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Microstrip patch antenna directivity optimization via Taguchi method

Mohd H.S. Alrashdan [a], Zouhair Al-qudah [b], Mohammad Al Bataineh [c,*]

[a] Department of Electrical Engineering, College of Engineering, Al-Hussein Bin Talal University, Ma'an 71111, Jordan
[b] Department of Communication Engineering, Al-Hussein bin Talal University, Ma'an, Jordan
[c] Electrical and Communication Engineering Department, United Arab Emirates University, Al Ain, United Arab Emirates

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ABSTRACT

Microstrip patch antennas have gained popularity due to their compact size, flat design, cost-efficiency, and ability to accommodate various design needs. Despite their advantages, optimizing directional properties for peak performance remains challenging. This study employs the Taguchi method, a statistical technique, to regulate the directivity of microstrip patch antennas. Thirteen input control factors are adjusted, including the patch dimensions, substrate, slot, feed line, array, and operating frequency. The Taguchi method efficiently assesses multiple experimental variables, minimizing the need for extensive experiments. The study identifies the frequency and the width of the extended feed line along the Y-axis as the most critical factors influencing directivity. The Taguchi analysis results are validated through the main effect screener analysis (MESA). As a case study, microstrip patch antennas with 30 dB directivity are designed using a tuning process of the control factors based on Taguchi results and COMSOL Multiphysics software. The simulated results at 40 GHz include a reflection coefficient of −0.098612 dB, lumped port impedance of 0.37939 + 29.012i Ω, and elevation (θ) and azimuth angles (φ) measuring 0.0 degrees. These findings indicate that the radiation pattern is being assessed in the broadside direction, directly perpendicular to the antenna, resulting in a directivity of 30 dB. This study offers a structured approach and methodology for both researchers and manufacturers to craft microstrip patch antennas tailored to precise applications, thereby minimizing the need for trial-and-error techniques. The outcomes contribute significantly to enhancing the efficacy of microstrip patch antennas across various domains such as communication, radar technology, and satellite communication.

1. Introduction

Microstrip patch antennas have become a pivotal advancement in radio frequency (RF) and microwave engineering [1,2]. They offer a remarkable combination of small size [3], adaptability [4], and effectiveness. These antennas have substantially transformed the landscape of wireless communication and have been employed in a wide range of applications spanning various industries [5,6]. Their significance stems from their capacity to meet the escalating requirements of contemporary wireless systems, along with delivering many benefits over traditional antenna designs.

Microstrip patch antennas, commonly known as "patch antennas," are recognized for their flat and compact design [7–9]. These antennas typically comprise a metallic patch or conductor printed on a dielectric substrate, with or without a ground plane [10,11]. Despite their unassuming appearance, these antennas play a pivotal role in various fields, including telecommunications [12], satellite communication [13], radar systems [14], internet of things (IoT) devices [15], and more. Further, microstrip patch antennas are inherently compact, making them ideal for applications with limited space [16]. Their flat design allows seamless integration into electronic devices, offering an inconspicuous yet effective wireless communication solution. The antennas' low profile suits applications where traditional bulky antennas are impractical [17]. Their sleek, unobtrusive form factor is well-suited for scenarios emphasizing aesthetics and form, such as consumer electronics and vehicular communication systems [18]. By adjusting their physical dimensions, patch antennas can be customized to operate across a broad frequency range, from microwave to millimeter-wave bands. This adaptability allows them to meet the diverse frequency requirements of various wireless standards and applications [19]. They can be manufactured using established printed circuit board (PCB) techniques, ensuring cost-effective and scalable production methods [20,21]. This ease of fabrication contributes to their widespread availability. Microstrip patch antennas can be integrated seamlessly with other RF

* Corresponding author at: Department of Electrical Engineering, College of Engineering, Al-Hussein Bin Talal University, Ma'an 71111, Jordan.
E-mail address: mffbataineh@uaeu.ac.ae (M. Al Bataineh).

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components, such as filters and amplifiers, on the same substrate, simplifying the overall design of RF systems [22–24]. Moreover, these antennas can be designed to produce directional radiation patterns [25,26], enabling precise control over signal coverage areas. This feature is particularly advantageous in applications like point-to-point communication, where directing signal energy in specific directions is essential. Microstrip patch antennas offer a blend of compactness, low profile, versatility, cost-effectiveness, integration capabilities, and directional radiation, making them indispensable in a wide range of modern applications

Managing the directional characteristics of microstrip patch antennas is crucial for customizing their performance to suit particular applications. Various techniques can be utilized to regulate the directionality of these antennas. Modifying the patch's shape and dimensions is one of the simplest ways to govern directionality. Parameters such as patch size, shape, and aspect ratio wield influence over beamwidth and radiation patterns [27]. For instance, larger patches relative to the wavelength typically yield narrower beam widths and enhanced directionality. Additionally, the choice of substrate material and its inherent characteristics, including dielectric constant (permittivity) and thickness [28,29], considerably impact antenna performance. Lower dielectric constants and thinner substrates generally result in wider beam widths, while higher dielectric constants and thicker substrates tend to produce narrower beam widths, thereby increasing directionality. Furthermore, the feeding method employed for the patch antenna plays a substantial role in directing its directionality. Microstrip patch antennas offer various feeding techniques, including microstrip feedlines [30], coaxial probes [31], and aperture coupling [28]. The choice of feed type and its location can influence the antenna's radiation pattern. For instance, proximity-coupled feeds tend to yield more directional radiation. Furthermore, the ground plane's size beneath the patch antenna can impact its directionality [32], with a larger ground plane often enhancing directivity, particularly concerning the front-to-back ratio.

Introducing dielectric layers above or below the patch (superstrates or substrates) can also affect the radiation pattern [33]. Superstrates can improve directionality by shaping the radiation pattern or suppressing undesired sidelobes. Additionally, incorporating slots or apertures in the patch or the ground plane can alter the radiation pattern, potentially creating additional radiation lobes or reshaping the primary lobe [34].

Manipulating directionality can also involve the use of parasitic elements, such as directors or reflectors [35,36]. Directors concentrate radiation in a specific direction, while reflectors enhance front-to-back ratios. Stacking multiple patches or adding extra dielectric layers can modify the radiation pattern and enhance directionality [37], often resulting in multiple radiation lobes and altered beam widths.

Another method involves tapering the patch edges to control directionality by modifying the phase distribution across the radiating element [38]. Adjusting the patch antenna's resonant frequency through dimensional changes can influence directionality [39], which proves valuable when operating at a specific frequency is essential.

Additionally, controlling the polarization of the microstrip patch antenna, whether linear or circular, can impact its directional characteristics [40,41]. Moreover, the aperture shape through which electromagnetic waves pass, whether radiated or received, can influence the radiation pattern and directionality [42].

It is worth noting that the techniques mentioned above for controlling microstrip patch antenna directionality have traditionally relied on a trial-and-error approach. This method involves making intuitive and ad hoc adjustments to antenna parameters, often requiring extensive experimentation to achieve the desired outcome. Unfortunately, this approach can be time-consuming, lack systematic methodology, and lead to inefficiencies, increased costs, and inconsistent results. Furthermore, it typically lacks robustness analysis, making it challenging to ensure consistent antenna performance across varying conditions.

Conversely, the Taguchi method [43], devised by the Japanese engineer and statistician Dr. Genichi Taguchi (delete), offers a systematic strategy for enhancing and optimizing processes, products, and systems. Its application spans various industries, encompassing manufacturing, engineering, and product design, aiming to attain enhanced quality, dependability, and performance while concurrently minimizing costs and variability [44–46]. Based on robust design principles and statistical experimentation, the Taguchi method is known for its efficiency and effectiveness [47,48]. It entails a well-structured matrix of experiments, meticulous data collection, and rigorous statistical analysis to effectively discern the optimal parameters governing antenna directionality [49,50].

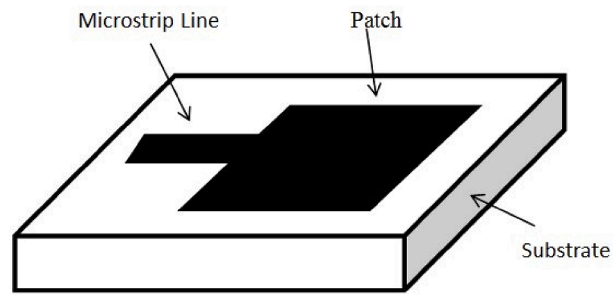

Fig. 1. 3D Geometry of Rectangular Microstrip Patch Antenna [51].

In the present study, the Taguchi method is employed to investigate the effects of thirteen specific parameters on microstrip patch antenna directivity. The central objective of this research is to establish a structured methodology that leverages the Taguchi method for examining critical factors influencing the directivity of microstrip patch antennas. These factors encompass elements like patch dimensions, substrate dimensions, slot dimensions, feed line characteristics, array dimensions, frequency, and other pertinent variables. This approach affords researchers a convenient means to design microstrip patch antenna configurations that can reliably achieve a specific desired level of directivity tailored for particular applications.

The rest of the paper is organized as follows: Section II explores the Microstrip Patch Antenna Theory. Section III outlines the methodology adopted for this research, and Section IV presents a comprehensive analysis of the findings and pertinent discussions. Finally, in Section V, a summary of the study's discoveries is provided.

2. Microstrip patch antenna theory

2.1. Microstrip patch antenna working principle

A microstrip patch antenna operates on the principle of emitting electromagnetic waves when stimulated by a radio frequency (RF) signal. Its functionality hinges on several key elements: 1) Patch: At the core of the antenna is a metallic or conductive patch, typically square, rectangular, or circular, serving as the radiating component. 2) Substrate: The patch is affixed to a dielectric substrate, often composed of low-loss material with a high dielectric constant (permittivity). The substrate offers mechanical support and influences the antenna's electrical properties, including resonant frequency. 3) Ground plane: A ground plane made from conductive material is constructed below the substrate. This ground plane acts as the antenna's counterpoise and plays a vital role in its operation. 4) Feed mechanism: RF energy is introduced to the patch antenna through a feeding mechanism, such as a microstrip transmission line or coaxial probe. The specific location of the feed point on the patch can significantly impact the antenna's performance.

Fig. 1 provides a 3D representation of a rectangular microstrip patch antenna for visual reference. Rectangular microstrip patch antennas are favored in numerous communication systems and electronic devices due to their simplicity, compactness, ease of manufacturing, versatility, and other beneficial features. Their widespread adoption in both research and practical applications is largely attributed to their design adaptability and dependable performance. Applying an RF signal to the patch via the feed mechanism triggers the generation of electromagnetic waves emitted into the surrounding space. The dimensions, size, and shape of the patch are crucial in determining the antenna's operating frequency and radiation pattern. Resonance is established within the patch and on the substrate by the electromagnetic fields, leading to the emission of radiation characterized by distinct attributes.

2.2. Design considerations

The design of a microstrip patch antenna encompasses several critical factors to attain the intended performance, including: 1) Frequency selection: Identifying the operational frequency of the antenna is crucial, as it governs the patch's dimensions. Typically, the patch's length and width are a fraction of the wavelength at the target frequency. 2) Patch geometry: Opting for an appropriate patch shape and size is paramount. The dimensions of the patch, coupled with the dielectric constant and thickness of the substrate, impact the antenna's resonant frequency and radiation pattern. 3) Substrate choice: The selection of a dielectric substrate with suitable attributes, encompassing attributes like low loss, high permittivity, and mechanical stability, is essential. The substrate material is pivotal in determining the antenna's impedance and bandwidth. 4) Feeding mechanism: Deciding on the feeding mechanism, whether a microstrip line or coaxial probe, and pinpointing the precise location of the feed point on the patch are critical steps. The chosen feed technique has repercussions on impedance matching and radiation patterns. 5) Ground plane dimensions: Ensuring the ground plane possesses adequate size to serve as the requisite counterpoise for the antenna is essential. Larger ground planes have the potential to enhance radiation efficiency. 6) Polarization specification: Establishing the preferred polarization of the antenna, such as linear or circular polarization, should align with the application's demands. 7) Bandwidth consideration: Factoring in the required bandwidth for the antenna is essential, as it exerts influence on both patch and substrate dimensions. These considerations collectively inform the design process, enabling the creation of a microstrip patch antenna tailored to specific performance objectives.

2.3. Configuration

Microstrip patch antennas exhibit diverse configurations tailored to their intended applications and design objectives. These configurations encompass 1) Single patch antenna: This represents the simplest form, featuring a lone patch positioned atop a dielectric substrate with an underlying ground plane. It serves purposes necessitating moderate gain and directional radiation. 2) Array antenna: Multiple patch elements are orchestrated into an array arrangement to amplify gain, enhance directivity, and enable beam steering capabilities. Array setups are prevalent in phased-array radar systems and wireless communication networks. 3) Dual polarized antenna: Certain microstrip patch antennas are engineered to simultaneously deliver horizontal and vertical polarization. These antennas prove invaluable in multiple input, multiple output (MIMO) systems and satellite communication. 4) Stacked or multi-layered antennas: By stacking multiple patches or incorporating dielectric layers between them, radiation patterns can be modified, and performance can be elevated.

Microstrip patch antennas operate on the fundamental principles of electromagnetic radiation and resonance. Their design is critical, encompassing the strategic selection of patch dimensions, substrate materials, feeding mechanisms, and configurations. This selection process is imperative to achieve the targeted operating frequencies, polarization orientations, and radiation characteristics, fulfilling specific application requirements. This versatility renders microstrip patch antennas indispensable in contemporary wireless communication systems.

Table 1
Microstrip Patch Antenna Control Factors with their Levels.

Control Factor	Level		
	L1	L2	L3
Patch size X-axis (mm), (P1)	1.5	1.7	1.9
Patch size Y-axis (mm), (P2)	1.5	1.7	1.9
Substrate size X-axis (mm), (P3)	4	5	6
Substrate size Y-axis (mm), (P4)	4	5	6
Slot size X-axis (mm), (P5)	0.6	0.7	0.8
Slot size Y-axis(mm), P(6)	0.10	0.15	0.20
Feed line width (X) (mm), P(7)	0.10	0.15	0.20
Extended Feed line width (mm) (Y), (P8)	0.4	0.5	0.6
Patch substrate thickness (mm), (P9)	0.05	0.10	0.15
Feed substrate thickness (mm), (P10)	0.05	0.10	0.15
Array size (X), (P11)	6	7	8
Array size (Y), (P12)	6	7	8
Frequency (GHz), (P13)	20	30	40

3. Methodology

The microstrip patch antenna comprises various essential elements influencing its directivity. In this study, we have identified thirteen factors, each with three distinct levels, to scrutinize their influence on the directivity of the array microstrip patch antenna. A detailed listing of these factors and their corresponding levels is presented in Table 1. Meanwhile, Table 2 delineates the unchanging parameters of the microstrip patch antenna. Fig. 2 provides a two-dimensional depiction of the microstrip patch antenna's layout as explored in this investigation.

The L27 orthogonal array constitutes a fundamental element within the framework of the Taguchi method, an influential robust optimization approach pioneered by Genichi(delete) Taguchi. Comprising 27 distinct experimental trials, this array is specifically constructed to proficiently investigate the influence of multiple variables on a particular process or system. A distinctive trait of orthogonal arrays lies in their systematic capacity to manipulate these variables, isolating their individual effects and pinpointing the most favorable combination conducive to achieving optimal outcomes. The L27 array proves exceptionally valuable in tackling complex systems with multiple variables, enabling engineers and researchers to effectively identify the most significant factors and their ideal settings while keeping the number of experiments to a minimum. This approach conserves time and resources and elevates the precision and reliability of results by diminishing the influence of random fluctuations. The L27 orthogonal array, embedded within the Taguchi method, is an indispensable instrument for crafting experiments, refining processes, and securing resilient outcomes spanning diverse industries and applications.

The examination of the influence exerted by thirteen distinct control factors, along with their corresponding levels, on the average directivity of a microstrip patch antenna is conducted through the utilization of the L27 Taguchi orthogonal array (OA), which is outlined in Tables 2 and 3. This method simplifies the inquiry, necessitating just 27 experiments to delve into the impact of each control factor on the directivity of the microstrip patch antenna. In contrast, opting for time-intensive trial-and-error techniques would demand thousands or hundreds of trials.

Examining the microstrip patch antenna in question is executed via COMSOL Multiphysics version 5.4 software. In exact terms, a series of 27 models were formulated, as described in Table 3. Across each experiment, unchanging parameters remain in effect, encompassing a wavelength of 0.0099931 m and a permittivity of 7.8, plastic-type for both the patch and feed substrate. The spacing between the antennas, consistently maintained, measures 6.5 mm along the x and y axes. Subsequently, these models are subjected to three tests, each targeting different reflection coefficients or return loss values (S11), as specified in Table 4. This parameter quantifies the extent of electromagnetic energy reflected from the antenna's input port. Typically expressed in decibels

Table 2
Taguchi L27 orthogonal array design experiments.

Exp #	P(1)	P(2)	P(3)	P(4)	P(5)	P(6)	P(7)	P(8)	P(9)	P(10)	P(11)	P(12)	P(13)
1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	2	2	2	2	2	2	2	2	2
3	1	1	1	1	3	3	3	3	3	3	3	3	3
4	1	2	2	2	1	1	1	2	2	2	3	3	3
5	1	2	2	2	2	2	2	3	3	3	1	1	1
6	1	2	2	2	3	3	3	1	1	1	2	2	2
7	1	3	3	3	1	1	1	3	3	3	2	2	2
8	1	3	3	3	2	2	2	1	1	1	3	3	3
9	1	3	3	3	3	3	3	2	2	2	1	1	1
10	2	1	2	3	1	2	3	1	2	3	1	2	3
11	2	1	2	3	2	3	1	2	3	1	2	3	1
12	2	1	2	3	3	1	2	3	1	2	3	1	2
13	2	2	3	1	1	2	3	2	3	1	3	1	2
14	2	2	3	1	2	3	1	3	1	2	1	2	3
15	2	2	3	1	3	1	2	1	2	3	2	3	1
16	2	3	1	2	1	2	3	3	1	2	2	3	1
17	2	3	1	2	2	3	1	1	2	3	3	1	2
18	2	3	1	2	3	1	2	2	3	1	1	2	3
19	3	1	3	2	1	3	2	1	3	2	1	3	2
20	3	1	3	2	2	1	3	2	1	3	2	1	3
21	3	1	3	2	3	2	1	3	2	1	3	2	1
22	3	2	1	3	1	3	2	2	1	3	3	2	1
23	3	2	1	3	2	1	3	3	2	1	1	3	2
24	3	2	1	3	3	2	1	1	3	2	2	1	3
25	3	3	2	1	1	3	2	3	2	1	2	1	3
26	3	3	2	1	2	1	3	1	3	2	3	2	1
27	3	3	2	1	3	2	1	2	1	3	1	3	2

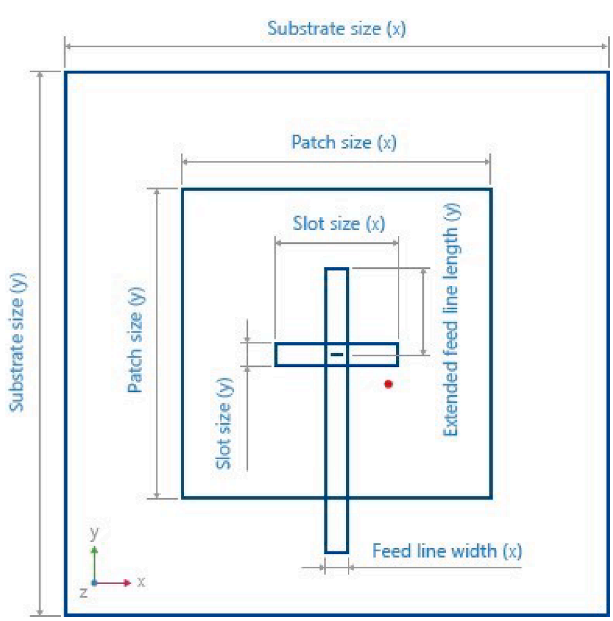

Fig. 2. 2D layout of the Microstrip Patch Antenna.

(dB), S11 signifies the proportion of reflected power to the incident power at a particular frequency. Incorporating three repetitions for each experiment is essential for accurately depicting real-world scenarios or practical tests. In this specific investigation, the procedure is reiterated three times, utilizing COMSOL Multiphysics software, with each iteration featuring a different reflection coefficient.

COMSOL Multiphysics is a versatile simulation software that finds extensive utility in electromagnetics and antenna design, encompassing the simulation of microstrip patch antenna directivity. Accurate electromagnetics, a component within COMSOL, offers a comprehensive platform tailored for simulating electromagnetic phenomena. It employs finite element analysis (FEA) to solve Maxwell's equations, thereby facilitating precise modeling of the complex electromagnetic interactions intrinsic to microstrip patch antennas. This precision proves pivotal in forecasting the antenna's directivity and radiation characteristics.

Microstrip patch antennas often exhibit complex geometries, encompassing multilayer structures and irregular shapes. COMSOL's robust 3D modeling capabilities empower engineers to faithfully represent these structures and explore their influence on directivity and radiation patterns. Consequently, COMSOL Multiphysics is invaluable for simulating microstrip patch antenna directivity and enhancing performance. Its unwavering accuracy, adaptability, and comprehensive feature set render it an indispensable resource for antenna designers and engineers striving to attain specific directivity objectives while satisfying other design constraints.

Implementing Taguchi analysis, a core element of quality enhancement approaches, can be efficiently executed through MINITAB 17 software. MINITAB 17, renowned for its user-friendly interface and tailored utilities, simplifies using the Taguchi method. It facilitates the efficient design of experiments and the subsequent analysis of outcomes. The software generates the L27 orthogonal array (OA), simplifying the systematic manipulation of variables to pinpoint the best parameter configurations while reducing the necessary number of experiments. MINITAB's array of statistical instruments empowers this endeavor to evaluate the effects of the thirteen selected factors on quality attributes and discern those with the most substantial influence. Furthermore, MINITAB 17′s graphical capabilities facilitate the visualization of main effects and interaction plots, thereby enriching the comprehension of experimental findings. In summary, by integrating the principles of Taguchi analysis with the computational capabilities offered by MINITAB 17, this research can effectively optimize processes, enhance product quality, and make informed decisions to attain the desired performance levels.

MINITAB 17 statistical software is exploited to examine microstrip patch antenna directivity data via the Taguchi method, employing metrics such as the signal-to-noise (S/N) ratio and data mean. The control factor exhibiting a superior S/N or mean value exerts a greater influence on the microstrip patch antenna's directivity in higher magnitude. Furthermore, it facilitates the execution of a mean effect screener analysis, enabling the assessment of the significance of factors

Table 3
Taguchi L27 orthogonal array design experiments with actual control parameters.

Exp #	P(1)	P(2)	P(3)	P(4)	P(5)	P(6)	P(7)	P(8)	P(9)	P(10)	P(11)	P(12)	P(13)
1	1.5	1.5	4	4	0.6	0.1	0.1	0.4	0.05	0.05	6	6	20
2	1.5	1.5	4	4	0.7	0.15	0.15	0.5	0.1	0.1	7	7	30
3	1.5	1.5	4	4	0.8	0.2	0.2	0.6	0.15	0.15	8	8	40
4	1.5	1.7	5	5	0.6	0.1	0.1	0.5	0.1	0.1	8	8	40
5	1.5	1.7	5	5	0.7	0.15	0.15	0.6	0.15	0.15	6	6	20
6	1.5	1.7	5	5	0.8	0.2	0.2	0.4	0.05	0.05	7	7	30
7	1.5	1.9	6	6	0.6	0.1	0.1	0.6	0.15	0.15	7	7	30
8	1.5	1.9	6	6	0.7	0.15	0.15	0.4	0.05	0.05	8	8	40
9	1.5	1.9	6	6	0.8	0.2	0.2	0.5	0.1	0.1	6	6	20
10	1.7	1.5	5	6	0.6	0.15	0.2	0.4	0.1	0.15	6	7	40
11	1.7	1.5	5	6	0.7	0.2	0.1	0.5	0.15	0.05	7	8	20
12	1.7	1.5	5	6	0.8	0.1	0.15	0.6	0.05	0.1	8	6	30
13	1.7	1.7	6	4	0.6	0.15	0.2	0.5	0.15	0.05	8	6	30
14	1.7	1.7	6	4	0.7	0.2	0.1	0.6	0.05	0.1	6	7	40
15	1.7	1.7	6	4	0.8	0.1	0.15	0.4	0.1	0.15	7	8	20
16	1.7	1.9	4	5	0.6	0.15	0.2	0.6	0.05	0.1	7	8	20
17	1.7	1.9	4	5	0.7	0.2	0.1	0.4	0.1	0.15	8	6	30
18	1.7	1.9	4	5	0.8	0.1	0.15	0.5	0.15	0.05	6	7	40
19	1.9	1.5	6	5	0.6	0.2	0.15	0.4	0.15	0.1	6	8	30
20	1.9	1.5	6	5	0.7	0.1	0.2	0.5	0.05	0.15	7	6	40
21	1.9	1.5	6	5	0.8	0.15	0.1	0.6	0.1	0.05	8	7	20
22	1.9	1.7	4	6	0.6	0.2	0.15	0.5	0.05	0.15	8	7	20
23	1.9	1.7	4	6	0.7	0.1	0.2	0.6	0.1	0.05	6	8	30
24	1.9	1.7	4	6	0.8	0.15	0.1	0.4	0.15	0.1	7	6	40
25	1.9	1.9	5	4	0.6	0.2	0.15	0.6	0.1	0.05	7	6	40
26	1.9	1.9	5	4	0.7	0.1	0.2	0.4	0.15	0.1	8	7	20
27	1.9	1.9	5	4	0.8	0.15	0.1	0.5	0.05	0.15	6	8	30

Table 4
The microstrip patch antenna return loss in the three trials.

	Trial 1 (T1)	Trial 2 (T2)	Trial 3 (T3)
S11 target (dB)	−15.0	−15.1	−15.2

Table 5
The microstrip patch antenna directivity results in the three trials.

Exp #	Directivity (dB) (T1)	Directivity (dB) (T2)	Directivity (dB) (T3)
1	17.52	17.52	17.52
2	22.74	22.74	22.74
3	23.79	23.79	23.79
4	25.93	25.93	25.93
5	18.31	18.31	18.31
6	23.32	23.32	23.32
7	23.39	23.39	23.39
8	23.17	23.17	23.17
9	18.01	18.01	18.01
10	22.37	22.37	22.37
11	19.67	19.67	19.67
12	23.8	23.8	23.8
13	23.66	23.66	23.66
14	24.87	24.87	24.87
15	19.78	19.78	19.78
16	20.0	20.0	20.0
17	23.53	23.53	23.53
18	24.01	24.01	24.01
19	22.77	22.77	22.77
20	24.37	24.37	24.37
21	19.42	19.42	19.42
22	20.59	20.59	20.59
23	23.89	23.89	23.89
24	22.10	22.10	22.10
25	23.14	23.14	23.14
26	19.53	19.53	19.53
27	23.75	23.75	23.75

and interactions while corroborating the outcomes obtained through the Taguchi method.

Finally, one of the experiments or models of the microstrip patch antenna, as detailed in Table 3 and Table 4, was revisited to create a fresh microstrip patch antenna model tailored to achieve a specific directivity of 30 dB, serving as a case study. For this purpose, the COMSOL Multiphysics 5.4 simulation software is once again employed. It is utilized to evaluate the performance of these microstrip patch antennas, involving the computation of their reflection coefficient (S11) in decibels or return loss, the assessment of lumped port impedance, determination of elevation and azimuth angles, as well as the examination of 2D and 3D far-field radiation patterns.

4. Results and discussion

Table 5 presents the directivity of microstrip patch antennas across all experiments conducted using COMSOL Multiphysics. Altering the S11 target (expressed in dB) from −15 dB to −15.2 dB in the three iterations of each experiment does not directly impact the directivity of a microstrip antenna. S11 serves as a metric gauging the reflection coefficient, specifically measuring the extent to which power is reflected back toward the source when energy is supplied to the antenna. It quantifies how much the antenna aligns with the transmission line or connected electronic components. In contrast, directivity measures the antenna's ability to concentrate or focus radiation in a particular direction [52]. It hinges on the physical configuration of the antenna, encompassing its dimensions, shape, and radiation pattern. Across any of the three trials, it is apparent that no direct or explicit correlation exists between the chosen variables and the directivity of the microstrip patch antenna. For instance, in experiments 1 and 2, an increase in the slot size along the X-axis from 0.6 mm to 0.7 mm led to an elevation in the directivity of the microstrip patch antenna, ascending from 17.52 dBi to 22.74 dBi. However, it is crucial to note that this correlation ceases to hold when comparing experiments 4 and 5, as other factors also come into play, exerting an influence on the directivity of the microstrip patch antenna. Another illustrative case is the shift in frequency from 30 GHz to 40 GHz, which yielded a directivity increase from 22.74 dBi to 23.79 dBi in experiments 2 and 3. Nevertheless, this direct association dissipates when examining experiments 7 and 8. Meanwhile, the Taguchi analysis of the mean value of the directivity data of the microstrip patch antenna in Table 6 reveals that the

Table 6
Microstrip patch antenna directivity responses based on means.

Level	P(1)	P(2)	P(3)	P(4)	P(5)	P(6)	P(7)	P(8)	P(9)	P(10)	P(11)	P(12)	P(13)
1	21.80	21.83	22.02	22.09	22.15	22.47	22.24	21.57	22.38	21.98	21.72	21.60	19.20
2	22.41	22.49	22.20	22.41	22.23	21.72	22.03	22.53	22.09	22.19	22.06	22.25	23.43
3	22.17	22.06	22.16	21.89	22.00	22.19	22.10	22.29	21.91	22.21	22.60	22.53	23.75
Delta	0.61	0.67	0.18	0.52	0.23	0.74	0.21	0.96	0.46	0.23	0.88	0.92	4.55
Rank	7	6	13	8	10	5	12	2	9	11	4	3	1

frequency control factor exhibits the highest delta function, consequently securing the top rank and yielding the most pronounced impact. Subsequently, the control parameters follow a descending order of influence from higher to lower as follows: Extended feed line width (Y), array size (Y), array size (X), slot size Y-axis, patch size Y-axis, patch size X-axis, substrate size Y-axis, patch substrate thickness, slot size X-axis, feed substrate thickness, feed line width (X), and substrate size X-axis. For a visual representation of the microstrip patch antenna directivity responses based on the mean value as determined by the Taguchi method, refer to Fig. 2. The data found in Fig. 2 is detailed in Table 6.

The frequency control factor, denoting the operational frequency of a microstrip patch antenna, undeniably wields considerable influence over the antenna's directivity. Nonetheless, it is imperative to acknowledge that various other factors, encompassing patch dimensions, substrate dimensions, slot dimensions, feed line specifications, substrate thickness, and array dimensions, also assume pivotal roles in determining the antenna's directivity. The degree to which each factor impinges on directivity depends on the precise design prerequisites and application demands.

Operating frequency, often expressed in terms of wavelength, directly dictates the physical dimensions of the antenna, including the patch size, inter-element spacing (e.g., slots in a slot antenna), and feed line proportions. The antenna's physical dimensions must be tailored at different frequencies to sustain resonance and effective radiation. Consequently, a shift in the operating frequency necessitates a redesign of the antenna to ensure proper matching and efficient radiation. Microstrip patch antennas are typically engineered for resonance at specific frequencies. Straying significantly from this resonance can result in suboptimal impedance matching and diminished radiation efficiency. Modifying the operating frequency directly impacts the antenna's aptitude to efficiently couple electromagnetic energy, thereby influencing its directivity. Furthermore, it is worth noting that the radiation pattern of a microstrip patch antenna can undergo variations with shifts in frequency. As the frequency is fine-tuned, the radiation pattern may shift, potentially affecting the antenna's directional characteristics. Specific patch antennas are designed explicitly for directionality at designated frequencies, and altering the frequency can subsequently reshape their directivity attributes.

Although the frequency control factor is of paramount importance in guaranteeing an antenna's operation within its intended frequency range and resonance parameters, other variables such as patch dimensions, substrate proportions, feed line specifications, and array dimensions also wield considerable influence:

The physical dimensions of the patch dictate the operational frequency, with the patch's geometry impacting the resultant radiation pattern. Larger patches have the potential to yield enhanced directivity and a more restricted beam width [53]. In parallel, substrate dimensions directly impact resonance frequency, bandwidth, and the antenna's radiation pattern.

It is worth emphasizing that while the frequency control factor plays a pivotal role in ensuring the antenna functions at the desired frequency [54], all the additional factors under consideration in this study interact synergistically, jointly molding the antenna's directivity. The precise extent of influence for each individual factor hinges upon the antenna's specific design and the sought-after performance criteria particular to a given application. Consequently, the design process for a microstrip patch antenna entails navigating a complex interplay among these factors to attain the desired level of directivity and fulfill other performance objectives.

The second factor that influences the directivity of the microstrip patch antenna pertains to the control of the extended feed line width. The width of the feed line plays a critical role in achieving proper impedance matching between the feed line and the antenna's structure. This impedance matching is instrumental in ensuring efficient power transfer and can significantly impact the overall radiation efficiency of the antenna. An inappropriate choice of feed line width can result in power losses and consequently affect the antenna's directivity. In specific scenarios, the feed line can also function as an integral component of the antenna's radiating structure, contributing to the antenna's radiation pattern and directivity [55]. A broader feed line, for instance, may have implications for both the radiation pattern and the characteristics of the antenna's directivity. Moreover, it is important to note that the feed line width can exhibit sensitivity to changes in frequency. Altering the feed line width can indirectly influence the antenna's operating frequency. These frequency adjustments, in turn, can potentially modify the antenna's resonance properties and radiation pattern, consequently influencing its directivity. In antenna design, striking a balance among various parameters is often necessary. For instance, fine-tuning the feed line width might harmonize impedance matching, bandwidth, and radiation characteristics to meet specific performance objectives, including attaining desired directivity. The influence of design parameters, such as feed line dimensions, patch size, substrate size, slot dimensions, and array size, on the directivity of a microstrip patch antenna can vary based on the specific antenna design, operating frequency, and the desired radiation characteristics. Nevertheless, the vertical dimension, represented by the y-axis, often tends to exert a more significant impact on the radiation pattern than its horizontal counterpart along the x-axis. Typically, microstrip patch antennas are planar, producing radiation patterns primarily confined to the plane of the substrate. Adjustments to the vertical dimensions directly affect the elevation (vertical) radiation pattern, a critical factor in controlling directivity in the vertical plane.

Furthermore, precise control over the antenna's elevation (vertical) radiation pattern becomes imperative in scenarios where beam steering is required, such as satellite tracking applications. This often involves fine-tuning the dimensions of the antenna elements along the y-axis to achieve the desired beam tilt or elevation angle. Modifying the vertical dimensions can also influence the polarization of the antenna's radiation pattern. For instance, alterations in the size or orientation of the feed line or slot can determine whether the antenna produces linear, circular, or elliptical polarization in the vertical plane. In specific applications, the primary objective is to achieve high directivity in the vertical plane to concentrate the antenna's radiation energy at specific elevation angles. In such cases, adjustments along the y-axis become pivotal for attaining this objective.

Additionally, in stacked patch antenna arrays, changes in the y-axis dimension, particularly the spacing between patches, can significantly impact the directivity in the elevation plane. Vertical stacking of patches can create multiple radiating elements and modify the antenna's directivity pattern. It is worth noting that the antenna's operating frequency can also play a role, with adjustments along the y-axis potentially becoming more critical in specific frequency bands to ensure

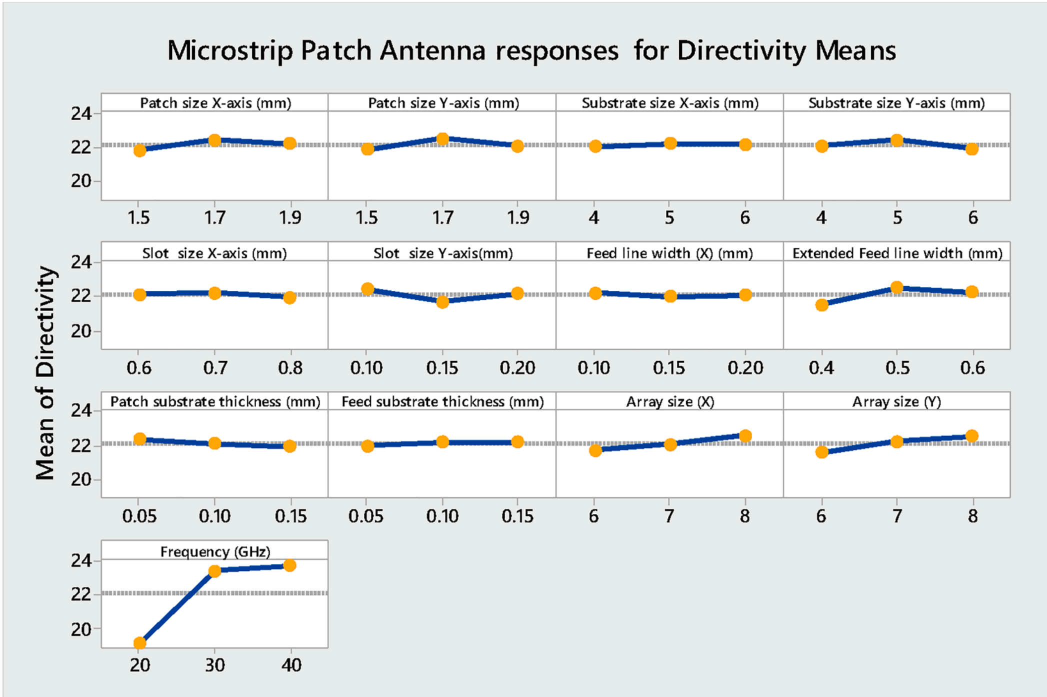

Fig. 3. Microstrip Patch Antenna Directivity responses based on Means.

proper resonance and desired radiation characteristics are achieved.

The prominence of the "Array size" control factor's impact on the directivity of a microstrip patch antenna, in comparison to the "Feed line," "Patch size," "Substrate size," and "Slot size" factors, hinges on the particular antenna design and the requirements of the given application. The influence of each of these design parameters on directivity can exhibit variability, and in certain instances, alterations in the array size can yield a more substantial effect on directivity. Microstrip patch antenna arrays are frequently employed in beamforming applications. By manipulating the array size, encompassing the number and spacing of individual antenna elements, it is possible to govern the orientation of the main lobe within the radiation pattern [56]. An expanded array, thoughtfully arranged in terms of element spacing, can generate a more tightly focused and directional beam, resulting in enhanced directivity.

The array size holds pivotal importance when devising phased array antennas. Phased arrays employ the relative phase of signals supplied to individual elements to steer the beam in a specified direction. The quantity of elements constituting the array and their separation determines the antenna's capability to control beam direction and, consequently, its directivity. Arrays also provide spatial filtering capabilities. By adjusting the array size and the spacing between elements, it becomes feasible to regulate the antenna's capacity to receive signals from designated directions while concurrently rejecting interference from other directions [57]. This capability is intrinsically linked to the antenna's directivity. Arrays effectively combine the radiations emitted by multiple individual elements, thereby forming a more robust and directed composite radiation pattern. The array's size and arrangement dictate how proficiently the individual elements cooperate to generate the desired degree of directivity. Furthermore, the array size influences the antenna's coverage area and the width of the primary lobe in the radiation pattern. Smaller arrays or closely spaced elements may lead to broader coverage, although with reduced directivity, whereas larger arrays, characterized by greater inter-element spacing, can produce narrower, more tightly focused beams.

Slot-size antennas rely on the fundamental concept of radiation occurring through openings or apertures in a conductive surface. The dimensions and configuration of these openings directly influence how electromagnetic waves are introduced to and emitted from the antenna. Consequently, slot size adjustments can substantially impact the radiation pattern and, by extension, the antenna's directivity.

Slot antennas frequently function based on the resonant characteristics of the slots themselves. Modifying the slot's size can induce shifts in the operating frequency, which, in turn, can impact impedance matching and radiation attributes—critical determinants of directivity. In specific scenarios, arrays of slot antennas are employed to achieve enhanced directivity via beamforming or interference phenomena. Within such arrays, the control factor of slot size gains greater significance for steering the primary lobe of the radiation pattern and attaining the desired directivity.

The orientation and dimensions of the slots can also influence the polarization of the emitted waves. This capability for polarization control is paramount in applications where attaining a specific polarization state is imperative for directivity management. It is noteworthy that slot antennas tend to be relatively sensitive to alterations in frequency due to variations in slot dimensions. This frequency sensitivity can lead to fluctuations in the directivity pattern as the slot size undergoes adjustments.

The size and dimensions of the patch in the Y-axis direction have the sixth order of effect on the antenna's radiation pattern. This sensitivity could result from the specific geometry of the microstrip patch antenna, where variations in the Y-axis dimensions play a crucial role in determining how electromagnetic waves are radiated. The Y-axis dimensions of the patch may be more critical in achieving resonance and impedance matching at the desired frequency. Achieving resonance is essential for efficient energy transfer and radiation, and variations in the Y-axis dimensions might significantly impact these characteristics. The electric field distribution on the patch, which determines the radiation characteristics, may be more sensitive to changes in the Y-axis dimensions. This sensitivity could result in variations in directivity based on alterations in the Y-axis patch size.

The impact of thirteen specific control factors and their respective levels on the average directivity of a microstrip patch antenna using the L27 experimental design is investigated using the Taguchi method.

Fig. 4 provides a visual representation of the data concerning the

Table 7
Microstrip patch antenna design trials with directivity of 30 dB.

Exp #	P(1)	P(2)	P(3)	P(4)	P(5)	P(6)	P(7)	P(8)	P(9)	P(10)	P(11)	P(12)	P(13)	Directivity
1. 3^{ed} trial	1.5	1.5	4	4	0.8	0.2	0.2	0.6	0.15	0.15	8	8	40	23.79
2	1.5	1.5	4	4	0.8	0.2	0.2	1.0↑	0.15	0.15	10↑	10↑	40	27.19
3	1.5	1.5	4	4	0.8	0.2	0.2	1.0	0.15	0.15	13↑	13↑	40	29.78
4	1.5	1.5	4	4	0.8	0.2	0.2	1.0	0.2↑	0.15	13	13	40	30.08
5	1.5	1.5	4	4	0.8	0.2	0.2	1.0	0.18↓	0.15	13	13	40	30.0

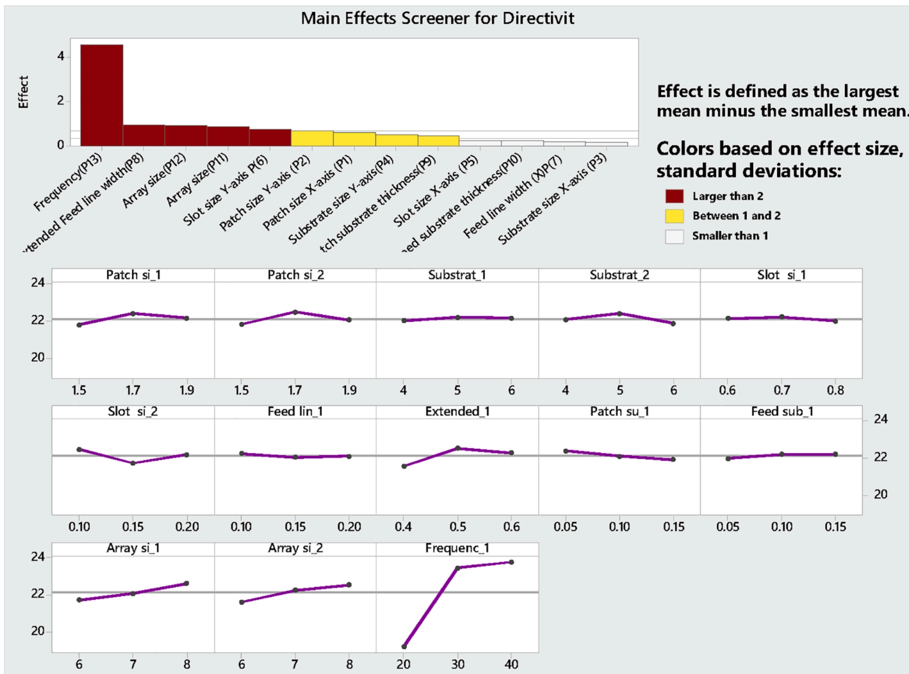

Fig. 4. Microstrip Patch Antenna Directivity results using Main Effect Screener analysis.

directivity of microstrip patch antennas, utilizing the main effects screener analysis (MESA) technique. This analysis serves as a valuable instrument in understanding the impact of each factor on the directivity of such antennas, effectively quantifying the magnitude of their respective effects. This approach empowers the current research to focus its resources, enhance processes, and base its conclusions on data-driven insights, as it pinpoints the most influential factors within a particular experiment or system. In a MESA, the control factor exhibiting a larger "size effect" exerts a more substantial influence on the heat generated. This "size effect" typically denotes the degree to which the factor impacts the response variable. During such an analysis, the research essentially evaluates the extent to which each factor contributes to the variation in the response, and this quantification is achieved using effect size metrics like eta-squared or partial eta-squared. A greater effect signifies that a larger fraction of the overall variance in the response can be attributed to that specific factor. In simpler terms, it wields a more considerable influence on the response variable. Consequently, when assessing the significance of control factors in a MESA, emphasis is placed on those exhibiting greater effect sizes, as they hold a more substantial sway over the response. This analysis yields identical outcomes to Taguchi's analysis predicated on the data mean, as portrayed in Table 6 and Fig. 3. This outcome validates and authenticates the findings derived from Taguchi's methodology.

To validate the work presented in this paper, a new, customized microstrip patch antenna model was designed to achieve a specific directivity of 30 dB as a case study in a direct way. The case study uses COMSOL Multiphysics 5.4 simulation software to assess the performance of the microstrip patch antennas, involving computations of reflection coefficient (S11) in decibels or return loss, evaluation of lumped port impedance, determination of elevation and azimuth angles, as well as examination of 2D and 3D far-field radiation patterns.

The simulated microstrip patch antenna, as outlined in Table 7, exhibits a directivity of 30 dB, along with a reflection coefficient (S11) dB or return loss of −0.098612 dB at 40 GHz. A negative value indicates a loss in reflected power, signifying that the antenna is well-aligned with its feedline or transmitter at the specified frequency of 40.000 GHz. A lower S11 dB value indicates a more favorable impedance match.

The lumped port impedance is represented as 0.37939 + 29.012i Ω, encompassing both real and imaginary components. In this context, the real component (0.37939 Ω) signifies resistance, while the imaginary component (29.012i Ω) denotes reactance. Effective impedance matching between the antenna and feedline is vital for efficient power transfer.

The parameter θ (theta) corresponds to the elevation angle (vertical), and φ (phi) pertains to the azimuth angle (horizontal). Both angles are precisely set at 0.0000 degrees, indicating that the radiation pattern is being assessed in the broadside direction—directly perpendicular to the antenna. A directivity of 30 dB underscores the antenna's high directive nature in its radiation pattern, focalizing most of its radiated power in a specific direction.

Control Factor	Level L1	L2	L3
Patch size X-axis (mm), (P1)	1.5	1.7	1.9
Patch size Y-axis (mm), (P2)	1.5	1.7	1.9
Substrate size X-axis (mm), (P3)	4	5	6
Substrate size Y-axis (mm), (P4)	4	5	6
Slot size X-axis (mm), (P5)	0.6	0.7	0.8
Slot size Y-axis(mm), P(6)	0.10	0.15	0.20

(continued on next page)

(*continued*)

Control Factor	Level		
	L1	L2	L3
Feed line width (X) (mm), P(7)	0.10	0.15	0.20
Extended Feed line width (mm) (Y), (P8)	0.4	0.5	0.6
Patch substrate thickness (mm), (P9)	0.05	0.10	0.15
Feed substrate thickness (mm), (P10)	0.05	0.10	0.15
Array size (X), (P11)	6	7	8
Array size (Y), (P12)	6	7	8
Frequency (GHz), (P13)	20	30	40

Fig. 5 illustrates the normalized far-field radiation pattern on the xy-plane of microstrip patch antennas, boasting a directivity of 30 dB. This holds significant importance in the field of antenna characterization and design. The radiation pattern is vital for understanding how the antenna disseminates electromagnetic energy across diverse directions. This encompasses the azimuthal plane (horizontal plane) denoted by the xy-plane, the elevation plane (vertical plane) represented by the yz-plane, and the xz-plane.

Fig. 6 shows the microstrip patch antenna return loss (S11) curve in the frequency range (10–40 GHz). A return loss curve showing a deep dip around 30 GHz implies good impedance matching at that frequency, meaning it efficiently absorbs power from the source. Additionally, a directivity of 30 dB signifies that the antenna has a highly directional radiation pattern, focusing most of its energy in a particular direction. This could be advantageous for applications requiring long-range communication or point-to-point links, as it concentrates the transmitted energy in the desired direction, thereby improving signal strength and reducing interference.

Fig. 7 shows the maximum gain and maximum directivity curves of a microstrip patch antenna. The gain of an antenna measures its ability to focus radiation in a particular direction compared to an isotropic radiator. It is typically represented as a function of frequency. At 30 GHz, the gain of a microstrip patch antenna is influenced by various design parameters such as the size and shape of the patch, substrate material, feed mechanism, and ground plane.

The maximum gain occurs at the frequency where the antenna is most efficient in radiating energy in the desired direction. For a well-designed microstrip patch antenna operating around 30 GHz, the gain curve should exhibit a peak at this frequency. Achieving maximum gain often involves optimizing the antenna's dimensions and feed configuration to maximize radiation efficiency and minimize losses.

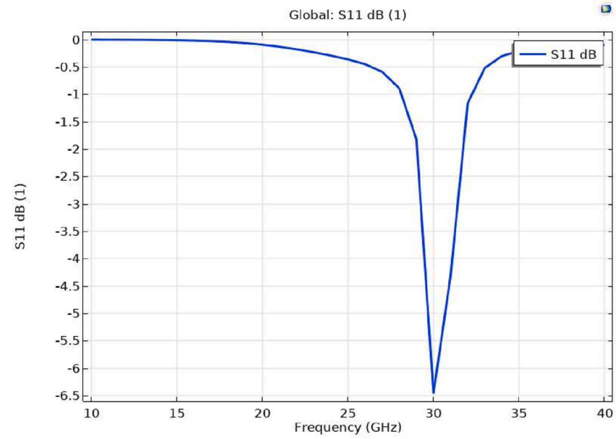

Fig. 6. The microstrip patch antenna return loss (S11) curve.

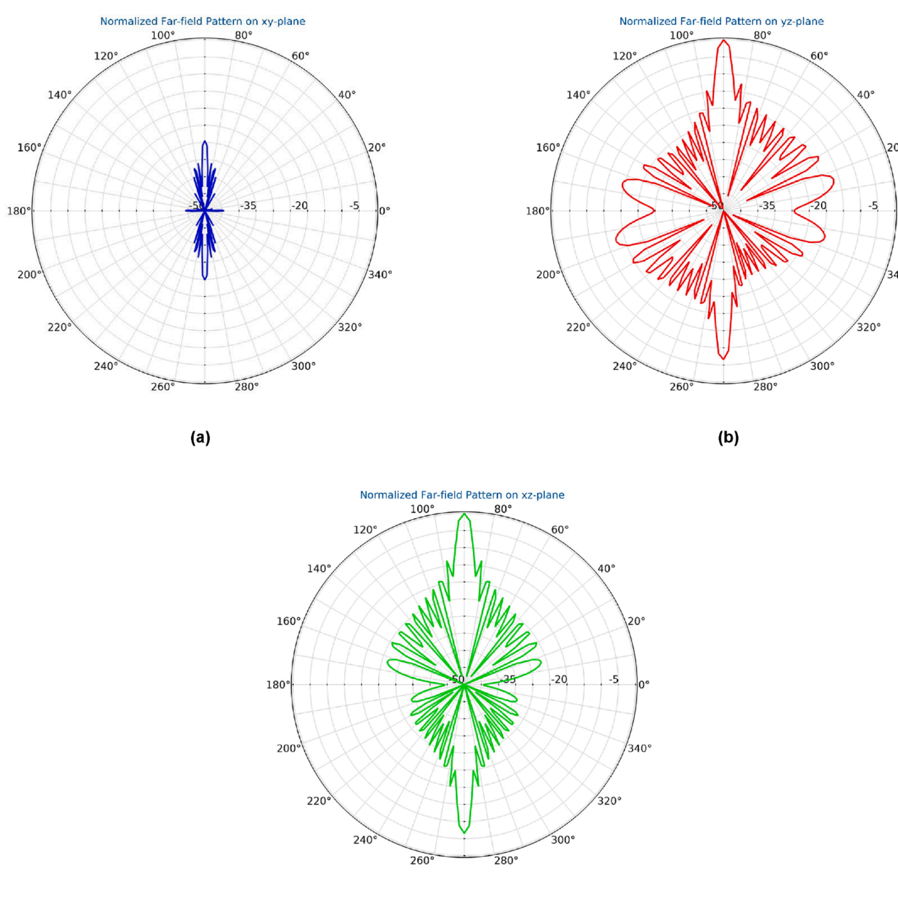

Fig. 5. (a) Normalized Far-field Pattern on xy-plane. (b) Normalized Far-field Pattern on yz-plane. (c) Normalized Far-field Pattern on xz-plane.

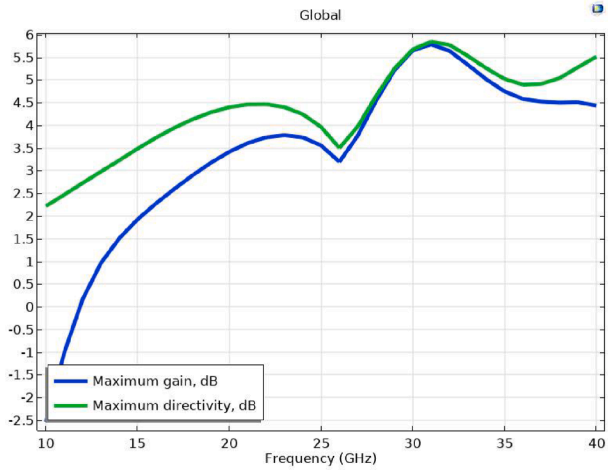

Fig. 7. The microstrip patch antenna's maximum gain and maximum directivity.

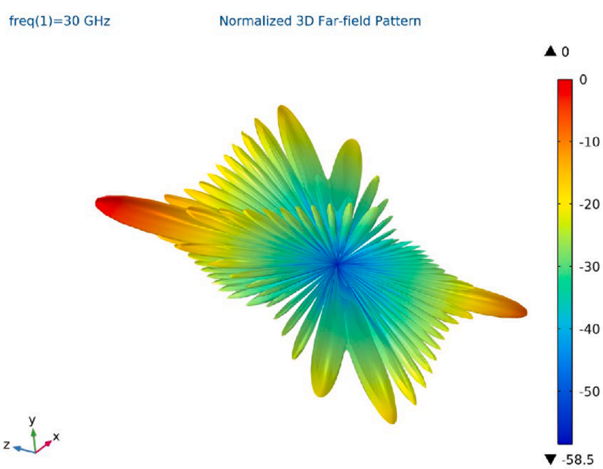

Fig. 8. Normalized 3D Far-field Pattern.

Directivity measures how well the antenna focuses its radiated power in a particular direction compared to an isotropic radiator. It is related to gain but is a dimensionless quantity. Directivity is a function of the antenna's radiation pattern, which is influenced by its geometry and feed structure.

To achieve a directivity of 30 dB, the antenna's radiation pattern should be highly directional, concentrating most of its radiated power in the desired direction. The directivity curve indicates how the antenna's performance varies with frequency, with the peak directivity occurring at the frequency where the antenna is most efficient in focusing its radiation. At 30 GHz, the directivity curve exhibits a peak corresponding to this frequency.

Fig. 8 exhibits the three-dimensional (3D) far-field radiation pattern of microstrip patch antennas, offering extensive insight into how these antennas disseminate electromagnetic energy in all directions. This comprehensive portrayal encompasses azimuthal (horizontal) and elevation (vertical) planes, presenting a holistic assessment of the antenna's performance from various angles.

In antenna performance metrics, gain and directivity take center stage. Under 3D radiation patterns, engineers can scrutinize these metrics from any vantage point surrounding the antenna. This enables the identification of peak gain directions and the evaluation of directivity across all dimensions. Certain microstrip patch antennas exhibit complex radiation characteristics, characterized by multiple lobes and nulls in diverse directions. The 3D radiation pattern is a lucid visualization tool for comprehending these complexities, facilitating engineers in fine-tuning antenna performance.

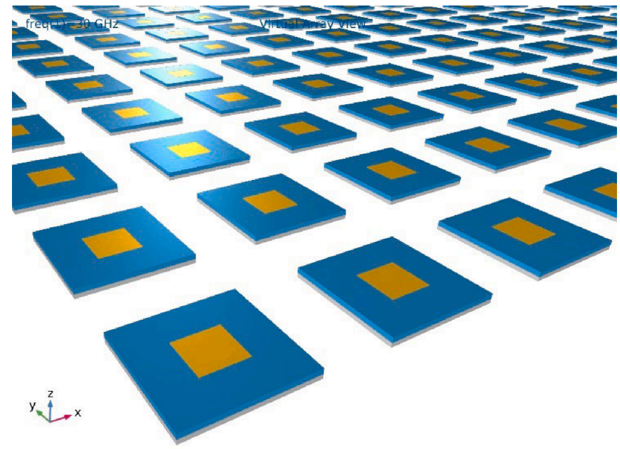

Fig. 9. Virtual Array View of microstrip patch antennas under study.

The 3D far-field radiation pattern of microstrip patch antennas supplies a comprehensive and complex representation of their radiation characteristics. This invaluable information equips antenna engineers and designers to optimize antenna performance, assess coverage across three dimensions, and strategize realistic deployments across diverse applications. These applications span a spectrum, including wireless communication, radar systems, satellite communication, and beyond. The 3D radiation pattern is indispensable for realizing desired performance and coverage objectives within intricate electromagnetic environments.

The Normalized 3D Field Pattern of a Microstrip Patch Antenna provides a comprehensive visualization of how the antenna radiates energy in three-dimensional space. This pattern accounts for the elevation (θ) and azimuth (φ) angles, allowing a thorough understanding of the antenna's radiation characteristics. In the case of the microstrip patch antenna described in this work, the elevation and azimuth angles are set at 0.0 degrees and the directivity is 30 dB. The elevation angle (θ) at 0.0 degrees signifies that the observation plane is aligned with the z-axis. This corresponds to the broadside direction, where the antenna's main radiation lobe is expected to be concentrated. At this elevation angle, the normalized 3D field pattern will show the intensity of the radiated electric field or power as a function of both azimuth (φ) and radial distance from the antenna. The azimuth angle (φ) at 0.0 degrees implies that the observation plane is in the plane containing the x-axis and z-axis. The radiation pattern will be displayed in this plane. The 3D pattern will illustrate how the antenna radiates energy as we move around the azimuthal direction, showing the directional characteristics in the horizontal plane. The specified directivity of 30 dB indicates a highly directive antenna that concentrates most of its radiated power in a specific direction. The 3D field pattern will exhibit a sharp main lobe, representing the primary direction of radiation, and potentially, the 3D field pattern provides a holistic view, showing how the antenna radiates energy in all directions around it. Peak intensities in the pattern correspond to the main lobe and any significant side lobes, providing information on the antenna's gain and directivity.

The pattern will show intensity variations as it moves away from the main lobe, depicting the antenna's ability to focus energy in specific directions. These antennas could be used in satellite ground stations or onboard satellite platforms for high-speed data transmission and reception in the Ka-band frequency range (26.5–40 GHz). They could also be employed in point-to-point communication links for high-capacity data transmission over short to medium distances, such as in wireless backhaul networks for cellular infrastructure.

Furthermore, Fig. 9 presents a simulated array view of microstrip

Table 8
Comparison between studies for antenna optimization using the Taguchi method.

#Control Factors	Frequency Range	Antenna Type	Ref
5	12.3 GHz – 12.8 GHz	microstrip Patch	[50]
4	30 MHz to 6 GHz.	Bi-log Hybrid	[58]
13	20 GHz – 40 GHz	microstrip Patch	Proposed work

patch antennas within the scope of this study.

Table 8, presented below, provides a comparative analysis of past research endeavors employing the Taguchi method for antenna optimization and the current study outlined in this paper. It is noteworthy that the number of control factors utilized in our research is distinct and innovative.

This study offers a methodical framework for both researchers and manufacturers in the design of microstrip patch antennas tailored to specific applications, minimizing the need for trial-and-error approaches. The results contribute to enhancing microstrip patch antenna performance across various applications.

5. Conclusion

These antennas exhibited specific characteristics, including a reflection coefficient or return loss of -0.098612 dB at 40 GHz, a lumped port impedance of $0.37939 + 29.012i\ \Omega$, and both elevation ($\theta$) and azimuth ($\varphi$) angles set at 0.0 degrees achieving the desired directivity and concentrating radiated power effectively.

This research simplifies the design process of microstrip patch antennas customized for specific applications by examining the impact of each control factor on antenna directivity. It presents a promising resolution to the typical design hurdles faced in traditional trial-and-error methods by refining the specific control parameters explored in this study. The chosen thirteen control parameters are optimized simultaneously through L27 OA instead of studying the effect of each control factor alone in trial a trial-and-error approach. This methodical approach promises to conserve time, material resources, and design costs associated with creating high-performance microstrip patch antennas tailored to precise directivity requirements for particular applications. Future work may extend optimization efforts to address challenges in achieving directivity across multiple frequency bands and explore the power handling capacity of optimized antennas, crucial for high-power transmission applications. Also, future work will include physical validation through lab tests for further assurance and validation of the finding of this paper.

CRediT authorship contribution statement

Mohd H.S. Alrashdan: Writing – original draft, Visualization, Software, Methodology, Conceptualization. **Zouhair Al-qudah:** Writing – review & editing, Validation, Investigation, Formal analysis, Data curation.

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References

[1] Zhi Wei Sim, Roger Shuttleworth, Martin J. Alexander, and Bruce D. Grieve, "Compact Patch Antenna Design for Outdoor RF Energy Harvesting in Wireless Sensor Networks," Progress In Electromagnetics Research, Vol. 105, 273-294, 2010. doi:10.2528/ PIER10052509.

[2] Hassan N, Zakaria Z, Sam WY, Mohd Hanapiah IN, Mohamad AN, Roslan AF, et al. Design of dual-band microstrip patch antenna with right-angle triangular aperture slot for energy transfer application. Int J RF Microwave Comput Aided Eng 2018; 29(1):e21666.

[3] S. Chen, Y. Jiang and W. Cao, "A Compact Ultra-Wideband Microstrip patch Antenna for 5G and WLAN," 2020 IEEE 3rd International Conference on Electronic Information and Communication Technology (ICEICT), Shenzhen, China, 2020, pp. 601-603, doi: 10.1109/ICEICT51264.2020.9334347.

[4] Nikolayev D, Joseph W, Skrivervik A, Zhadobov M, Martens L, Sauleau R. Dielectric-loaded conformal microstrip antennas for versatile in-body applications. IEEE Antennas Wirel Propag Lett 2019;18(12):2686–90. https://doi.org/10.1109/LAWP.2019.2948814.

[5] Colaco J, Lohani R. "Multi-band microstrip square patch antenna design for iot based RFID technology and its various applications," 6th international conference for convergence in technology (I2CT). Maharashtra, India 2021;2021:1–7. https://doi.org/10.1109/I2CT51068.2021.9417894.

[6] Rana M, Rahman Smieee M. Design and analysis of microstrip patch antenna for 5G wireless communication systems. Bull. Electri. Eng. Informatics 2022;11(6): 3329–37. https://doi.org/10.11591/eei.v11i6.3955.

[7] H. M. Tun, Z. T. Thu Lin, D. Pradhan and P. K. Sahu, "Slotted Design of Rectangular Single / Dual Feed Planar Microstrip Patch Antenna for SISO and MIMO System," 2021 International Conference on Electrical, Computer and Energy Technologies (ICECET), Cape Town, South Africa, 2021, pp. 1-6, doi: 10.1109/ICECET52533.2021.9698738.

[8] Lavadiya SP, Sorathiya V, Kanzariya S, Chavda B, Naweed A, Faragallah OS, et al. Low profile multiband microstrip patch antenna with frequency reconfigurable feature using PIN diode for S, C, X, and Ku band applications. Int J Commun Syst 2022;35(9):e5141.

[9] Chang L, Liu H. Low-Profile and Miniaturized Dual-Band Microstrip Patch Antenna for 5G Mobile Terminals. IEEE Trans Antennas Propag 2022;70(3):2328–33. https://doi.org/10.1109/TAP.2021.3118730.

[10] T. O. Olawoye and P. Kumar, "A High Gain Microstrip Patch Antenna with Slotted Ground Plane for Sub-6 GHz 5G Communications," 2020 International Conference on Artificial Intelligence, Big Data, Computing and Data Communication Systems (icABCD), Durban, South Africa, 2020, pp. 1-6, doi: 10.1109/icABCD49160.2020.9183820.

[11] Gupta A, Dargar SK, Raghavaiah B, Rao AVN. "Comparison between Rectangular Microstrip Patch Antenna with and without Defected Ground Structure at 1.85 GHz,", International Conference for Advancement in Technology (ICONAT). Goa, India 2022;2022:1–4. https://doi.org/10.1109/ICONAT53423.2022.9726044.

[12] Davoudabadifarahani, H., & Ghalamkari, B. (2019). High efficiency miniaturized microstrip patch antenna for wideband terahertz communications applications. Optik, 194, 163118. https://doi.org/ 10.1016/j.ijleo.2019.163118.

[13] Gupta N, Saxena J, Bhatia KS, et al. Design of metamaterial-loaded rectangular patch antenna for satellite communication applications. Iran J Sci Technol Trans Electr Eng 2019;43(Suppl 1):39–49. https://doi.org/10.1007/s40998-018-0118-9.

[14] Masuk A, Kende OM, Husam A, Balajti I. "Cyber-physical system aspects of microstrip patch antenna of radar sensor application,", 23rd international radar symposium (IRS). Gdansk, Poland 2022;2022:378–83. https://doi.org/10.23919/IRS54158. 2022.9904974.

[15] Shahidul Islam M, Islam MT, Ullah MA, Kok Beng G, Amin N, Misran N. A modified meander line microstrip patch antenna with enhanced bandwidth for 2.4 GHz ISM-band internet of things (IoT) applications. IEEE Access 2019;7:127850–61. https://doi.org/10.1109/ACCESS.2019.2940049.

[16] Mahendran K, Gayathri DR, Sudarsan H. Design of multi band triangular microstrip patch antenna with triangular split ring resonator for S band, C band and X band applications. Microprocess Microsyst 2021;80:103400. https://doi.org/10.1016/j.micpro.2020.103400.

[17] Fan T-Q, Jiang B, Liu R, Xiu J, Lin Y, Xu H. A novel double U-slot microstrip patch antenna design for low-profile and broad bandwidth applications. IEEE Trans Antennas Propag 2022;70(4):2543–9. https://doi.org/10.1109/TAP.2021.3125382.

[18] Yang J, Li J, Zhou S, Li D, Yang G. A polarization and frequency reconfigurable microstrip antenna for vehicular communication system application. IEEE Trans Veh Technol 2023;72(1):623–31. https://doi.org/10.1109/TVT.2022.3202973.

[19] Han M, Liu Y, Rakhmanov R, Israel C, Saleh Tajin MA, Friedman G, et al. Solution-processed Ti3C2Tx MXene antennas for radio-frequency communication. Adv Mater 2020;33(1):2003225. https://doi.org/10.1002/adma.202003225.

[20] Fernandez MD, Herraiz D, Herraiz D, Alomainy A, Belenguer A. Design of a wide-bandwidth, high-gain and easy-to-manufacture 2.4 GHz floating patch antenna fed with the through-wire technique. Appl Sci 2021;12(24):12925. https://doi.org/10.3390/app122412925.

[21] M. Y. Mohamed, A. M. Dini, M. M. Soliman and A. Z. M. Imran, "Design of 2×2 Microstrip Patch Antenna Array at 28 GHz for Millimeter Wave Communication," 2020 IEEE International Conference on Informatics, IoT, and Enabling Technologies (ICIoT), Doha, Qatar, 2020, pp. 445-450, doi: 10.1109/ICIoT48696.2020.9089458.

[22] Kim G, Kim S. Design and analysis of dual polarized broadband microstrip patch antenna for 5G mmwave antenna module on FR4 substrate. IEEE Access 2021;9: 64306–16. https://doi.org/10.1109/ACCESS.2021.3075495.

[23] Wang D, Zhang S, Wang G, Vardaxoglou Y, Whittow W, Cadman D, et al. Cold sintered CaTiO3-K2MoO4 microwave dielectric ceramics for integrated microstrip patch antennas. Appl Mater Today 2020;18:100519. https://doi.org/10.1016/j.apmt.2019.100519.

[24] Luo Y, Lai J, Yan N, An W, Ma K. Integration of aperture-coupled multipoint feed patch antenna with solar cells operating at dual compressed high-order modes. IEEE Antennas Wirel Propag Lett 2021;20(8):1468–72. https://doi.org/10.1109/LAWP.2021.3087500.

[25] R. George and T. Anita Jones Mary, "Design of Directional Two L shaped Microstrip Patch Antenna for WSN Applications Using Sea Lion Optimization Algorithm,"

2021 International Conference on Advances in Electrical, Computing, Communication and Sustainable Technologies (ICAECT), Bhilai, India, 2021, pp. 1-6, doi: 10.1109/ICAECT49130.2021.9392454.
[26] J. J. J. Sheela, S. Vanaja, R. Krishnan, V. Avinash., D. Aruna and D. Harini, "Novel Directional Antennas for Microwave Breast Imaging Applications," 2020 International Conference on Smart Electronics and Communication (ICOSEC), Trichy, India, 2020, pp. 599-603, doi: 10.1109/ICOSEC49089.2020.9215243.
[27] Chung KL, Wang L, Luo J, Li Y, Li Y. Comparative study on directional sensitivity of patch-antenna-based strain sensors. Int J RF Microwave Comput Aided Eng 2020; 30(11):e22398.
[28] D. S. Kumar, B. E. Caroline, K. Sagadevan, G. Sakthiganesh and R. Saravanan, "Investigation of High Directional Gain Pentagonal Shaped Patch Antenna," 2020 7th International Conference on Smart Structures and Systems (ICSSS), Chennai, India, 2020, pp. 1-6, doi: 10.1109/ICSSS49621.2020.9202223.
[29] Nagaraju S, Gudino L, Kadam B, Khairnar VV, Rodrigues JX, Ramesha CK, et al. 12th international symposium on communication systems, networks and digital signal processing (CSNDSP). Porto, Portugal 2020;2020:1–6. https://doi.org/10.1109/CSNDSP49049.2020.9249489.
[30] Mahbub F, Akash SB, Al-Nahiun SAK, Islam R, Hasan RR, Rahman MA, et al. IEEE 11th annual computing and communication workshop and conference (CCWC). NV, USA 2021;2021:1185–9. https://doi.org/10.1109/CCWC51732.2021.9376114.
[31] Zhang D, Wu Q. "A tri-band microstrip antenna with triple polarization characteristics,", 13th international symposium on antennas, propagation and EM theory (ISAPE). Zhuhai, China 2021;2021:1–3. https://doi.org/10.1109/ISAPE54070.2021.9753321.
[32] D. Surender, T. Khan and F. A. Talukdar, "A Pentagon-Shaped Microstrip Patch Antenna with Slotted Ground Plane for RF Energy Harvesting," 2020 URSI Regional Conference on Radio Science (URSI-RCRS), Varanasi, India, 2020, pp. 1-4, doi: 10.23919/URSIRCRS49211.2020.9113536.
[33] Khaleel S, Hamad E, Saleh M. High-performance tri-band graphene plasmonic microstrip patch antenna using superstrate double-face metamaterial for THz communications. J Electr Eng 2022;73(4):226–36. https://doi.org/10.2478/jee-2022-0031.
[34] Chen C. A wideband coplanar l-probe-fed slot-loaded rectangular filtering microstrip patch antenna with high selectivity. IEEE Antennas Wirel Propag Lett 2022;21(6):1134–8. https://doi.org/10.1109/LAWP.2022.3159230.
[35] Huang G, Xiang R, Chen C, Wu R. Beam steering patch antennas using reconfigurable parasitic elements of tunable electrical size. Int J RF Microwave Comput Aided Eng 2022;32(11):e23366.
[36] Basiri R, Zareian-Jahromi E, Aghazade-Tehrani M. A reconfigurable beam sweeping patch antenna utilizing parasitic graphene elements for terahertz applications. Photonics Nanostruct Fundam Appl 2022;51:101044. https://doi.org/10.1016/j.photonics.2022.101044.
[37] Kacar M, Weller TM, Mumcu G. 3D printed wideband multi-layered dual-polarized stacked patch antenna with integrated MMIC switch. IEEE Open Journal of Antennas and Propagation 2021;2:38–48. https://doi.org/10.1109/OJAP.2020.3041959.
[38] R. M, R. Thomas D, M. Abbas A, M. K, T. Chitra U and B. N, "Design and Implementation of Linear Taper Slot Antenna for Multiband Applications," 2022 International Conference on Power, Energy, Control and Transmission Systems (ICPECTS), Chennai, India, 2022, pp. 1-4, doi: 10.1109/ICPECTS56089.2022.10046919.
[39] Sağık M, Altıntaş O, Ünal E, et al. Optimizing the gain and directivity of a microstrip antenna with metamaterial structures by using artificial neural network approach. Wireless Pers Commun 2021;118:109–24. https://doi.org/10.1007/s11277-020-08004-8.
[40] Kiani N, Hamedani FT, Rezaei P. Polarization controlling idea in graphene-based patch antenna. Optik 2021;239:166795. https://doi.org/10.1016/j.ijleo.2021.166795.
[41] Kiani N, Hamedani FT, Rezaei P. Polarization controlling plan in graphene-based reconfigurable microstrip patch antenna. Optik 2021;244:167595. https://doi.org/10.1016/j.ijleo.2021. 167595.
[42] Reese R, et al. A millimeter-wave beam-steering lens antenna with reconfigurable aperture using liquid crystal. IEEE Trans Antennas Propag 2019;67(8):5313–24. https://doi.org/10.1109/TAP.2019.2918474.
[43] Taguchi G. Quality engineering (Taguchi methods) for the development of electronic circuit technology. IEEE Trans Reliab 1995;44(2):225–9. https://doi.org/10.1109/24.387375.
[44] Alrashdan MHS. Exchange current density at the positive electrode of lithium-ion batteries optimization using the Taguchi method. J Solid State Electrochem 2023. https://doi.org/10.1007/s10008-023-05672-x.
[45] Al-Sawalmeh W, Alrashdan M, Alnaanah M, Alasha'ary H, Daqrouq K. Study of the effects of control factors on speech features using taguchi method. International Review of Electrical Engineering (IREE) 2022;17(1):99–104. https://doi.org/10.15866/iree.v17i1.21145.
[46] Alrashdan MHS, Alnaanah M, Al-Qudah Z, et al. T-Shape MEMS PMPG design at low frequency range using Taguchi method. Microsyst Technol 2023;29:745–54. https://doi.org/10.1007/s00542-023-05443-8.
[47] Alrashdan MH. MEMS piezoelectric micro power harvester physical parameter optimization, simulation, and fabrication for extremely low frequency and low vibration level applications. Microelectron J 2020;104:104894. https://doi.org/10.1016/j.mejo.2020.104894.
[48] Alrashdan MH. Data relating to mems piezoelectric micro power harvester physical parameter optimization, for extremely low frequency and low vibration level applications. Data Brief 2020;33:106571. https://doi.org/10.1016/j.dib.2020.106571.
[49] Smida A, Ghayoula R, Gharsallah A. "Beamforming multibeam antenna array using Taguchi optimization method,", 2nd World Symposium on Web Applications and Networking (WSWAN). Sousse, Tunisia 2015;2015:1–4. https://doi.org/10.1109/WSWAN.2015.7209082.
[50] M. Spasos, R. Nilavalan, K. Tsiakmakis, N. Charalampidis, S. W. Cheung, "Optimization of a 12.5 GHz Microstrip Antenna Array Using Taguchi's Method", International Journal of Antennas and Propagation, vol. 2011, Article ID 458569, 9 pages, 2011. https://doi.org/10.1155/2011/458569.
[51] Mishra R, Kuchhal P, Kumar A. Effect of height of the substrate and width of the patch on the performance characteristics of microstrip antenna. Int J Electric Comput Eng (IJECE) 2015;5(6):1441–5. https://doi.org/10.11591/ijece.v5i6.pp1441-1445.
[52] Liton Chandra Paul, Sarker Saleh Ahmed Ankan, Tithi Rani, Muharrem Karaaslan, Md. Najmul Hossain, Ahmed Jamal Abdullah Al-Gburi, Himel Kumar Saha, Fatih Özkan Alkurt, "A Wideband Highly Efficient Omnidirectional Compact Antenna for WiMAX/Lower 5G Communications", International Journal of RF and Microwave Computer-Aided Engineering, vol. 2023, Article ID 7237444, 10 pages, 2023. https://doi.org/10.1155/2023/7237444.
[53] L. C. Paul, R. K. Pramanik, M. M. ur Rashid, M. N. Hossain, M. Z. Mahmud and M. T. Islam, "Wideband Inset Fed Slotted Patch Microstrip Antenna for ISM Band Applications," 2019 Joint 8th International Conference on Informatics, Electronics & Vision (ICIEV) and 2019 3rd International Conference on Imaging, Vision & Pattern Recognition (icIVPR), Spokane, WA, USA, 2019, pp. 79-84, doi: 10.1109/ICIEV.2019.8858553.
[54] Paul LC, Jim MTR, Rani T, et al. A low-profile antenna with parasitic elements and a DGS-based partial ground plane for 5G/WMAN applications. Discov Appl Sci 2024;6:22. https://doi.org/10.1007/s42452-024-05669-9.
[55] Paul LC, Hye SA, Rani T, Hossain MI, Karaaslan M, Ghosh P, et al. A compact wrench-shaped patch antenna with a slotted parasitic element and semi-circular ground plane for 5G communication. E-Prime - Advances in Electrical Engineering, Electronics and Energy 2023;6:100334. https://doi.org/10.1016/j.prime.2023.100334.
[56] Liton Chandra Paul, Sarker Saleh Ahmed Ankan, Tithi Rani, Md. Tanvir Rahman Jim, Muharrem Karaaslan, Sk. A. Shezan, Lulu Wang, "Design and Characterization of a Compact Four-Element Microstrip Array Antenna for WiFi-5/6 Routers", International Journal of RF and Microwave Computer-Aided Engineering, vol. 2023, Article ID 6640730, 13 pages, 2023. https://doi.org/10.1155/2023/6640730.
[57] Al-Gburi A. A deep analysis of CPW-fed planar antennas for frequencies 2.6 up to 13.6 GHz. Przegląd Elektrotechniczny 2023;1(3):157–61. https://doi.org/10.15199/48.2023.03.27.
[58] Lee C, Lin D. An optimization design of bi-log hybrid antenna with taguchi's method for EMI measurements. Appl Sci 2022;13(21):11792. https://doi.org/10.3390/app132111792.

Mohd H.S. Alrashdan, Dair Abi Said, April 1, 1983, received a BS in Biomedical Engineering from Jordan University of Science and Technology in 2006. He received MS and PhD degrees in Electrical Engineering -Microelectronics from the National University of Malaysia (UKM) in 2007 and 2016, respectively. From 2016 until now, he has worked as an Associate Professor at Al-Hussein Bin Talal University – Maán, Jordan. During 2007-2016, he finished his PhD and focused on the modeling, simulation, and fabrication of piezoelectric micropower generators for low-frequency applications using MEMS technology. Nowadays, he focuses on power electronics and power systems analysis. Dr. Mohd Alrashdan is a member of the Jordan Engineers Association and collaborates with the Institute of Microengineering and Nanoelectronics. E-mail: moh.alrashdan@ahu.edu.jo

Zouhair Al-qudah received the B.Sc., M.Sc., and PhD, all in Electrical Engineering, from Yarmouk University, Jordan, in Sep. 2002, Kalmar University College, Sweden, in Nov. 2006, and Southern Methodist University at Dallas, Texas, in May 2013, respectively. Since August 2013, he has been with Al-Hussein Bin Talal University at Ma'an, Jordan, where he is a Professor of Wireless Communications. His research interests include coding and information theory in wireless communication systems, cooperative communications 5G communication, resource allocation problems, interference management, and signal processing.

Mohammad Al Bataineh received his BS with high honors in Telecommunications Engineering from Yarmouk University, Jordan, in 2003. He furthered his studies at the Illinois Institute of Technology (IIT), USA, earning his MS in 2006 and Ph.D. in Electrical Engineering in 2010. Subsequent to his academic pursuits, he held noteworthy positions at institutions, including Yarmouk University, where he was promoted to Associate Professor in 2018, and roles at Argonne National Laboratories and MicroSun Technologies. In August 2020, Dr. Al Bataineh joined the United Arab Emirates University (UAEU) as an Assistant Professor. His research interests are centered on the application of communications, coding theory, and information theory to the interpretation and understanding of information flow in biological systems, particularly gene expression. His additional research avenues encompass machine learning, network information theory, and optimization.