A Beamwidth Reconfigurable Antenna Array With Triple Dual-Polarized Magneto-Electric Dipole Elements

BOTAO FENG1, (Member, IEEE), YATING TU1, KWOK L. CHUNG2, (Senior Member, IEEE), AND QINGSHENG ZENG3, (Senior Member, IEEE)

1College of Electronic Science and Technology, Shenzhen University, Shenzhen 518060, China
2School of Communications and Electronic Engineering, Qingdao University of Technology, Qingdao 266033, China
3College of Aeronautics, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China

Corresponding author: Kwok L. Chung (klchung@qut.edu.cn)

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ABSTRACT A novel linearly dual-polarized antenna array with triple elements is proposed for beamwidth reconfigurable base-station communications. By cutting off the arc-shaped corners on the radiated patches, the single dual-polarized antenna unit can obtain a wide bandwidth of 78.4% for SWR ≤ 2, ranging from 1.63 to 3.73 GHz for 2G/3G/LTE and 3.5-GHz C-band (3.4–3.6 GHz) applications. In addition, with the box-shaped reflector and the inherent characteristic of the ME dipole antenna, the average gain of the dual-polarized antenna element is about 11.5 dBi. Finally, by employing a two-stage circuit with several power dividers, a three-element antenna array with a widely adjustable beamwidth in both the E-plane and H-plane is investigated, which could meet the demand of the future smart applications.

INDEX TERMS Dual polarized antenna, magneto-electric(ME) dipole, beamwidth reconfigurable antenna, wideband antenna.

I. INTRODUCTION

Due to the outstanding advantages such as combating the multipath fading, reducing the number and size of antennas, etc., dual polarized antennas have been widely studied and used in modern mobile communication systems. For base-station antenna designs, a wide bandwidth with stable high gain is an extremely important factor affecting the channel capacity and transmission distance. Hence, many dual polarized base-station antennas have been proposed to meet the stringent requirement [1]–[4]. In [1], two Y-shaped feeding lines cooperate with four folded dipoles to obtain an impedance bandwidth of 27.8% (1.7–2.25 GHz) for 2G/3G applications. A differential cross-shaped feeding structure together with additional rings near the radiated patches have been employed to obtain a wider bandwidth of 52% and a better port isolation of more than 26.3 dB [2]. By introducing the asymmetrical magnetic coupling structures, a port isolation better than 45 dB over the frequency band of 2.35–2.85 GHz can was reported [3]. In addition, in order to provide anti-interference feature, two orthogonal dipoles in cross pair and C-shaped stubs placed near the feeding line was presented [4], a wide bandwidth of 52.6% along with a sharp notch band from 2.27 to 2.53 GHz can be obtained to cover the 2G/3G/4G bands. Although many excellent characteristics have been obtained by the above studies, their operating bandwidths are unable to meet the demand of future 5G application [5].

Recently, a great deal of attention has been attracted to the wide beamwidth reconfigurable antennas. By dynamically adjusting its radiation beamwidth, the spectrum utilization can be improved and the communication congestion can also be effectively mitigated [6]–[9]. In [6], two long and two short dipoles together with a reflector are designed to obtain a stable 3-dB beamwidth of 63.3 ± 2.9 degrees in H-plane. Furthermore, by using the trapezoid-shaped plane ground and three shorted walls at different altitudes, a beamwidth of 120° in H-plane can be obtained by the modified magneto-electric (ME) dipole antenna [7]. For flexible adjustment,
a three-element ME dipole array is proposed to realize beamwidth reconfiguration, whose beamwidth in the H-plane can be switched between the $37^\circ$ and $136^\circ$ [8]. Moreover, by introducing four parasitic radiated patches and some connected variable capacitors near the ME dipole antenna, a continuously tuning range from $72^\circ$ to $133^\circ$ in H-plane can be achieved [9]. However, these reconfigurable antennas suffer from either narrow bandwidth or narrow tunable beamwidth in a single radiation plane.

In this paper, a three-element dual-polarized antenna array with wide bandwidth, high gain and wide adjustable beamwidth in both the E-plane and H-plane is proposed. Firstly, by cutting off the arc-shaped corners on the radiated patches, a wide impedance bandwidth of 78.4% for SWR $\leq 2$ can be obtained for the future 5G communication frequency band. In addition, with the box-shaped reflector and the inherent characteristic of the ME dipole antenna, a high gain of about 11.5 dBi can also be achieved by a dual-polarized antenna element. Furthermore, the gain of the three-element array can be enhanced to 17.3 dBi. Finally, by employing a two-stage tunable circuit with several power dividers, a three-element beamwidth reconfigurable antenna array with widely adjustable features is attained, which ranges from $24^\circ$ to $97^\circ$ in H-plane for port 1, and from $22^\circ$ to $100^\circ$ in E-plane for port 2 over the whole operating frequency band, respectively. In the following sections, this promising reconfigurable antenna for future 5G base-stations will be detailed.

**TABLE 1. Geometrical parameters.**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>$H$</th>
<th>$W$</th>
<th>$L$</th>
<th>$S$</th>
<th>$G$</th>
<th>$P$</th>
<th>$F_{W1}$</th>
<th>$F_{W2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values/mm</td>
<td>29.6</td>
<td>14</td>
<td>29.7</td>
<td>6.5</td>
<td>160</td>
<td>35</td>
<td>4.5</td>
<td>4.5</td>
</tr>
<tr>
<td>Parameters</td>
<td>$F_{H1}$</td>
<td>$F_{H2}$</td>
<td>$F_{L1}$</td>
<td>$F_{L2}$</td>
<td>$F_{d1}$</td>
<td>$F_{d2}$</td>
<td>$F_{gap}$</td>
<td>$F_{tau}$</td>
</tr>
<tr>
<td>Values/mm</td>
<td>23.5</td>
<td>26</td>
<td>26</td>
<td>26</td>
<td>11.3</td>
<td>10.7</td>
<td>1</td>
<td>2.5</td>
</tr>
<tr>
<td>Parameters</td>
<td>$L_a$</td>
<td>$L_b$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Values/mm</td>
<td>8.4</td>
<td>0.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**II. ANTENNA GEOMETRY AND WORKING MECHANISM**

The geometry and detailed dimensions of the dual-polarized magneto-electric dipole antenna element are shown in Fig. 1 and Table 1, respectively. The proposed ME dipole element consists of two pairs of electric dipoles with arc-shaped corners cut off, two vertically oriented shorted-wall patches, two orthogonal $\eta$-shaped feeding line and a box-shaped reflector. The radiated patch of the antenna has a square shape with a dimension of $29.7 \times 29.7$ mm$^2$ ($L \times L$). The height of the shorted wall is 29.6 mm. The gap between two vertical walls is 6.5 mm ($S$). In order to excite the antenna and obtain high isolation, the two orthogonal $\eta$-shaped feeding lines are separated by a height of 2.5 mm ($F_{tau}$). Noting that the orthogonal parts of the feeding line are decreased to obtain the better isolation and impedance matching. The reflector with an optimized height of 35 mm ($P$) helps to suppress the beam division and improve the gain.
As shown in Figs. 2 and 3, the linear array gener-
ally consists of three dual-polarized antenna elements which are mounted on a rectangular ground plane and fed by a three-way feeding network. The feeding network built on a 0.787-mm-thick Rogers dielectric substrate (\(\varepsilon_r = 2.33\)) is mounted underneath the ground plane as described in Fig. 3(a). The feeding network can be divided as two stages. Firstly, the first three Wilkinson power dividers are used to broaden the impedance bandwidth and equally allocate the power. Secondly, the following two Wilkinson power dividers are only used in the input ports to allocate the power. In addition, the proposed feeding network can provide much wider bandwidth and dual polarized operation. As a result, both the adjustable E-plane and H-plane beamwidths can be obtained.

III. PARAMETRIC STUDY AND RESULT DISCUSSION

In order to study how the antenna performances are affected by the structures and the dimensions, such as wide impedance bandwidth, wide H-plane, and diversity performances, etc., some critical parameters are investigated by ANSYS electromagnetic simulation software High Frequency Structure Simulation (HFSS) [12]. In addition, the antenna prototype was fabricated and measured to verify the results, as shown in Fig. 5.

To understand the antenna operation, the current distributions on the radiated electric patches from the two input ports in a period are depicted in Fig. 6. For port 1, at time \(t = 0\), the currents on the radiated patches achieve the strongest intensity and are dominated in the minus y-direction, whereas the currents on the surfaces of the magnetic dipoles get the minimum strength. Then at time \(t = T/4\) (where \(T\) is a period of time), the currents on the radiated electric patches become as the following formulas (assuming \(M_{a1} = M_{a3} = a_2, \psi_2 = \psi_1 + \beta = \psi_3 + \beta\)):

\[
F(\theta) = \left[ a_1e^{-j(kr_1 + \psi_1)} + a_2e^{-j(kr_2 + \psi_2)} + a_3e^{-j(kr_3 + \psi_3)} \right]f(\theta)
\]

\[
AF = a_1 [2\cos(kd\sin\theta) + M\cos\beta - jM\sin\beta]
\]

where \(F(\theta), a_n, \psi_n (n = 1, 2, 3), f(\theta)\) represent the radiation field in the yoz-plane, the amplitudes, the phases and the radiation pattern of a single antenna element, respectively, in formula (1), while \(AF\) and \(M\) stand for the array factor and the multiple, respectively, in formula (2). Hence, a smaller beamwidth value and a larger one can be switched between path 1 and path 2 by a switch. Different from [8], the switch paths are reduced to two ways. In addition, the proposed feeding network can provide much wider bandwidth and dual polarized operation. As a result, both the adjustable E-plane and H-plane beamwidths can be obtained.

![Figure 2. 3D view of the proposed beamwidth reconfigurable antenna array.](image)

![Figure 3. The proposed feeding network and its schematic diagram (\(Z_0 = 50\Omega, Z_1 = 50\Omega, Z_2 = 50\Omega, Z_3 = 50\Omega, Z_4 = 50\Omega, Z_5 = 50\Omega, Z_6 = 50\Omega, Z_7 = 50\Omega, R_1 = 150\Omega, R_2 = 200\Omega, R_3 = 250\Omega, R_4 = 150\Omega\), \(\lambda\) refers to 2.6 GHz.). (a) The proposed feeding network. (b) Schematic diagram.](image)
minimum and turn to the minus x-direction, whereas the currents on the surfaces of the magnetic dipoles get the maximum strength and are dominated. At time $t = T/2$, the currents on the radiated patches attain the strongest intensity and are dominated in the positive y-direction, whereas the currents on the surfaces of the magnetic dipoles changes to the minimum strength. Finally, at time $t = 3T/4$, the currents on the radiated electric patches turn to the minimum intensity and turn to the positive x-direction again, whereas the currents on the surfaces of the magnetic dipoles get the maximum strength and are dominated. That is to say, the electric and magnetic dipoles alternate in domination to work together and hence complementary unidirectional patterns can be obtained in a period. For port 2, the varied condition is similar to port 1 except that the polarized direction is vertical to port 1. The phase difference between the equivalent electric and magnetic dipoles is $90^\circ$ and they are orthogonal to each other. As a result, wide frequency bandwidth and low back lobe radiation pattern can be obtained.

Fig. 7 shows the effect of the number of the multi-level power dividers. It can be easily seen that, as the frequency increases, the central resonance frequencies move to the upper frequency band. In the meantime, the bandwidth ($S_{11} \leq 10$) gets wider. However, the high order of harmonic frequencies increase sharply and cannot cover the lower frequency band of 2G communication. In order to obtain a wide enough frequency bandwidth and keep harmonic frequency stable for the 2G/3G/LTE/5G communication (eg. 1.71-2.69 GHz and 3.4-3.6 GHz) at the same time, the triple-level power divider is chosen for the first stage of the feeding network.

Fig. 8 shows the effect of radiated patch in different shapes. Compared to the other two different shaped patches, the SWR curves of both port 1 and port 2 cover the widest bandwidth and are more stable. Consequently, the corresponding gains are more stable and much higher than the others, especially in the upper frequency band. Besides, different shaped horizontal coupling strips are compared in the aspects of port isolation and SWR, as shown in Fig. 9. It can be observed that by cutting a pair of rectangular notches on the horizontal coupling strips, the isolation can obviously be improved about 5 dB on average, while there is no significant change in the SWR curves.

Fig. 10 shows the SWR and gains of a single antenna element in both ports. As depicted, the simulated and measured bandwidth range from 1.56 to 3.78 GHz, and from 1.63 to 3.73 GHz, respectively. Both of them cover the 2G/3G/LTE and 3.5-GHz C- frequency band. Over the whole operating frequency band, the corresponding simulated and measured gains vary from 10.5 to 12.3 dBi, and from 10.1 to 12.9 dBi’, respectively. The gain is stable and high enough for the base-station communication. As shown in Fig. 11, both of the simulated and measured front to back ratios (FBR) of the two ports are larger than 20 dB, whereas the simulated isolation and measured are under $-28$ dB and $-25$ dB, respectively, in the whole working frequency band. The trends of the curves are almost identical except some light frequency shifts. For a dual polarized base-station antenna, the isolation should be under $-25$ dB. Hence, the proposed antenna can meet the anti-interference demand. Fig. 12 shows the radiation patterns of the single antenna element over the entire operating band. As depicted, the stable and nearly identical radiation patterns in both E- and H- planes can be achieved. The cross polarized levels are all below $-22$ dB over the operating frequency band. The measured results are in accordance with the simulated ones.
In order to showcase the matching and radiating performances, the SWR and gains of the dual-polarized antenna array at different modes are shown in Fig. 13. At mode 1, the simulated bandwidth ranges from 1.84 to 3.68 GHz with a gain varying from 12.5 to 16.8 dBi, while the measured bandwidth ranges from 1.73 to 2.77 GHz, and from 3.2 to 3.68 GHz with a gain varying from 12.9 to 16.6 dBi, respectively. Similarly, at mode 2, the simulated bandwidth ranges from 1.91 to 3.88 GHz with a gain varying from 8.8 to 14 dBi, while the measured bandwidth ranges from 1.69 to 3.06 GHz, and from 3.15 GHz to 3.71 GHz with a gain varying from 8.9 to 14 dBi, respectively. In comparison with the antenna element, the working frequency band of antenna array slightly moves towards the upper frequency.

Fig. 14 shows the 3-dB beamwidth in the E- and H- planes at different frequencies and different modes. The results can be summarized in Table 2. The measured results agree well with the simulated ones except some fabricated errors. It can be seen that, for port 1 at mode 1, the measured beamwidth in the E- plane is $56^\circ \pm 4.3^\circ$ with a gain of $13.8 \pm 2.8$, while the beamwidth in the H- plane is $26^\circ \pm 2.1^\circ$. The condition of port 2 at mode 1 is just opposite to port 1 at mode 1. On the other hand, for port 1 at mode 2, the beamwidth in the E- plane is $60^\circ \pm 6.6^\circ$ with a gain of $11.6\pm 2.4$, whereas
the beamwidth in the H-plane is up to $92^\circ \pm 4.8^\circ$. The condition of port 2 at mode 2 is also opposite to port 1 at mode 2 with a slight variation. In other words, for port 1, the 3-dB beamwidth in H-plane can vary on a large scale, while the one in the E-plane keeps stable. The condition of port 2 is the exact opposite. Furthermore, Fig. 15 shows the simulated and measured 3dB-beamwidths of the dual-polarized antenna array over the operating frequency band. As shown, for port 1, the measured beamwidth in H-plane varies between $22^\circ$ and $100^\circ$, whereas the measured beamwidth in E-plane keeps almost constant at about $60^\circ$. Similarly, for port 2, the measured beamwidth in E-plane varies between $24^\circ$ and $97^\circ$, whereas the measured beamwidth in H-plane remains nearly unchanged at about $59^\circ$. The values shown in Table 2 is complementary with Fig. 15. Therefore, it is suitable to switch beamwidth between the rush and rest times with a result of improving the channel utilization and the green energy saving.

Table 3 demonstrates the comparison between the proposed antenna and other referenced base-station antennas in terms of bandwidth, 3-dB beamwidth, dual polarization, peak gain and reconfigurability. As easily observed, the proposed antenna is superior in the widest bandwidth, the wider 3-dB beamwidth in the dual polarization directions, the higher gain and enabled reconfigurability.
The concept of the proposed antenna array is similar to the conventional beam-steering phased deviation array. However, the size is much smaller and the structure is more simple. Owing to its simple design at low cost, the antenna with the above-mentioned superior characteristics is potentially competitive for the smart communication.
TABLE 3. Comparison of the proposed antenna with other referenced antennas.

<table>
<thead>
<tr>
<th>Refs.</th>
<th>Bandwidth (Relative BW/GHz)</th>
<th>3-dB Beamwidth In H-plane (deg)</th>
<th>Dual-Polarization</th>
<th>Peak Gain (dBi)</th>
<th>Reconfigurable</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>The Proposed Antenna (elements/array)</td>
<td>78.4% (1.63–3.73)</td>
<td>65</td>
<td>Yes</td>
<td>12.9 (EL)</td>
<td>Yes</td>
<td>Wide Beamwidth; Dual-Polarization; Beamwidth Reconfigurable; High Gain.</td>
</tr>
<tr>
<td>[1]</td>
<td>30% (1.7–2.3)</td>
<td>65 ± 5</td>
<td>Yes</td>
<td>15.8 (AR)</td>
<td>No</td>
<td>Narrow Beamwidth.</td>
</tr>
<tr>
<td>[2]</td>
<td>52% (1.7–2.9)</td>
<td>66.2 ± 3.8</td>
<td>Yes</td>
<td>8.5 (EL)</td>
<td>No</td>
<td>Wide Beamwidth.</td>
</tr>
<tr>
<td>[3]</td>
<td>20% (2.5–2.7)</td>
<td>72</td>
<td>Yes</td>
<td>9 (EL)</td>
<td>No</td>
<td>High Gain; Narrow Beamwidth.</td>
</tr>
<tr>
<td>[4]</td>
<td>52.6% (1.6–2.86)</td>
<td>60 ± 4</td>
<td>Yes</td>
<td>7.57 ± 0.6 (EL)</td>
<td>No</td>
<td>Wide Beamwidth; Low Gain.</td>
</tr>
<tr>
<td>[6]</td>
<td>59.7% (1.55–2.87)</td>
<td>63.3 ± 2.9</td>
<td>No</td>
<td>8.7 ± 0.4 (EL)</td>
<td>No</td>
<td>Wide Beamwidth; Low Gain.</td>
</tr>
<tr>
<td>[7]</td>
<td>45% (2.37–3.76)</td>
<td>120</td>
<td>No</td>
<td>6.7 ± 0.35 (EL)</td>
<td>No</td>
<td>Wide Beamwidth; Low Gain.</td>
</tr>
<tr>
<td>[8]</td>
<td>15% (1.8–2.1)</td>
<td>136</td>
<td>No</td>
<td>9.8 ± 0.3 (AR)</td>
<td>Yes</td>
<td>Narrow Beamwidth.</td>
</tr>
<tr>
<td>[9]</td>
<td>10% (1.9–2.1)</td>
<td>133</td>
<td>Yes</td>
<td>7.4 ± 0.3 (EL)</td>
<td>Yes</td>
<td>Wide Beamwidth; Low Gain.</td>
</tr>
<tr>
<td>[13]</td>
<td>64.5% (1.71–2.69)</td>
<td>\</td>
<td>Yes</td>
<td>7 (EL)</td>
<td>No</td>
<td>Wide Beamwidth; Low Gain.</td>
</tr>
<tr>
<td>[14]</td>
<td>58% (1.6–2.9)</td>
<td>65 ± 10</td>
<td>Yes</td>
<td>15.5 (AR)</td>
<td>No</td>
<td>Wide Beamwidth; Narrow Beamwidth.</td>
</tr>
<tr>
<td>[15]</td>
<td>45% (1.7–2.7)</td>
<td>68 ± 2</td>
<td>Yes</td>
<td>14 ± 1.1 (AR)</td>
<td>No</td>
<td>Wide Beamwidth; Low Gain.</td>
</tr>
<tr>
<td>[16]</td>
<td>56% (1.63–2.9)</td>
<td>65 ± 8</td>
<td>Yes</td>
<td>16 (AR)</td>
<td>No</td>
<td>Wide Beamwidth; Narrow Beamwidth.</td>
</tr>
<tr>
<td>[17]</td>
<td>65.9% (1.7–3.4)</td>
<td>62 ± 2</td>
<td>Yes</td>
<td>9.5 (EL)</td>
<td>No</td>
<td>Wide Beamwidth; High Gain; Narrow Beamwidth.</td>
</tr>
<tr>
<td>[18]</td>
<td>687% (0.95–1.92)</td>
<td>56 ± 5</td>
<td>Yes</td>
<td>9.5 (EL)</td>
<td>No</td>
<td>Wide Beamwidth; High Gain; Narrow Beamwidth.</td>
</tr>
<tr>
<td>[19]</td>
<td>19% (0.79–0.96) 12% (1.71–2.17)</td>
<td>65 ± 8</td>
<td>Yes</td>
<td>15 ± 0.1 (AR) 17 ± 3 (AR)</td>
<td>No</td>
<td>Dual Beamwidth; High Gain; Narrow Beamwidth.</td>
</tr>
<tr>
<td>[20]</td>
<td>45% (1.71–2.69)</td>
<td>65 ± 4</td>
<td>Yes</td>
<td>8.3 ± 0.6 (EL)</td>
<td>No</td>
<td>Wide Beamwidth; Narrow Beamwidth.</td>
</tr>
</tbody>
</table>

Where EL and AR are short for element and array, respectively.

IV. CONCLUSION
A beamwidth reconfigurable antenna array with triple dual-polarized magneto-electric dipole elements is proposed for the base-station communication. By delicately cutting off the arc-shaped corners on the radiating patches and employing the box-shaped reflector, a wide impedance bandwidth (SWR ≤ 2) of 78.4% with a stable gain about 11.5 dBi can be obtained over the 2G/3G/LTE/5G-C frequency band. Moreover, by introducing a two-stage tunable circuit composed of power dividers and a phase shifter, a widely adjustable beamwidth ranging from 24° to 97° in H-plane for port 1 and a tunable beamwidth ranging from 22° to 100° in E-plane for port 2 are achieved within the operating bandwidth, respectively. In view of the aforementioned performances, the proposed reconfigurable antenna array is a promising candidate for the future 5G smart communications.

REFERENCES


**BOTAOFENG** (M’14) received the B.S. and M.S. degrees in communication engineering from the Chongqing University of Posts and Telecommunications, Chongqing, China, in 2004 and 2009, respectively, and the Ph.D. degree in communication and information system from the Beijing University of Posts and Telecommunications, Beijing, China, in 2015. He joined the Dongguan Branch of Nokia Mobile Phones Ltd., China, as a Senior Communication Engineer, in 2004. From 2009 to 2012, he served as a Senior Research Fellow in charge of mobile network optimization with China United Network Communications Co., Ltd. He is currently a Post-Graduate Advisor and a Post-Doctoral Advisor with Shenzhen University, Shenzhen, Guangdong, China. He is also the Head of the Laboratory of Wireless Communication, Antennas and Propagation of Shenzhen University, the Director of the Joint Laboratory of Antenna and Electromagnetic Propagation, Shenzhen University–Rihai Communication Technology Co., Ltd., and the Director of the Joint Laboratory of Antenna and Microwave Technology, Shenzhen University–Skywave Communication Technology Co., Ltd. He has authored over 30 SCI- and EI-indexed papers. He holds 10 invention patents. His research interests include base-station antenna, microcell antenna, indoor antenna, and wireless network optimization. He and his team members are conducting over 10 projects on antenna development and design for 5G and future communications, which are supported by natural science research funds and industrial cooperation research and development funds. He serves as a peer reviewer of several IEEE/IET journals and a technical committee member of conferences on microwave technique and antenna.

**YATINGTU** was born in Zhanjiang, Guangdong, China, in 1994. She received the B.S. degree from Shenzhen University in 2017, where she is currently pursuing the M.S. degree. Her research interests include the design of wideband antenna, base-station antenna, and reconfigurable antenna.

**KWOK L.CHUNG** (S’00–M’05–SM’11) received the B.E. (Hons.) and Ph.D. degrees in electrical engineering from the University of Technology Sydney, Australia, in 1999 and 2005, respectively. He joined the Faculty of Engineering, University of Technology Sydney, as a Lecturer, in 2004. In 2006, he joined The Hong Kong Polytechnic University, where he spent about six years in the teaching of electronic engineering. In 2012, he joined the Institute for Infrastructure Engineering, Western Sydney University, as a Research Fellow. In 2015, he joined the Qingdao University of Technology (QUT), China, as a Cross-Disciplinary Research Professor, and a Supervisor of Ph.D. students. He has authored and co-authored over 100 publications (SCI and EI) in various areas of electrical and civil engineering. His current research interests include passive wireless sensors for structural health monitoring, cement-based materials design and characterization, microwave antennas, and metasurface designs. He is a Core Member of the Taishan Scholar Priority Discipline Talent Group, QUT, and a member of the International Steering Committee of the IEEE International Workshop on Electromagnetics. He was the Vice-Chair and the Chairman of the IEEE AP/MTT Hong Kong Joint Chapter in 2010 and 2011, respectively. He has been the Founding Chair for the IEEE Qingdao AP/MTT/COM Joint Chapter since 2017. He is currently an Associate Editor of the IEEE ACCESS and acts as a reviewer for numerous IEEE, IET, Elsevier, and other international journals.

**QINGSHENG ZENG** (S’97–M’02–SM’11) received the Ph.D. degree from the University of Ottawa, Canada. He is currently a Distinguished Professor and a Ph.D. Advisor with the Nanjing University of Aeronautics and Astronautics, an Adjunct Professor and a Ph.D. Advisor with the University of Ottawa, Carleton University, the Université du Québec, and the Institut National de la Recherche Scientifique–Centre Énergie, Matériaux et Télécommunications, and a Guest Professor of Harbin Engineering University, Northwestern Polytechnic University, the Beijing University of Posts and Telecommunications, and Beijing Jiaotong University. He has been a Research Engineer and a Senior Research Engineer with the Communications Research Centre Canada, Government of Canada. His research interests include antenna analysis and design, electromagnetic compatibility (EMC) and electromagnetic interference, ultra wideband technology, radio wave propagation, and computational electromagnetics. He is a member of the IEEE Canada Industry Relations Committee. He has been a member of the Strategic Projects Grant Selection Panel (Information and Communications Technologies B) for the Natural Sciences and Engineering Research Council of Canada (NSERC), and the Site Visit Committee of the NSERC Industrial Research Chair. He is the Chair of Antennas and Propagation/Microwave Theory and Techniques Joint Chapter and the Secretary of EMC Chapter of IEEE Ottawa. He is a reviewer of the NSERC Industrial Research and Development Fellowships. He has authored over 100 SCI- and EI-indexed papers and technical reports, one book, and co-authored two book chapters, one of which has been downloaded over 3000 times only in one year after it was published in 2011. His work on the project Aggregate Interference Analysis and Suitability of Some Propagation Models to Ultra-Wideband Emissions in Outdoor Environments has formed one part of Consultation Paper on the Introduction of Wireless Systems Using Ultra Wideband Technology, Spectrum Management and Telecommunications Policy, Industry Canada, and has been taken as a significant contribution to the International Telecommunication Union. He has been serving as an editorial board member and a reviewer for a number of technical books and scientific journals, a conference co-chair, a session chair, an organizer, a technical program committee co-chair, a member, a reviewer, a short course/workshop/tutorial presenter, and a keynote speaker for many international and national symposia. He received several technical and technical service awards, was ranked as one of the researchers at the Communications Research Centre Canada with the strongest impacts in 2011, and selected as a Distinguished Expert under the Plan of Hundreds of Talents of Shannxi Province, China, in 2015, and an Overseas Prestigious Advisor of Guangdong Province in 2017.