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A Novel MIMO Antenna Integrated with a Solar Panel and Employing AI-Equalization for 5G Wireless Communication Networks

Humam Hussein[1], Nouf Abd Elmunim[2], Ferhat Atasoy[1], Bal S. Virdee[3], Taha A. Elwi[4,5]*, Nasr Rashid[6,7], Renu Karthick Rajaguru Jayanthi[3], Mohammad Alibakhshikenari[8]*, Ernesto Limiti[9]*

[1]Department of Computer Engineering, Karabuk University, Karabuk, Turkey; eng.humam94@gmail.com, erhatatasoy@karabuk.edu.tr
[2]Department of Electrical Engineering, College of Engineering, Princess Nourah Bint Abdulrahman University, Riyadh, Saudi Arabia; naasmail@pnu.edu.sa
[3]Center for Communications Technology, London Metropolitan University, London N7 8 DB, U.K.; b.virdee@londonmet.ac.uk, r.rajagurujayanthi1@londonmet.ac.uk
[4]Islamic University Centre for Scientific Research, The Islamic University, Najaf, Iraq
[5]International Applied and Theoretical Research Center (IATRC), Baghdad, Iraq; taelwi8@gmail.com
[6]Department of Electrical Engineering, Faculty of Engineering, Al-Azhar University, Nasr City, Cairo 11884, Egypt; nasrrashid34.el@azhar.edu.eg
[7]Department of Electrical Engineering, College of Engineering, Jouf University, Sakaka 72388, Saudi Arabia
[8]Department of Signal Theory and Communications, Universidad Carlos III de Madrid, 28911 Leganés, Madrid, Spain; mohammad.alibakhshikenari@uc3m.es
[9]Electronics Engineering Department, University of Rome “Tor Vergata”, 00133 Rome, Italy; limiti@ing.uniroma2.it

*Corresponding Authors: Taha Elwi, Mohammad Alibakhshikenari, Ernesto Limiti

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ABSTRACT In this paper, we propose a novel MIMO antenna array configuration that incorporates metamaterial isolation surfaces to enhance overall performance. We demonstrate that the directivity of this antenna array can be precisely electronically reconfigured using PIN diode switches. Additionally, we show the feasibility of integrating solar panels with the proposed MIMO antenna array. Adopting solar panels in 5G base stations is expected to reduce dependency on traditional grid power sources, thereby decreasing energy usage and operational expenses, and supporting the goal of achieving net-zero emissions in communication systems. Furthermore, we demonstrate the effectiveness of an artificial intelligence (AI)-enabled equalizer in mitigating degradation in channel capacity caused by signal power fluctuations, thereby enhancing the reliability and efficiency of wireless communication systems. We demonstrate multifaceted benefits of combining these technologies.

KEYWORDS MIMO, antennas, solar panel, AI-equalizer, channel capacity, metamaterial.

I. Introduction

In recent years, the field of wireless communication has undergone rapid evolution, driven by a surging demand for increased channel capacity and improved reliability in data transmission [1]. Among the pivotal advancements that have emerged to meet these escalating demands, Multiple Input Multiple Output (MIMO) technology stands out as a cornerstone [2]. By enabling the simultaneous transmission and reception of multiple data streams over the same radio channel, MIMO has revolutionized various aspects of wireless communication [3, 4]. This technology significantly enhances network capacity and data transfer rates by exploiting spatial diversity and multipath propagation, thereby mitigating signal degradation and improving overall system performance [3, 4].

A critical aspect of MIMO technology lies in its ability to dynamically adapt to diverse communication scenarios, frequencies, and environmental conditions through reconfiguration mechanisms [5]. This adaptability affords several advantages, including enhanced frequency agility, improved spectrum efficiency, effective interference mitigation, and adaptive beamforming techniques [6]. The effectiveness of MIMO systems is closely tied to their ability to optimize signal reception and transmission in response to changing propagation conditions and user requirements, making them indispensable in modern wireless networks [7].

In parallel, advancements in antenna design have introduced technologies such as coplanar waveguide (CPW) antennas and electromagnetic band gap (EBG) structures. CPW antennas offer advantages such as easy fabrication, cost-effectiveness, compact size, and the ability to operate across multiple frequency bands [8]. On the other hand, EBG structures, including soft and hard surface defects, frequency-selective surfaces, and artificial magnetic conductors, have gained prominence for their ability to manipulate electromagnetic waves by suppressing surface waves and controlling radiation patterns [9, 10]. These technologies play a vital role in improving antenna performance, enhancing signal integrity, and optimizing energy efficiency in wireless communication systems [9, 10].

The deployment of 5G communication networks further underscores the need for innovative strategies to manage increasing energy demands while maintaining seamless and efficient communication capabilities. In this context, integrating renewable energy sources such as solar panels with MIMO antenna arrays presents a promising solution. By harnessing solar energy, this integration reduces reliance on conventional grid power sources and helps lower operational costs associated with powering 5G base stations and other network infrastructure [11]. Moreover, leveraging solar panels aligns with global initiatives aimed at reducing carbon footprints and promoting environmentally sustainable technologies within the telecommunications sector [11].

The integration of solar panels with MIMO antennas not only addresses energy efficiency challenges but also enhances the overall sustainability of 5G communication networks. This approach not only contributes to reducing greenhouse gas emissions but also supports long-term cost savings and operational resilience. Additionally, by incorporating high isolative walls for supplementary shielding, the proposed solution aims to mitigate electromagnetic interference and elevate signal quality, crucial factors for ensuring optimal performance in dense urban environments and challenging propagation conditions [12].

Through rigorous empirical research and real-world testing in urban and rural settings, this study seeks to demonstrate the feasibility and effectiveness of integrating solar panels with MIMO antennas for enhancing energy efficiency and sustainability in 5G communication networks. By advancing the understanding and implementation of energy-efficient technologies in telecommunications, this research aims to pave the way for a greener and more sustainable future in wireless communications.

In this paper have proposed a novel MIMO antenna array with metamaterial isolation surfaces to improve its overall performance. It is shown that the directivity of this antenna array can be dynamically reconfigured using PIN diode switches controlled by a microprocessor. We have demonstrated that integrating solar panels with a MIMO antenna array can reduce dependency on grid power, resulting in lower energy consumption and operational costs. Additionally, we have shown the effectiveness of employing an AI-enabled equalizer in mitigating the degradation of channel capacity caused by signal power fluctuations during wireless communication.

II. MIMO Antenna Design and Concept of the Proposed Work

The proposed MIMO antenna system comprises four antenna elements strategically positioned around the sides of a cuboid structure, as illustrated in Fig. 1(a). Initially, the antenna specifications were determined in accordance with the application requirements. The antennas were fabricated on a substrate from the AD1000 family of Rogers, which has a thickness of 1 mm, a relative permittivity (ε_r) of 10.2, and a loss tangent (tanδ) of 0.00021. The cuboid hosting the MIMO antenna has dimensions of 30×38×38 mm³.

Each of the four antennas forming the 4×1 MIMO array was energized via a common power divider. Structurally, each MIMO antenna consisted of a configuration of 3×5 radiation elements, with each radiating element comprising four triangular-shaped radiators arranged to form a square shape, separated by a small gap. These elements were framed within microstrip lines connected to a shared 50Ω feedline at the base of the antenna, as depicted in Fig. 1(a). On the reverse side of the antenna, a truncated ground plane was employed, with each MIMO antenna backed by a conductive reflector. Adjacent to each reflector were 2×6 conductive reflectors arranged in a configuration mirroring the triangular radiation elements.

The design parameters were tailored for operation within the sub-6 GHz frequency band (2.2 GHz to 6 GHz), with the requirement of $S_{11} \leq -6$ dB. Utilizing a 3D full-wave finite element method via CST Studio Suite, the antenna's performance was carefully designed and optimized. The final dimensions of the optimized antenna are presented in Fig. 1. Following fabrication, the proposed MIMO antenna, as shown in Fig. 1(b), underwent measurement for validation purposes. The design specifications ensure that the proposed MIMO antenna maintains isolation (S_{12}, S_{13}, and S_{14}) better than -15 dB across the entire frequency band of interest.

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Furthermore, the antenna achieves a maximum gain of 7.4 dBi at 5.8 GHz, aligning with the demands of 5G systems, as well as LTE, GSM, WiMAX, and Bluetooth applications.

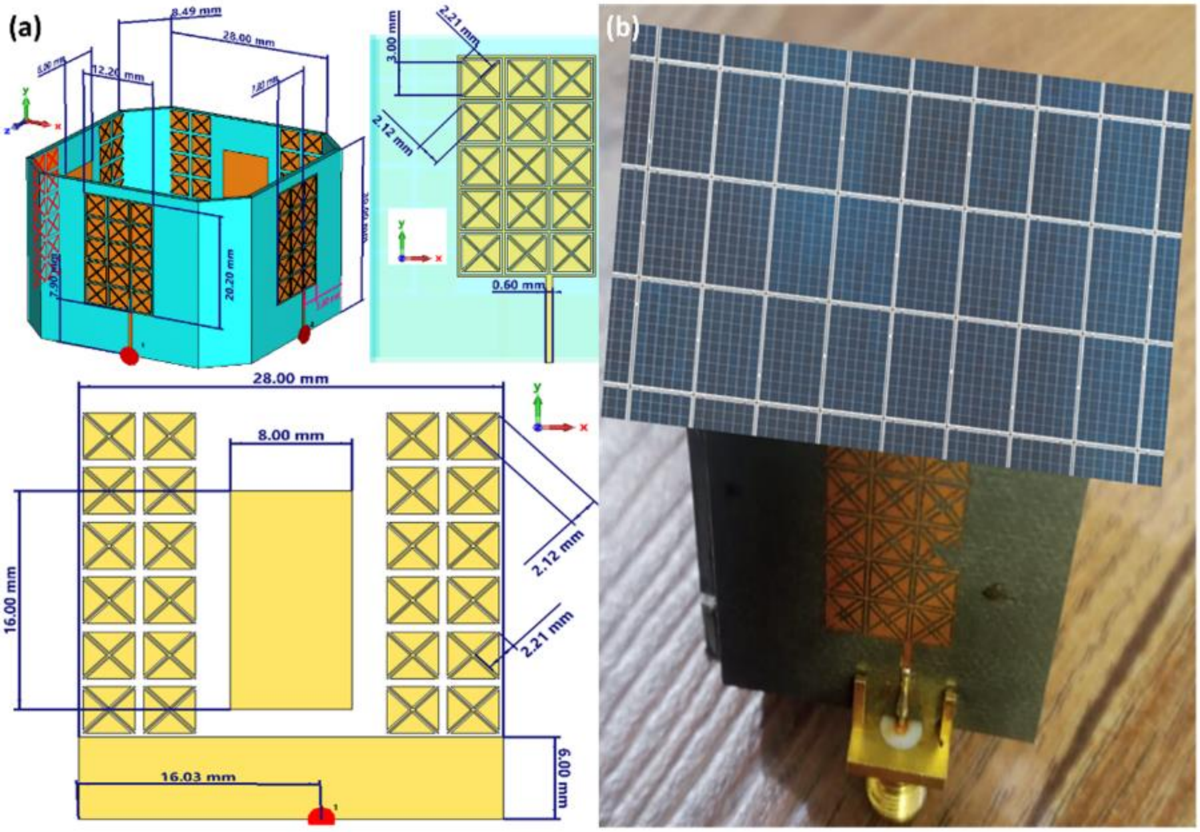

Fig. 1. The proposed MIMO antenna, (a) 3D antenna structure, and (b) the fabricated prototype with solar panel.

III. Antenna Design Methodology and Analysis

The proposed antenna design was simulated using CST Studio Suite, followed by a thorough performance analysis via a parametric study to achieve an optimal design. The design methodology employed is detailed in this section. The process for implementing the proposed antenna is illustrated in Fig. 2.

A. Single Antenna

Initially, the antenna geometry was designed to conform to a standard microstrip patch configuration with a ground plane, and it was edge-fed using a 50Ω feedline. In the first step, the antenna exhibited a narrow impedance bandwidth of better than -10 dB at 4.3 GHz and 5.9 GHz, with an average gain of approximately 4 dBi across the 2 GHz to 6 GHz range. To broaden the antenna's impedance bandwidth, the ground plane was truncated in the second step. This adjustment extended the impedance bandwidth to better than -10 dB between 3 GHz and 5.3 GHz, albeit with a slightly reduced average gain of around 3.5 dBi within the 2 GHz to 6 GHz range.

In the third step, the single patch antenna was partitioned into 3×5 elements, with each radiating element consisting of four triangular-shaped radiators arranged in a square configuration with small gap between them. A single conductive reflector was etched onto the back of these radiating elements. Although this modification extended the impedance bandwidth predominantly between 3 GHz and 5.5 GHz, the average gain diminished to approximately 3.0 dBi across the 2 GHz to 6 GHz spectrum.

In the fourth step, 2×6 conductive reflectors, designed to mirror the triangular radiation elements, were placed on the backside, effectively acting as metamaterial surfaces. While this adjustment contracted the impedance bandwidth to between 2.8 GHz and 4.2 GHz, the average gain experienced a modest increase to approximately 3.5 dBi within the 2 GHz to 6 GHz range.

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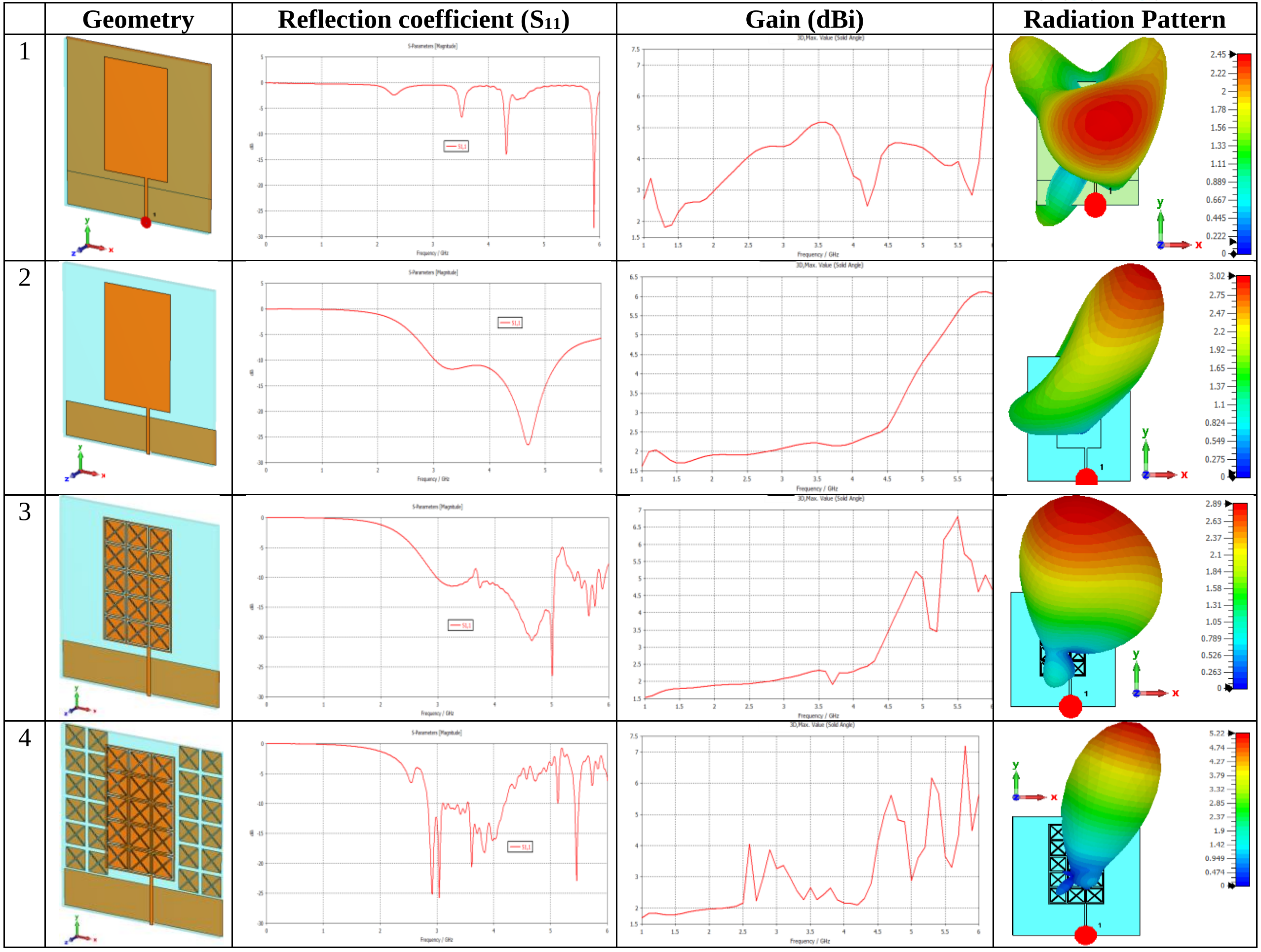

Fig. 2. Design steps and associated antenna characteristics.

B. *MIMO Antenna*

In the setup depicted in Fig. 1, antennas are positioned on each of the four sides of a cuboid structure. To determine the optimal distance between the antennas and the metamaterial-based reflective surface, a parametric study was conducted. Fig. 3 shows the impact of varying this distance, ranging from 2 mm to 6 mm, on both the reflection coefficient (S_{11}) and the isolation between different ports (S_{12}, S_{13}, S_{14}). The study indicates that a gap of 6 mm yields a significantly improved reflection coefficient compared to a 2 mm gap, especially when the electromagnetic coupling between the antennas and the reflective surfaces is weak. Furthermore, maintaining a 6 mm gap results in an average improvement of approximately 15 dB in isolation across the frequency range from 2 GHz to 6 GHz. This underscores the effectiveness of a larger 6 mm gap in optimizing the reflection coefficient and enhancing isolation, particularly within the specified frequency range.

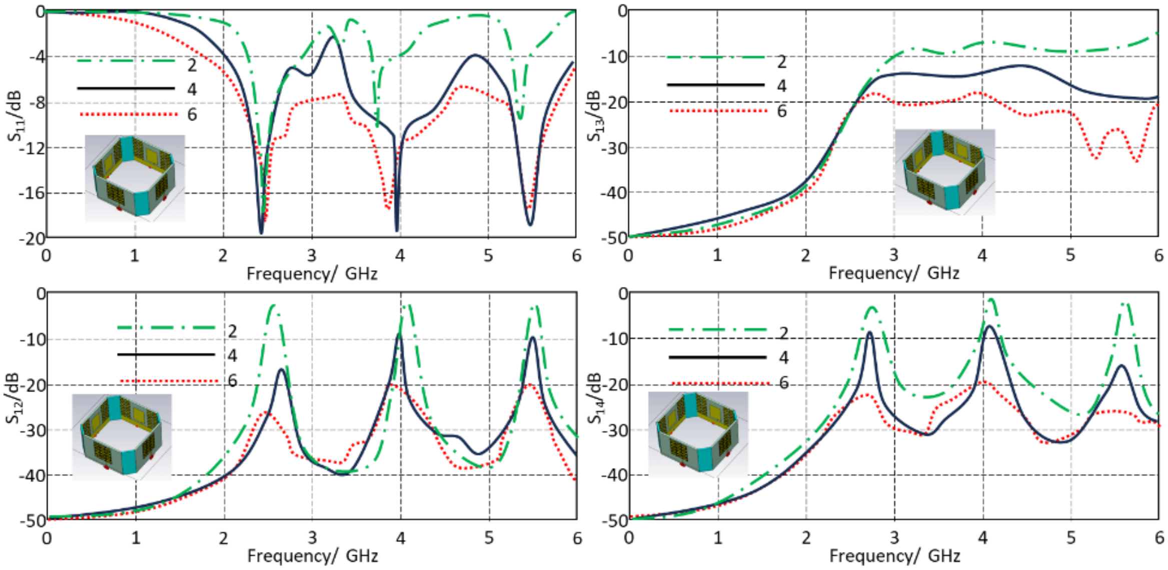

Fig. 3. Spectra of reflection coefficient (S_{11}) and isolation between ports 2 to 1 (S_{12}), 3 to 1 (S_{13}), and 4 to 1 (S_{14}) of the proposed MIMO antenna array.

C. *Solar Panel Integration*

The solar panels were strategically positioned on top of the MIMO antenna array to maximize exposure to sunlight. The solar panels were connected to inverters to convert solar energy into usable electrical power to the proposed MIMO system's requirements. A robust mounting structure was used to secure both the antenna array and solar panels.

To explore the impact of the vertical distance between the solar panel and the array, a systematic parameter study was conducted, varying the distance from 1 mm to 4 mm in 1 mm increments. This investigation aimed to assess how these variations influenced the array's reflection coefficient (S_{11}) and the isolation between different ports (S_{12}, S_{13}, S_{14}). Fig. 4 shows that a vertical gap of 4 mm provides the most favorable reflection coefficient response, exhibiting an enhancement of approximately 4 dB across the frequency range from 2 GHz to 4 GHz. Correspondingly, the isolation between ports experiences a notable improvement of approximately 15 dB within the same frequency span when maintaining this 4 mm gap. This finding underscores the significance of optimizing the vertical distance between the solar panel and the antenna array to achieve optimal performance in both reflection coefficient and isolation metrics.

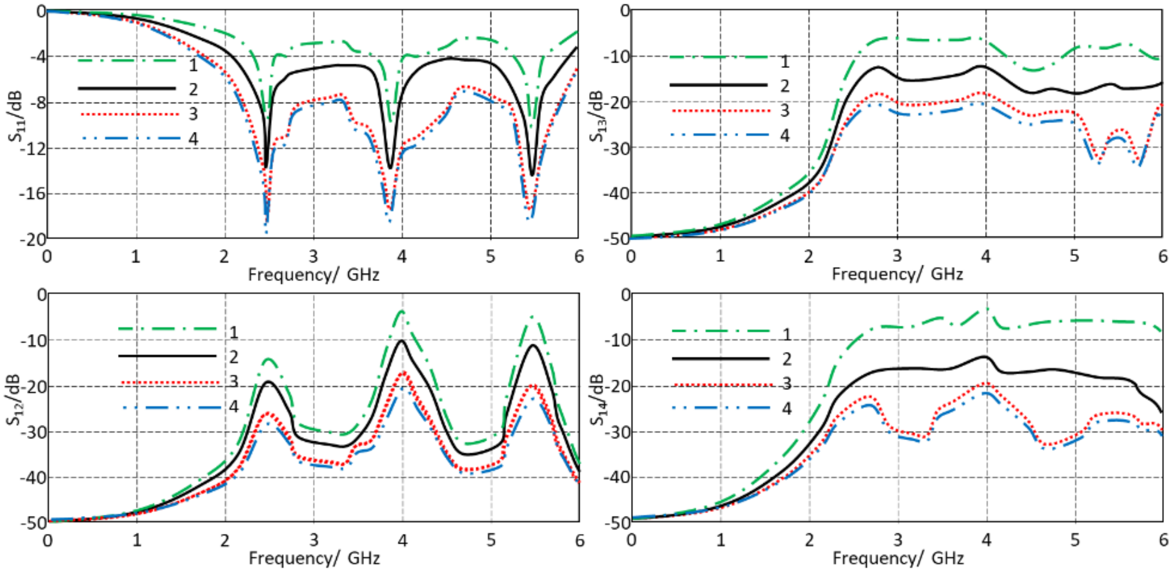

Fig. 4. Spectra of reflection coefficient (S_{11}) and isolation between ports 2 to 1 (S_{12}), 3 to 1 (S_{13}), and 4 to 1 (S_{14}) of the proposed MIMO antenna array with a solar panel.

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D. Configuration scenarios

The proposed antenna has been engineered to exhibit adaptable radiation performance by influencing its surface currents. This was accomplished through the integration of five PIN diode switches connected between the antenna reflector and the partial ground plane.

The efficacy of this design was assessed using the Mean Square Error (MSE) to ascertain path loss (γ) through an AI regression algorithm. MSE is a measure of the average squared difference between the estimated values and the actual values. The transmitted signal is often corrupted by noise during transmission. At the receiver, MSE is used to quantify the accuracy of the estimation of the original signal from the noisy observations. A lower MSE indicates a more accurate estimation of the transmitted signal.

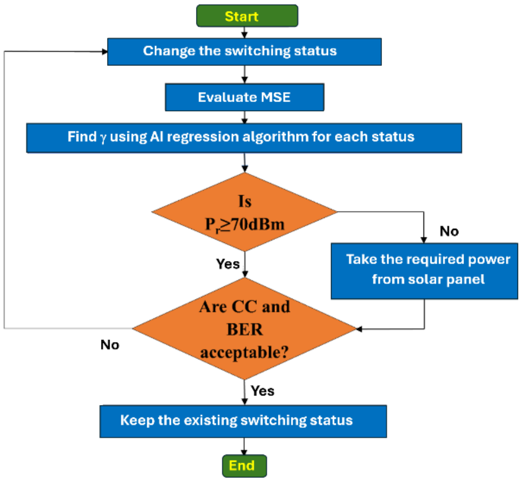

Fig. 5. Flowchart followed to maintain acceptable channel capacity and bit error rate for effective and reliable communication link.

In communication links, a power management system often uses a threshold around -70 dBm to assess received signal power, which is a common reference point for maintaining moderate signal quality in wireless communications [13, 14]. If this criterion is met, the system taps into solar panel reserves to amplify the incoming signal. Subsequently, an AI algorithm evaluates the channel's quality by analyzing channel capacity (CC) and bit error rate (BER). If these parameters fall below acceptable thresholds, the algorithm orchestrates a modification in the antenna's radiation directionality. This adjustment is achieved by activating or deactivating the PIN diode switches using a microprocessor. The flowchart in Fig. 5 depicts the sequence in which the instructions and conditions are followed.

In our design of the MIMO antenna system tailored for Non-Orthogonal Multiple Access (NOMA) applications, we've implemented a mechanism to reconfigure the radiation direction. This functionality is essential for optimizing signal transmission efficiency in NOMA scenarios. The mechanism involves the incorporation of five PIN diode switches, strategically connected between the antenna reflector and a partial ground plane, as depicted in Fig. 6. This figure demonstrates that activating any combination of these diodes has minimal impact on the array's reflection coefficient, ensuring stability in signal performance. However, by selectively switching these diodes, the surface currents on the antennas are altered, consequently influencing the radiation pattern, as visually represented in the figure. Notably, when all diodes are switched from the off state, the radiation direction undergoes a distinct 90-degree change. This dynamic functionality enables precise control over the directionality of radiation, crucial for optimizing signal transmission in NOMA applications.

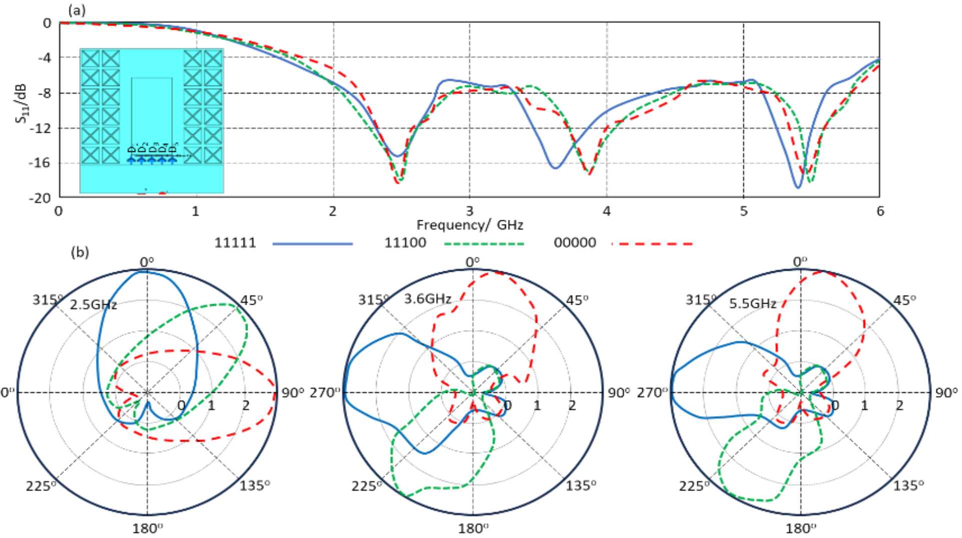

Fig. 6. Performance of the proposed MIMO antenna array under different PIN diode switching scenarios: (a) S_{11} spectra, and (b) radiation patterns.

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IV. Antenna Performance Measurements

The MIMO antenna array we devised was manufactured using a standard chemical etching process. Subsequently, we evaluated the performance of the fabricated antennas by measuring their S-parameters and radiation patterns. Fig. 7 compares the measured performance against simulated results, showing an excellent level of agreement between the two responses. Our proposed antenna exhibits optimal reflection coefficient performance, surpassing 15 dB at key frequencies of 2.3 GHz, 3.8 GHz, and 5.5 GHz. Correspondingly, the gains achieved at these frequencies are noteworthy, measuring 5.2 dBi, 6.59 dBi, and 7.4 dBi, respectively. Additionally, the isolation between the antenna ports exceeds 20 dB, indicating robust signal separation capabilities.

Moreover, our investigations into the radiation patterns under various PIN diode activation scenarios revealed a remarkable capability: a 90-degree alteration in radiation direction when all five PIN diodes transition from the 'off' to the 'on' state. This dynamic functionality underscores the versatility and precision of our antenna design in adapting to diverse communication requirements.

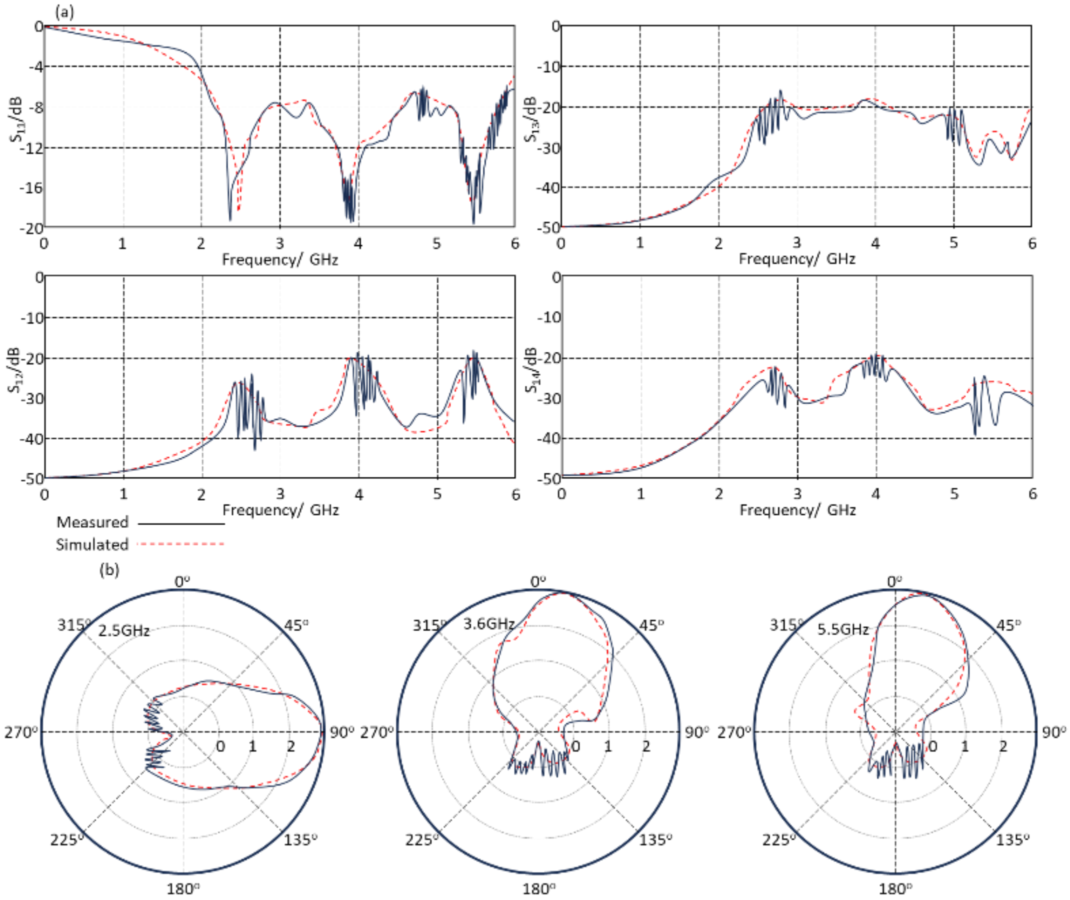

Fig. 7. The measured antenna performance: (a) S-parameters, and (b) radiation patterns with different PIN diode activation status: left pattern 11111, middle pattern 11100, right pattern 0000.

V. Channel Performance

The performance of our proposed MIMO antenna array was evaluated under real-world conditions in Baghdad, Iraq. The test location featured three base-station towers, as depicted in Fig. 8. Tower 1 was approximately 19 m from the test site, while the other two towers were situated at distances of 49 m and 97 m, respectively. We conducted empirical data collection specifically for the n79-band mobile network, which comprises multiple cells, through driving tests conducted in both urban and rural areas of the city. Fig. 9(a) outlines the fundamental setup of our drive test scenario.

In this setup, the mobile base-station tower stood at a height of h_t and was positioned at a defined geographic latitude and longitude (φ_T, λ_T), transmitting with power P_t. Our MIMO antenna array was mounted atop a mast located within the base-station cell site at coordinates (φ_i, λ_i), with a mast height of h_r. The diagonal distance (d_i) between the array and the base-station was calculated, accounting for a 34 m height difference between h_t and h_r. The coverage radius of

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the base station extended up to 600 m. To calculate the received power (P_r), we utilized Eqn. (1) [2]:

$$P_r(d_i) = P_r(d_o) - 10\gamma \log\left(\frac{d_i}{d_o}\right) + X_\sigma \qquad (1)$$

Fig. 8. Testing location I Bagdad, Iraq.

Here, $P_r(d_o)$ represents the measured power at d_o, a reference distance close to the base-station, ensuring d_i always exceeds d_o. The parameter γ denotes the rate of received power decay with distance, while X_σ accounts for fading, modeled as a zero-mean Gaussian-distributed random variable (in dB) with standard deviation σ. For our specific scenario, we determined γ at frequencies of 2.5 GHz, 3.6 GHz, and 5.5 GHz to be 2.2, 2.3, and 2.7, respectively, employing a regression analysis-based AI algorithm. Fig. 9(b) illustrates both the measured received power versus distance at the three spot frequencies and different ERP. Fig. 10 shows how the PIN diode activation scenario affects the percentage of users as a function of distance from the array that received signal strength greater than or equal to -70 dBm.

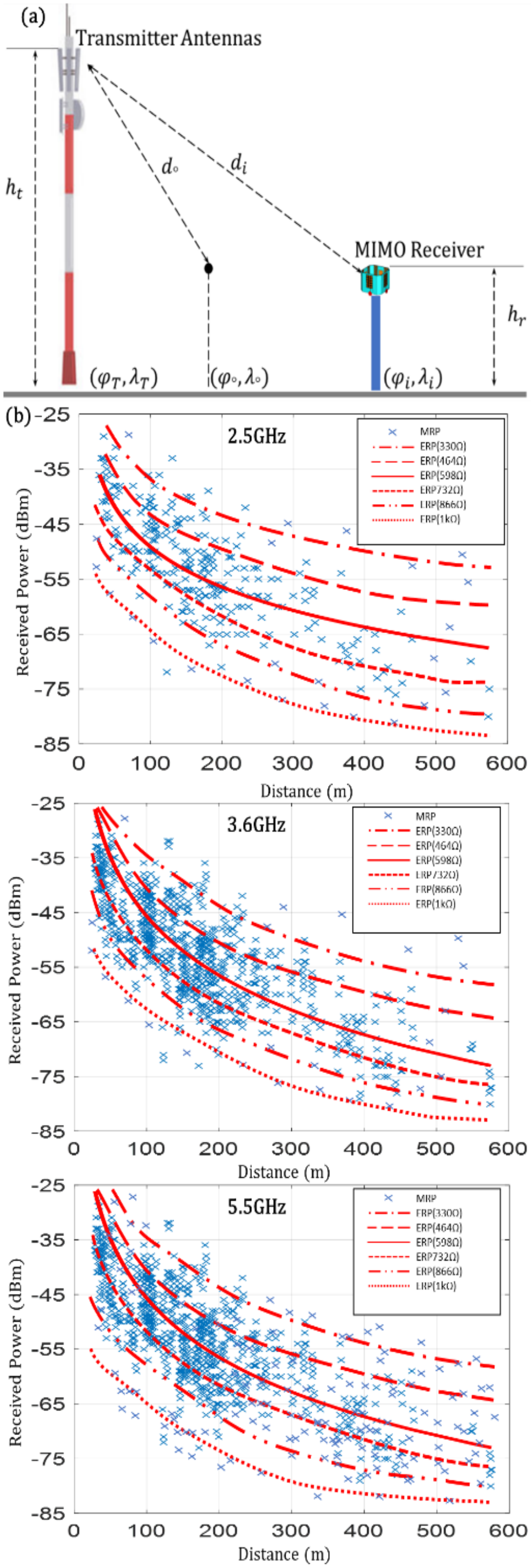

Fig. 9. (a) Measuring setup, and (b) Regression estimation at the predefined spot frequencies.

In Fig. 11, we observe the effective channel diversity of the proposed MIMO antenna array, characterized by Gain Diversity (DG) and Envelope Correlation Coefficient (ECC) spectra. The array demonstrates a favorable combination of low ECC and high DG within the frequency band of interest, spanning from 2 GHz to 6 GHz. These findings position the proposed antenna as a highly promising candidate for various applications within 5G MIMO systems. Its ability to maintain low envelope correlation alongside high gain diversity suggests robust performance and suitability for diverse communication scenarios within this frequency range.

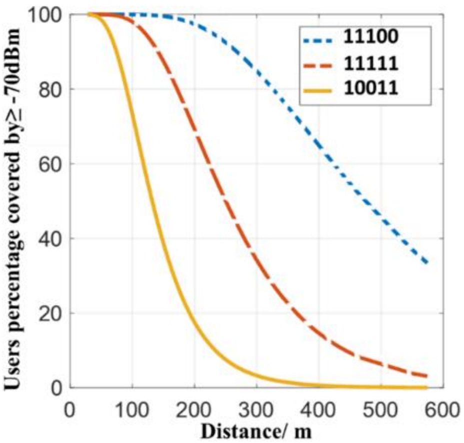

Fig. 10. Percentage of users as a function of distance from the array that receive signal strength greater than or equal to -70 dBm for different PIN diode switching combinations.

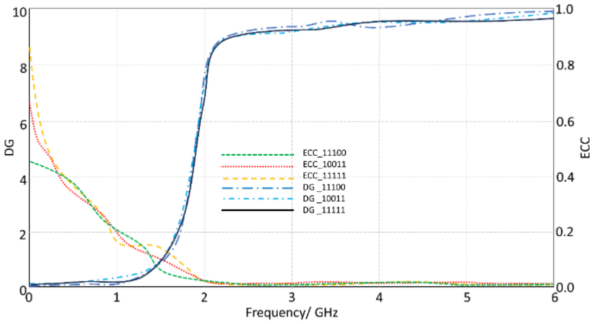

Fig. 11. Gain diversity and envelope correlation coefficient of the proposed MIMO antenna array.

VI. Impact of Solar Panel on the MIMO Antenna Array

In this work the solar panel was mounted on top of the proposed MIMO antenna array. The IV characteristics of the solar panel for load resistance (R_L) change from 0 Ω to 1 MΩ in Fig. 12 show a sharp drop in output current for loads greater than 5 Ω.

The channel capacity represents the maximum rate at which information can be reliably transmitted over a communication channel. It is affected by various factors, including the distance from the base-station weather conditions. Channel capacity is given by:

$$C = B.\log_2\left(1+\frac{S}{N}\right) \qquad (2)$$

Where B is the channel bandwidth (Hz), S is the signal power (W) and N is noise power (W). Signal attenuation poses a significant challenge as it can degrade the signal-to-noise ratio (SNR) at the receiver, thereby affecting the quality of service (QoS). Additionally, the received signal power diminishes inversely with the distance between the transmitter and receiver, as described by the Friis transmission equation. To mitigate this issue, an amplifier was employed to enhance the received signal power at the MIMO array, utilizing a solar panel for power supply. The efficiency of the solar panel is given by:

$$\eta = \frac{P_o}{EA_c} \times 100\% \qquad (3)$$

Where P_o is the power output (W), E is incident solar radiation flux (W/m^2) and A_c is area of panel (m^2).

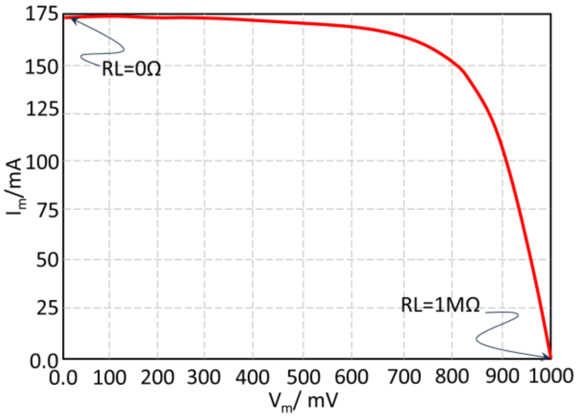

Fig. 12. I-V characteristics measurements.

Fig. 13 illustrates the relationship between solar panel output voltage and channel capacity as a function of the distance between the base station and the MIMO antenna array. The empirical results clearly show that as the voltage output required to drive the amplifier increases, the achievable distance between the base station and the array for a given channel capacity also increases.

An AI equalizer was employed in conjunction with the proposed MIMO antenna array to enhance channel capacity. Fig. 14 illustrates the improvement in channel capacity as a function of the signal-to-noise ratio at frequencies of 2.5 GHz, 3.6 GHz, and 5.5 GHz. Generally, higher signal-to-noise ratios correspond to greater channel capacities. With AI equalization, a notable enhancement of 3 dB is achieved at a signal-to-noise ratio of 20 dB.

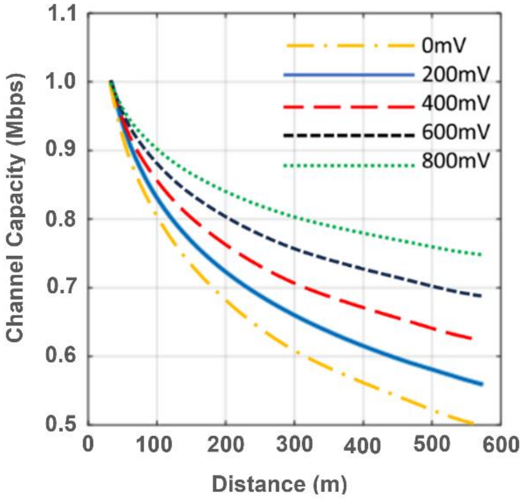

Fig. 13. Channel capacity measurement using the proposed MIMO antenna array.

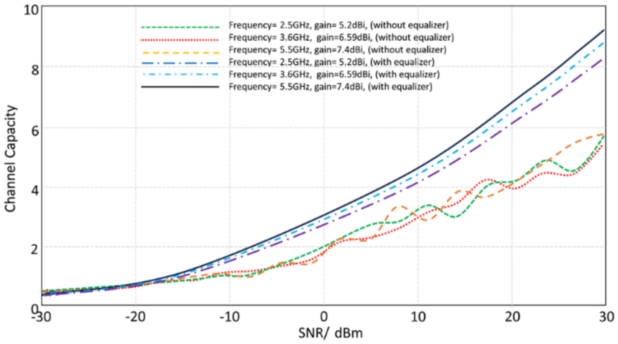

Fig. 14. (a) P_{amp} measurements, and (b) Channel capacity evaluation in Mbits/s.

The performance of the proposed antenna was evaluated by comparing it to similar antennas documented in the literature, as presented in Table 1. The comparison highlights significant advantages of the proposed antenna, particularly its considerably smaller footprint, significantly higher antenna gain, and excellent coupling isolation.

VII. Conclusions

Firstly, we have experimentally demonstrated the effectiveness of the proposed MIMO antenna array, which includes metamaterial isolation. Secondly, we established the feasibility of electronically controlling the radiation beam of the MIMO array using PIN diode switches. We employed an AI algorithm to dynamically adjust the antenna's radiation pattern by controlling the activation of PIN diodes, enabling precise beam steering to improve signal quality and reduce interference. Selectively activating certain combinations of these diodes allows manipulation of the antenna's directivity over a 90-degree range. Thirdly, integration of a solar panel with the array has been successfully achieved without compromising its performance. Using solar panels to power antenna arrays promotes sustainability by reducing reliance on conventional energy sources and lowers carbon footprints. This integration offers a sustainable solution, as solar energy harvested can amplify the received signal at the array. This energy-efficient approach has the potential to decrease base-station energy consumption, contributing to greenhouse emissions reduction and aligning with net-zero emissions goals by 2050. Furthermore, applying an AI equalizer alongside the MIMO antenna array has demonstrated the capability to enhance the channel capacity of wireless communication systems.

Table 1: Comparison of the proposed MIMO antenna with others.

Ref.	Antenna size (mm^2)	Number of ports	Frequency bandwidth (GHz)	Maximum Gain (dBi)	Coupling isolation (dB)	DG (dBi)	ECC
[15]	130×100	8	5.15-5.925	2.1	-15	---	0.05
[16]	150×75	4	5.15-5.85	1.9	-14	9.8	0.06
[17]	136×60	8	5.15-5925	1.9	-10	9.3	0.09
[18]	150×75	12	4.8-5.1	2.6	-12	9.7	---
[19]	150×80	8	5.147-5.95	2.2	-10	9.2	0.11
[20]	133×133	4	3.3-5.8	1.1	-15	9.3	0.10
[21]	160×70	2	5.6-5.67	12	-30	10	0.06
This work	38×38	4	2.3-2.6 3.6-4.1 5.3-5.6	7.4	-20	9.7	0.1

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Humam Hussein, born in Salah Aldin-Iraq in 1994, got a bachelor's degree in First rank with honors degree from the faculty of Engineering - Department of Computer Technologies Engineering/Communication Networks from Al-Hadbaa University-Iraq (2011-2015). Obtained the MSc degree from Altibas University-Turkey, School of Science and Engineering department of Electrical and Computer Engineering with a GPA of (3.86/4.00). These days, Ph.D. student at Karabuk University-Turkey, Institute of Science and Technology, Computer Engineering department. Currently, work as a Lecturer in Tikrit University-Iraq faculty of Computer Science and Mathematics Department of Computer Science.

Bio of **Dr. Nouf Abd Elmunim** was not available at the time of submission.

Ferhat Atasoy, born in Ankara-Turkiye, got a bachelor's degree (2003-2008) from Gazi University-Turkiye, Faculty of Technical Education, Department of Electronics and Computer Education. Obtained the MSc and Ph.D. (2008-2010) and (2010-2017) respectively from Karabuk University-Turkiye, Institute of Natural and Applied Science, Computer Engineering department. Currently, working in Karabuk University Computer Engineering department as an assistant professor.

Bal S. Virdee (SM'08) received the B.Sc. and MPhil degrees in Communications Engineering from the University of Leeds, UK, and his Ph.D. in Electronic Engineering from the University of London, UK. He has worked in industry for various companies including Philips (UK) as an R&D-engineer and Teledyne Defence and Space as a future products developer in RF/microwave communications. He has taught at several academic institutions before joining London Metropolitan University where he is a Senior Professor of Communications Technology in the School of Computing and Digital Media where he is Head the Communications Technology Research Center. His research, in collaboration with industry and academia, is in wireless communications encompassing mobile-phones to satellite-technology. Prof. Virdee has chaired technical sessions at IEEE international conferences and published numerous research papers. He is Executive Member of IET's Technical and Professional Network Committee on RF/Microwave-Technology. He is a Fellow of IET and a Senior-Member of IEEE.

Taha A. Elwi received his B.Sc. in Electrical Engineering Department (2003) (Highest Graduation Award), and Postgraduate M.Sc. in Laser and Optoelectronics Engineering Department (2005) (Highest Graduation Award) from Al-Nahrain University Baghdad, Iraq. From April 2005 to August 2007, he worked with Huawei Technologies Company, in Baghdad, Iraq. In January 2008, he joined the University of Arkansas at Little Rock and he obtained his Ph.D. in December 2011 in system engineering and Science. He is considered of Stanford University's top 2% scientists in 2022. His research areas include wearable and implantable antennas for biomedical wireless systems, smart antennas, WiFi deployment, electromagnetic wave scattering by complex objects, design, modeling, and testing of metamaterial structures for microwave applications, design and analysis of microstrip antennas for mobile radio systems, precipitation effects on terrestrial and satellite frequency re-use communication systems, effects of the complex media on electromagnetic propagation and GPS. His research is conducted to consider wireless sensor networks based on microwave terminals and laser optoelectronic devices. The nano-scale structures in the entire electromagnetic spectrum are a part of his research interest. Also, his work is extended to realize advancements in reconfigurable intelligent surfaces and control the channel performance. Nevertheless, the evaluation of modern physics phenomena in wireless communication networks including cognitive radio networks and squint effects is currently part of his research. His research interests include pattern recognition, signal and image processing, machine learning, deep learning, game theory, and medical image analysis-based artificial intelligence algorithms and classifications. He serves as an editor in many international journals and publishers like, MDPI, IEEE, Springer, and Elsevier. He is currently the head of the International Applied and Theoretical Research Center (IATRC), Baghdad Quarter, Iraq. Also, he has been a member of the Iraqi scientific research consultant since 2016. He is leading three collaborations around the world regarding biomedical applications using microwave technology. He is the supervisor of many funded projects and Ph.D. theses with corresponding of more than 150 published papers and holding 10 patents.

Nasr Rashid was born in Egypt, in 1973. He received the B.Sc. (with highest honors), M.Sc, and PhD in Electronics and Communication Engineering from Al-Azhar University, Cairo, Egypt in 1996, 2004, and 2009 respectively. He is currently an Assistant Professor in the Department of Electrical Engineering, College of Engineering, Jouf University, Sakaka, Saudi Arabia. His research interests include wireless communications, antennas and wave-propagations, multiple input multiple output (MIMO) systems, impedance matching circuits, microwave components, and gap waveguide technology.

Renu Karthick Rajaguru Jayanthi is a researcher and academic at London Metropolitan University. His research encompasses biomedical sensors, robotics, electronics embedded systems, artificial intelligence (AI), and wireless communications systems.

Mohammad Alibakhshikenari (Member, IEEE) was born in Mazandaran, Iran, in February 1988. He received the Ph.D. degree with the European label in electronics engineering from the University of Rome ‘‘Tor Vergata’’, Italy, in February 2020. From May 2018 to December 2018, he was a Ph.D. Visiting Researcher at the Chalmers University of Technology, Gothenburg, Sweden. His training during this Ph.D. research visit included a research stage in the Swedish Company “Gap Waves AB”. During his Ph.D. program (Nov. 2016 – Feb. 2020), he has attended in thirteen European Doctoral Schools organized by various European universities and organizations, and he successfully achieved all the credits leading him to obtain his Ph.D. degree with the European label. From February 2020 to July 2021, he was postdoctoral research fellow at the University of Rome “Tor Vergata”, Italy. Since July 2021 he is with the Department of Signal Theory and Communications, Universidad Carlos III de Madrid (uc3m), Spain, as a Principal Investigator of the CONEX (CONnecting EXcellence)-Plus Talent Training Program and Marie Skłodowska-Curie Actions. For academic year 2021–2022, he was a lecturer of the “electromagnetic fields” and “electromagnetic laboratory” at uc3m and he received the “Teaching Excellent Acknowledgement” certificate for the course of “electromagnetic fields” from the Vice-Rector of studies. From December 2022 to May 2023, he had a six months industrial research visit in SARAS Technology Ltd Company in Leeds, UK aligned with his CONEX-Plus Talent Training Program and Marie Skłodowska-Curie Actions project. In addition, he had research visits each up to one-week in the following universities (i) University of Catania, Sicily, Italy in May 2024 along with an invited lecture entitled “Terahertz Antennas based on Metasurface and SIW” for master and PhD students, and postdoctoral researchers; (ii) University of Messina, Sicily, Italy in May 2024; (iii) University of Bradford, West Yorkshire, UK in May 2023; (iv) Edinburgh Napier University, Edinburgh, UK in April 2023. His research interests include electromagnetic systems, antennas and wave-propagations, metamaterials and metasurfaces, sensors, synthetic aperture radars (SAR), 5G and beyond wireless communications, multiple input multiple output (MIMO) systems, RFID tag antennas, substrate integrated waveguides (SIWs), impedance matching circuits, microwave components, millimeter-waves and terahertz integrated circuits, gap waveguide technology, beamforming matrix, and reconfigurable intelligent surfaces (RIS), which led to publishing eight book chapters and more than 250 research papers in scientific journals and international conferences including 42 in-person presentations (oral and poster) in 28 conferences and 26 on-line presentations in 12 conferences. Such research activities helped him to achieve more than 6200 citations and H-index above 49 reported by Scopus, Google Scholar, and ResearchGate. He was a recipient of the (i) three years Principal Investigator research grant funded by Universidad Carlos III de Madrid and the European Union’s Horizon 2020 Research and Innovation Program under the Marie Skłodowska-Curie Grant started in July 2021, (ii) two years postdoctoral research grant funded by the University of Rome ‘‘Tor Vergata’’ started in November 2019, (iii) three years Ph.D. Scholarship funded by the University of Rome ‘‘Tor Vergata’’ started in November 2016, and (iv) two Young Engineer Awards of the 47th and 48th European Microwave Conferences held in Nuremberg, Germany, in 2017, and in Madrid, Spain, in 2018, respectively. In April 2020 his research article entitled “High-Gain Metasurface in Polyimide On-Chip Antenna Based on CRLH-TL for Sub Terahertz Integrated Circuits, *Scientific Reports*, volume 10, Article number 4298 (2020)” was awarded as the Best Month Paper at University of Bradford, UK. He is the editor of the book project entitled “Ultra-Wideband Technologies - Diverse Techniques and Applications” to be published by IntechOpen, the world's leading publisher of Open Access books. In addition, he serves the role of an Associate Editor for two scientific journals of (i) *Radio Science*, and (ii) *IET Journal of Engineering*. He acts as a referee in several highly reputed journals and international conferences. In addition, he is member of the reviewer panel of (i) The Dutch Research Council (NWO), (ii) The UK Research and Innovation (UKRI) Funding Service, also he was External examiner of several PhD dissertations from various universities.

Ernesto Limiti (S’87–M’92–SM’17) is a full professor of Electronics in the Engineering Faculty of the University of Roma Tor Vergata since 2002, after being research and teaching assistant (since 1991) and associate professor (since 1998) in the same University. Ernesto Limiti represents University of Roma Tor Vergata in the governing body of the MECSA (Microwave Engineering Center for Space Applications), an inter-universitary center among several Italian Universities. He has been elected to represent the Industrial Engineering sector in the Academic Senate of the University for the period 2007-2010 and 2010-2013. Ernesto Limiti is actually the president of the Consortium “Advanced research and Engineering for Space”, ARES, formed between the University and two companies. Further, he is actually the president of the Laurea and Laurea Magistrale degrees in Electronic Engineering of the University of Roma Tor Vergata. The research activity of Ernesto Limiti is focused on three main lines, all of them belonging to the microwave and millimetre-wave electronics research area. The first one is related to characterisation and modelling for active and passive microwave and millimetre-wave devices. Regarding active devices, the research line is oriented to the small-signal, noise and large signal modelling. Regarding passive devices, equivalent-circuit models have been developed for interacting discontinuities in microstrip, for typical MMIC passive components (MIM capacitors) and to waveguide/coplanar waveguide transitions analysis and design. For active devices, new methodologies have been developed for the noise characterisation and the subsequent modelling, and equivalent-circuit modelling strategies have been implemented both for small and large-signal operating regimes for GaAs, GaN, SiC, Si, InP MESFET/HEMT devices. The second line is related to design methodologies and characterisation methods for low noise circuits. The main focus is on cryogenic amplifiers and devices. Collaborations are currently ongoing with the major radioastronomy institutes all around Europe within the frame of FP6 and FP7 programmes (RadioNet). Finally, the third line is in the analysis methods for nonlinear microwave circuits. In this line, novel analysis methods (Spectral Balance) are developed, together with the stability analysis of the solutions making use of traditional (harmonic balance) approaches. The above research lines have produced more than 250 publications on refereed international journals and presentations within international conferences. Ernesto Limiti acts as a referee of international journals of the microwave and millimetre wave electronics sector and is in the steering committee of international conferences and workshops. He is actively involved in research activities with many research groups, both European and Italian, and he is in tight collaborations with high-tech italian (Selex - SI, Thales Alenia Space, Rheinmetall, Elettronica S.p.A., Space Engineering …) and foreign (OMMIC, Siemens, UMS, …) companies. He contributed, as a researcher and/or as unit responsible, to several National (PRIN MIUR, Madess CNR, Agenzia Spaziale Italiana) and international (ESPRIT COSMIC, Manpower, Edge, Special Action MEPI, ESA, EUROPA, Korrigan, RadioNet FP6 and FP7 …) projects. Regarding teaching activities, Ernesto Limiti teaches, over his istitutional duties in the frame of the Corso di Laurea Magistrale in Ingegneria Elettronica, “Elettronica per lo Spazio” within the Master Course in Sistemi Avanzati di Comunicazione e Navigazione Satellitare. He is a member of the committee of the PhD program in Telecommunications and Microelectronics at the University of Roma Tor Vergata, tutoring an average of four PhD candidates per year.