 GHz are obtained. However, in a practical scenario two separate band pass filters can be deployed at the output of matching networks. The each band pass filter allows the frequency band to pass, whose power transfer is being maximized by the respective impedance matching network and rejects the high-frequency components which consequently results in the undesired harmonic re-radiation and electromagnetic interferences [13].

Table 1: Physical parameters of the proposed antenna

Parameters	Dimensions (mm)
Rectangular patch	Length $L_P = 21$ Width $W_P = 24$
Ground plane	Length $L_B = 41$ Width $W_B = 44$
Rectangular slot	Length $h_4 = 5.98$ Width $W_1 = 20$
Microstrip feed line	Width $W_2 = 3$
Inset gap	Length $h_3 = 5.2$ Width $W_3 = 2$
Circle	Radius r = 3
Remaining parameters	$h_1 = 26$ $h_2 = 10$

C. Voltage rectifier circuit

RF signals are converted into DC voltage at the given frequency band to energize the low power devices/ circuits. The main elements of the voltage rectifier are diodes; we have used the silicon-based HSMS-2850 Schottky diodes with a threshold voltage of 250 mV and diode capacitance of 0.18 pF. It provides low forward voltage, low substrate leakage and has a unidirectional flow of current [14]. Figure 4 shows the proposed RF energy harvesting system. A coupler is used to combine the antenna model with the rest of circuit. Selection of the number of stages is very crucial so that output voltage can be maximized. An optimal number of stages should be added to the system because parasitic losses of nonlinear devices also increase by increasing the number of stages.

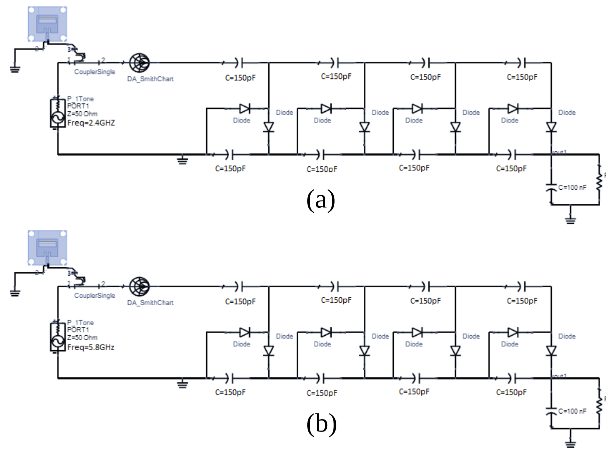


Fig. 4. Schematic diagram of 4-stage RF energy harvesting system for: (a) 2.4 GHz and (b) 5.8 GHz.

III. SIMULATION RESULTS

The proposed antenna is designed and simulated using ADS software. It can be seen in Fig. 5 that, the antenna has two operating bands around the center frequencies of 2.4 GHz and 5.8 GHz with sharp resonance. In a low band, the simulated 10 dB bandwidth is between 2.39-2.52 GHz, and similarly, at 5.8 GHz, the bandwidth is between 5.65-5.85 GHz. Moreover, it can be noticed that measured and simulated results agree well.

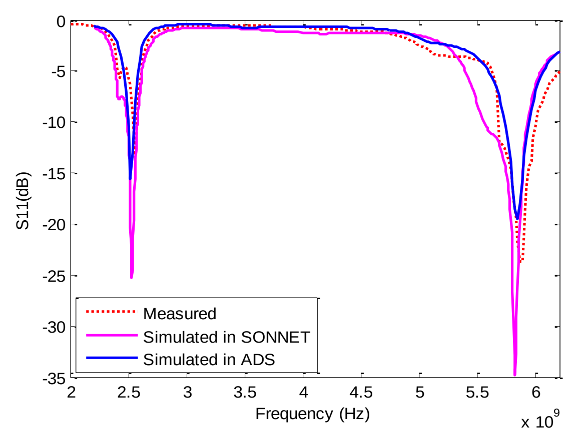


Fig. 5. Input reflection coefficients (S11) of the proposed antenna.

In order to analyze the complete energy harvesting system the designed antenna model that contains the S11 information and retains its resonant frequencies after impedance matching is exported to the schematic for co-simulation with rest of the energy harvesting circuit as shown in Fig. 4. The S-parameter and harmonic balance methods are used to interpret the relation between RF source parameters with output power. It is clearly seen in Fig. 5 that the two resonant frequencies at 2.4 GHz and 5.8 GHz are excited with good impedance matching. Best possible values of matching network are obtained using smith chart tools, which ultimately provides minimum input return loss (S11). Our results mainly focus the output power obtained versus input power, a gain of the proposed antenna, maximum power transfer from source to load and antenna efficiency in terms of its radiation pattern.

A. Effect of input power on output

The parameter sweep for an input power of -15 dBm to 0 dBm is plotted against the output power. Figure 6 shows that the output power increases with the increase of input power. Moreover, it can also be inferred that, at high resonating frequency power obtained is low as the higher frequencies are more vulnerable to path-loss and attenuation.

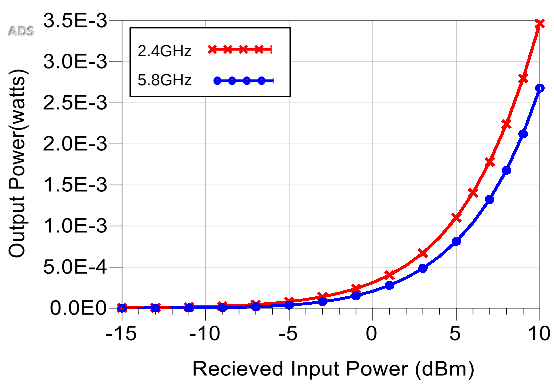


Fig. 6. Output power versus input received power at 2.4 GHz and 5.8 GHz.

B. Antenna directivity and radiation intensity

Directivity describes the direction in which the antenna has maximum gain. Radiation pattern shows the variation of the power radiated by an antenna as a function of the direction. From Fig. 7, it can be observed that antenna's maximum gain (directivity) at 2.4 GHz is 5.53 dBi in θ = 0° direction and at 5.8 GHz, the directivity is 6.3 dBi. It can also be noticed that the simulated and measured results of radiation patterns are in well agreement with each other. At both the frequencies, the radiation patterns are almost the same, thus they maintain the same polarization. Moreover, the graph shows clear deterioration at θ = 90° when operates at 2.4 GHz. Similarly, when the antenna operates at 5.8 GHz, deterioration appears at θ = 90°.

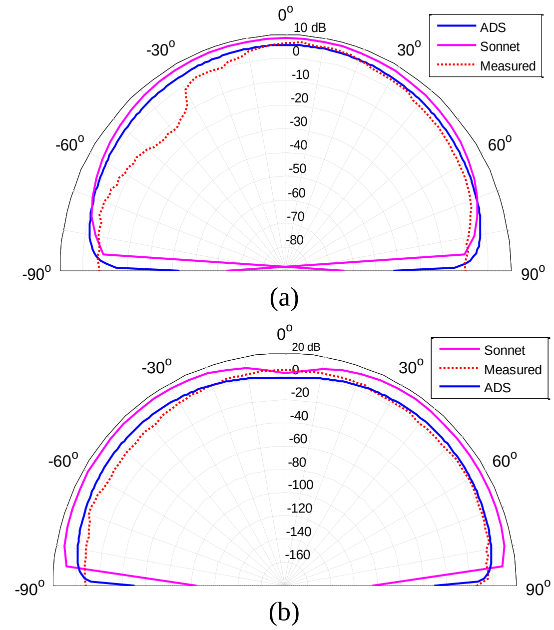


Fig. 7. Directivity of the antenna: (a) at 2.4 GHz and (b) at 5.8 GHz.

D. Effect of number of stages of rectifier

The output voltage at the first stage of the rectifier is usually too low for energizing a low power device and the conversion efficiency is also not very high. Therefore, for designing RF energy harvesting system multiple stages of voltage rectifier are connected in series one after the other stage, so as to achieve sufficient amount of voltage at the output to power the particular device. Figure 8 shows the effect of number of stages on the output voltage versus input power. It can be seen that voltage is directly proportional to the stages. Four stages have been used in the designed circuit which provides enough voltage at the output that can be used to power the required WSN applications.

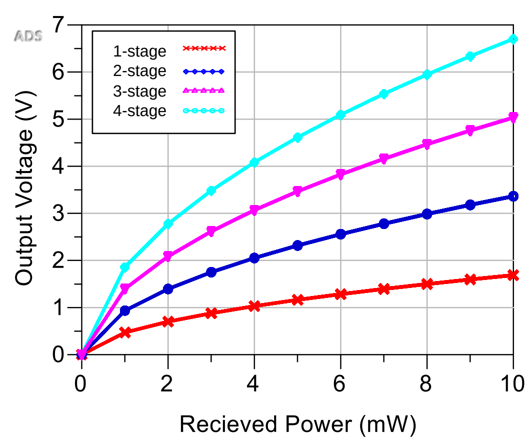


Fig. 8. Effect of number of stages on the output voltage.

IV. EFFICIENCY OF PROPOSED SYSTEM

In the proposed system two separate circuits for dual resonating frequencies are designed with different LC matching networks as shown in Fig. 4. HSMS-2850 Schottky diodes are used which provide higher conversion efficiency as they have low built-in voltage [12]. The overall efficiency of the energy harvesting system is defined as the ratio of DC power at the output to the input received power on the receiving antenna. The graph that measures the efficiency of the system against the input received power is called efficiency curve. It is of paramount importance to measure the efficiency of the designed system. Figure 9 shows the system response, when the input received power is varied between 1 mW to 10 mW. The proposed system can provide maximum output power of 4.5 mW for an input received power of 10 mW with an efficiency of 45%. The efficiency of RF energy harvesting system depends on accurate matching, efficient antenna and the power efficiency of the voltage rectifier that converts the received RF signals to DC voltage.

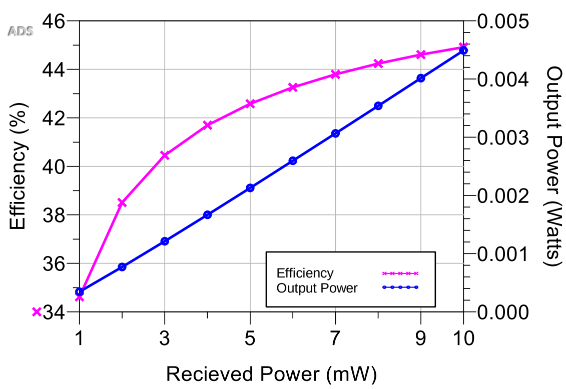


Fig. 9. Effect of incident RF power on efficiency of the proposed system.

V. CONCLUSION

In this paper, energy harvesting from WLAN source with dual-band antenna is designed in ADS Agilent and Sonnet Software. The designed antenna is fabricated on FR4 substrate and S-parameter and radiation pattern are measured. The results show that the simulated and measured results are in well agreement. Furthermore, the designed antenna is integrated with the rest of energy harvesting circuit that includes an impedance matching network, 4-stage voltage rectifier and a storing circuit. Our proposed network is designed to be used for RF energy harvesting from Wi-Fi frequency bands. The results show a reflection coefficient of almost -22 dB and maximum gain of 5.5 dBi at 2.4 GHz. Similarly, at 5.8 GHz reflection coefficient of -48 dB and maximum gain of 6.3 dBi is obtained. Moreover, result shows that 10 mW of RF incident power on antenna can generate 4.5 mW power at output resistance of 10 kΩ with an overall efficiency of 45%.

REFERENCES

[1] X. Lu, P. Wang, D. Niyato, D. Kim, and Z. Han, “Wireless networks with RF energy harvesting: A contemporary survey,” *IEEE Communication Survey & Tutorials*, vol. 17, no. 2, May 2015.

[2] T. Soyata, L. Copeland, and W. Heinzelman, “RF energy harvesting for embedded systems: A survey of tradeoffs and methodology,” *IEEE Circuits and Systems Magazine*, Feb. 2016.

[3] S. W. Munir, O. Amjad, E. Zeydan, and A. Ö. Ercan, “Optimization and analysis of WLAN RF energy harvesting system architecture,” *International Symposium on Wireless Communication Systems (ISWCS)*, pp. 429-433, Oct. 2016.

[4] Y. Uzun, “Design of an efficient triple band RF energy harvester,” *ACES Journal*, vol. 30, no. 12, Dec. 2015.

[5] S. Shrestha, S. Noh, and D. Choi, “Comparative study of antenna designs for RF energy harvesting,” *International Journal of Antennas and Propagation*, Jan. 2013.

[6] M. Hoang, H. Phan, T. Q. V. Hoang, and T. P. Vuong, “Efficient compact dual-band antennas for GSM and Wi-Fi energy harvesting,” *IEEE International Conference on Advanced Technologies for Communications*, Oct. 2014.

[7] X. Li, J. Wang, X. Wu, and H. Zaho, “A dual-band integrated wireless energy harvesting system,” *International Applied Computational Electromagnetics Society Symposium (ACES)*, Sept. 2017.

[8] M. Aboualalaa, A. B. Abdel-Rahman, A. Allam, H. Elsadek, and R. K. Pokharel, “Design of a dual-band microstrip antenna with enhanced gain for energy harvesting applications,” *IEEE Antennas and Wireless Propagation Letters*, vol. 16, pp. 1622-1626, Jan. 2017.

[9] M. Palandoken, “Microstrip antenna with compact anti-spiral slot resonator for 2.4 GHz energy harvesting applications,” *Microwave and Optical Letters*, vol. 58, no. 6, Mar. 2016.

[10] M. A. Jamshed and O. Amjad, “Multicore energy efficient scheduling with energy harvesting for wireless multimedia sensor networks,” *International Multi-topic Conference (INMIC)*, Feb. 2018.

[11] M. Arrawaita, M. S. Baghini, and G. Kumar, “RF energy harvesting systems from cell towers in 900 MHz band,” *IEEE-Conference In Communications*, pp. 1-5, Jan. 2011.

[12] P. Nintanavongsa, U. Muncuk, D. R. Lewis, and K. R. Chowdhury, “Design optimization and implementation for RF energy harvesting circuits,” *IEEE Journal on Emerging and Selected Topics in Circuits and Systems*, vol. 2, no. 1, pp. 24-33, Mar.

2012.
[13] B. Schauwecker, "Design of processing circuitry for an RF energy harvester," *University of Arkansas, Fayettevill*, May 2016.
[14] K. K. A. Devi, N. Md. Din, and C. K. Chakrabarty, "Optimization of the voltage doubler stages in an RF-DC convertor module for energy harvesting," *Circuits and Systems*, vol. 3, no. 3, July 2012.

Osama Amjad has received his B.S. degree in Electrical Engineering from COMSATS Institute of Information Technology (CIIT), Islamabad, Pakistan, in 2014 and his M.S. degree in Electrical and Electronics Engineering from Özyegin University in 2017. He is currently a Ph.D. student and a graduate assistant at Lakehead University, Canada since September 2017. His research interests are in the areas of wireless communications and wireless networks.

Syeda Wajiha Munir has completed her B.S. Electrical Engineering with Gold Medal from COMSATS Institute of Information Technology (CIIT), Islamabad, Pakistan, in 2014 and her M.S. degree in Electrical and Electronics Engineering from Özyeğin University in 2017. Her research interests are in the areas of wireless communications and wireless networks.

Şehabeddin Taha İmeci received the B.Sc. degree in Electronics and Communications Engineering from Yildiz Technical University, Istanbul, Turkey in 1993, and the M.S.E.E. and Ph.D. Degrees from Syracuse University, Syracuse, NY in 2001 and 2007, and Associate Professorship degree from Istanbul Commerce University, Istanbul Turkey in 2014, respectively. Imeci was appointed as Full Professor in Int. Univ. of Sarajevo in Nov. 2017. He is working as the Dean of FENS (Faculty of Engineering and Natural Sciences) in Sarajevo. He was with Anaren Microwave Inc., East Syracuse, NY from 2000 to 2002, and Herley Farmingdale, New York from 2002 to 2003, and PPC, Syracuse, NY from 2003 to 2005, and Sonnet Software Inc., Liverpool, NY from 2006 to 2007. He was a Teaching Assistant in the Department of Electrical Engineering and Computer Science at Syracuse University from 2005 to 2006. His current research areas are microwave antennas and electromagnetic theory.

Ali Özer Ercan received his B.S. degree in Electrical and Electronics Engineering from Bilkent University, Ankara, Turkey in 2000, and his M.S. and Ph.D. degrees in Electrical Engineering from Stanford University, CA, USA in 2002 and 2007 respectively. From 2007 until 2009, he was with the Berkeley Wireless Research Center of University of California, Berkeley, CA, USA, for post-doctoral studies. He joined Özyegin University, Istanbul, Turkey, in September 2009 as an Assistant Professor. He is the recipient of FP7 Marie Curie International Reintegration Grant and TUBITAK Career (3501) Award. He served as the Publications Chair of IEEE 3DTV Conference (3DTV-CON) in 2011, and Technical Program Co-chair and Publications Chair of IEEE Signal Processing and Communication Applications Conference (SIU) in 2012. His research interests are in the areas of signal and image processing, and wireless communication networks. Ercan is a Senior Member of the IEEE.