

# MULTICHANNEL S-BAND ARRAY ANTENNA DESIGN AND PERFORMANCE EVALUATION FOR CPS APPLICATIONS

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**Abstract:** The study focuses on the design and performance assessment of a new triangular microstrip patch array antenna for cyber-physical system applications. The antenna design uses advanced simulation tools like MATLAB Antenna Design Toolbox and KiCad to optimize performance. The antenna design process includes selecting materials, configuring patch dimensions, and optimizing feed networks for improved gain and impedance matching. The proposed antennas operate in the S-band at 3.0 GHz with a bandwidth of 500 MHz, with a gain of 14.89 dBi and an efficiency of 92%. The study offers valuable insights into antenna design and evaluation, addressing challenges like gain optimization, radiation patterns, and matching impedance.

**Keywords:** Cyber-physical system, Antenna design, MATLAB, Array, Cyber-physical system applications

## 1. Introduction

The S-band antenna is defined by a frequency band that ranges from 2.0 GHz to 4.0 GHz and a wavelength ( $\lambda$ ) range that varies from 75 mm to 150 mm. As the research frequency is 3.0 GHz for in situ measurements, the designed Printed Circuit Board (PCB) Triangular Microstrip Patch (TMP) array antenna with Cu belongs to the S-band. Wireless sensor technology is growing rapidly and tremendously improving public life.

Recent research trends have led to various antenna designs in new wireless communication technologies, as standard antennas can be used in various systems [1, 2]. The S-band antenna is utilized by radars that keep track of the weather and defense systems on surface vessels, as well as by the National Aeronautics and Space Administration (NASA) and the Indian Space Research Organization (ISRO) for communication with the International Space Station (ISS) and space aircraft [3]. A phased-array antenna constitutes an array antenna with the ability to adjust the phase shifts among its individual radiators. This feature enables the conversion of the collective antenna pattern into an electrical signal [4]. Electronic steering offers superior flexibility and minimal maintenance compared to mechanical steering [5].

The antennas being studied were developed via KiCad and FlatCAM PCB design software, and calculations were conducted via the MATLAB Antenna Design Toolbox. These antennas, known as Microstrip Patch Antenna (MPA) array antennas, are predominantly constructed on PCBs. MPA-array PCB antennas are widely used in modern Cyber-Physical Systems (CPSs). With a greater number of elements incorporated into the array antenna, a carefully designed array can achieve increased directivity. This enhanced directivity leads to higher gain levels, improved interference suppression, and enhanced measurement accuracy [6].

The CPS idea is projected to remain high owing to enhanced radar sensor technology and new domains, including CPS implementation in the cost-effective construction of MPAs [7, 8]. In 1953, the microstrip antenna was introduced by Electrical Engineer Georges Deschamps [9].

After the 1970s invention of PCB technology, this idea took approximately 20 years to implement [10]. Since then, MPAs have been the most popular type of antenna and are lightweight, inexpensive, compact in design, geometrical, easy to conform, supreme portable, suitable for arrays, simple to fabricate, and light integrated with sensors [11]. A conducting patch of any planar or non-planar shape can be used to create an MPA [12]. This patch was placed on one side of the dielectric substrate, and the opposite side of the substrate was a ground plane. It is a printed resonant antenna that is widely applied in microwave wireless communication networks [13]. This study extends previous research; numerous evaluations of this work are available at [14, 15].

In recent years, advancements in microstrip antenna technology, including the use of meta-materials and meta-surfaces, have significantly enhanced performance parameters including gain, bandwidth, and radiation efficiency. For example, Torabi and Omid [16] demonstrated how meta-materials can increase isolation in Multiple Input Multiple Output (MIMO) antennas, which is crucial for millimeter-wave applications. The incorporation of these materials into microstrip designs offers promising opportunities for further improving the performance of array antennas [17]. These developments have led to the design of compact and high-performance antennas for upcoming communication systems [18].

In addition, meta-material-based microstrip antennas have shown great potential in areas including energy harvesting and satellite communication [19]. Meta-surface integration also allows for dynamic reconfigurability of antennas for modern applications, similar to frequency tuning or beam steering, which is needed for the modern Internet of Things (IoT) and CPS [20, 21]. Recent research suggests the use of

graphene-based meta surface designs for tunable THz antennas [22], which could enable high-frequency, high-bandwidth communication.

Inspired by this progress, this paper investigates a TMP array antenna that is replenished from omnidirectional antennas and is activated in CPS cases. Furthermore, triangular TMP array antennas were designed and analyzed to determine whether they are suitable for use in CPS applications. Antennas possess characteristics including high gain, wide bandwidth, and compact size, rendering them very efficient for wireless communication [23-25]. The design of TMP antennas involves the utilization of an FR-4 substrate, which has a dielectric constant of 4.4 mm [26, 27]. The performance analysis of the antennas is conducted by employing software tools such as the High-Frequency Structure Simulator (HFSS) for modeling and simulation purposes. This enables the evaluation of several parameters, including the return loss, gain, and radiation pattern [28]. The improved gain, bandwidth, and low backward radiation of TMP antennas make them well suited for IoT applications [29]. Moreover, TMP antennas have the potential to be utilized in Radio Frequency (RF) energy-harvesting applications because of their ability to operate within the frequency range typically employed for electronic device transmission, including Wi-Fi [30]. An investigation of the design characteristics and fabrication constraints pertaining to TMP antennas on PCBs has also been conducted within the domain of Radar Sensor Systems (RSSs) in CPSs. The TMP array antenna design shows an improvement in gain of 0.3 dB compared with the previous designs presented by Koziel et al. [31], where only a single element patch was utilized for IoT applications. Furthermore, the enhanced directivity and gain achieved by our  $2 \times 4$  array configuration demonstrate a substantial improvement over designs utilizing smaller arrays or single-element configurations. The presented antenna is a traditional PCB-based structure with advanced design abilities based on applied discovery tools from simulations that improve the gain, bandwidth, and efficiency. Featured enhancements in the microstrip antenna domain as well as seamless demands of CPS contexts that rely critically on robust wireless communication set this work among the technological convergences of today.

*Figure 1* shows the layered structure of the single-element TMP antenna. The copper (Cu) layer forms the radiating patch and ground plane, whereas the FR4 substrate separates these layers. The FR4 substrate, with its dielectric constant of 4.4 and thickness of 1.6 mm, plays a crucial role in determining the antenna's resonant frequency and bandwidth. The copper thickness (0.03556 mm) affects the antenna's conductivity and efficiency. PCB technology has made it very common to install an antenna along with a fixed-circuit board for a variety of CPSs. As demonstrated above, TMP antennas are an excellent choice for use in applications involving satellites, missiles, and airplanes. Together, these studies make it easier to understand TMP array antennas and how they can be used in CPSs. However, the testing site known as in situ has not been previously investigated in terms of the modifications required to facilitate the development of advanced measuring systems for CPSs. The present study is intended to assess the performance of TMP array antennas in the context of CPSs, thus contributing to the research gap in this area.

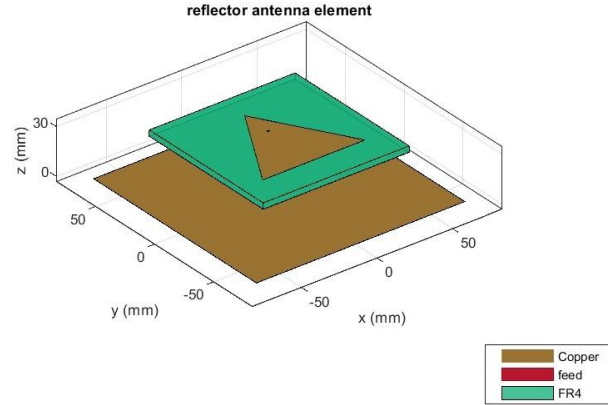


Fig. 1. Schematic layout of Cu and FR4 in the designed TMP single-element antenna

The TMP antenna allows size compactness and excellent directivity. For space applications where space is at a premium, triangular patches are the best choice compared with other patch types [32]. The TMA was fabricated with a patch of radiation-emitting triangular dielectric material down into the ground. The patch can be triangular with equal angles or symmetrical. Triangular patch formation was initially described by Helszajn and James [33]. The equilateral triangular layout was chosen because of its compact size, high directivity, and suitability for space-limited applications similar to CPSs. Compared with rectangular patches, triangular patches reduce the resonant size, making them ideal for applications requiring miniaturized antennas.

The feeding mechanism employs a microstrip line feed optimized for a  $50 \Omega$  impedance. This ensures maximum power transfer and minimal reflection. The positioning of the feed enables an even distribution of current across the patch, enhancing the radiation efficiency and providing a balanced feed.

Recent advancements in microstrip patch antenna design for CPS, Photovoltaics (PV) and IoT applications include studies by Haq et al. [34, 35], who explored the energy-harvesting capabilities of TMP antennas, and Benkalfate et al. [36], who focused on triangular patch antennas for enhanced IoT communication. These developments are built upon by optimizing the array configuration to enhance gain, bandwidth, and impedance matching, specifically for CPS environments.

Designing microwave antennas using copper (Cu) is challenging [37] because current manufacturing methods have difficulty producing conducting polymer films with thicknesses many times the skin depth. Cu nanoparticles ranging from 1 to 100 nm in size can be produced through natural processes or chemical synthesis [38]. Cu is twice as conductive as aluminum (Al) and six times as conductive as steel, making it an excellent choice for antenna materials [39]. Among the materials investigated, antennas using copper materials [40] as the patch and ground provide the lowest return loss -41.84 dB at the corresponding resonant frequency of 8.55 GHz, whereas stainless steel with the lowest conductivity provides the highest bandwidth, 0.656 GHz [10].

PCB technology has made it very common to install an antenna [41] along with a fixed-circuit board for a variety of CPSs. As demonstrated above, TMP antennas are an excellent choice for use in applications involving satellites, missiles, and airplanes. Together, these studies make it easier to understand TMP array antennas and how they can be used in CPSs. However, the testing site known as in situ has not been previously investigated in terms of the modifications required to facilitate the development of advanced measuring systems for CPSs. The present study is intended to assess the performance of TMP array antennas in the context of CPSs, thus contributing to the research gap in this area.

## 2. Theory and formula

In this section, the proposed antenna parameters, materials, and methods used to simulate and fabricate a TMP array antenna are discussed.

TMP antennas have a ground plane and conducting patch on one side of a dielectric substrate. Fabrication of the design takes place on the dielectric substrate FR4, with a dielectric permittivity consistent with that of the substrate  $\epsilon_r = 4.8$  and a substrate thickness = 3.86 mm. For maximum power transfer from the RF circuit to the antenna with minimal reflection, the input impedance of the antenna must be matched to  $50 \Omega$ . Many Triangular Microstrip Patch Array (TMPA) antennas have been examined. An extensive list of geometries and their key characteristics is available. One of the ideal advantages of the microstrip patch antenna is that it is more cost-effective and generally less expensive than other antenna types. They can also be made with low weight. *Figure 2* shows a TMPA antenna with  $2 \times 4$  array elements.

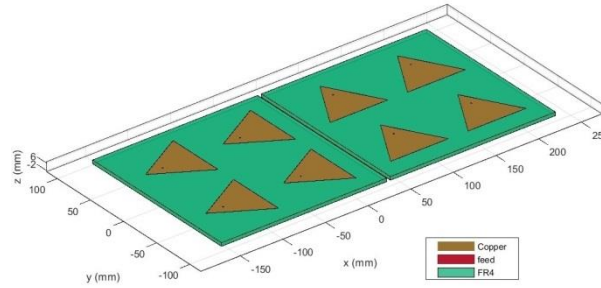


*Fig. 2.* TMP rectangular array antenna

In *Fig. 2*, as it is illustrated, the isolation between array elements is crucial for minimizing mutual coupling and improving overall array performance. The configuration of each element was likely optimized through parametric studies via simulation software. This process involves adjusting parameters including the patch dimensions, feed position, and substrate characteristics to achieve the desired resonant frequency, bandwidth, and radiation pattern.

Table 1 lists the antenna parameters used for designing and fabricating different S-band (3.0 GHz frequency) PCB TMP array element antennas. The array configuration was optimized via simulation tools that analyze the mutual coupling between the elements, radiation patterns, and directivity. The distance between radiating elements was calculated via the following formula:

$$d = \frac{\lambda}{2} \quad (1)$$

where  $\lambda$  is the wavelength at the operating frequency of 3.0 GHz. This ensures minimal interference between elements and optimizes the gain.

Table 1. PCB TMP array antenna parameters

| Name                              | Designed antenna Parameters<br>(S-band - 3.0 GHz frequency) | Fabricated antenna Parameters<br>(S-band - 3.0 GHz frequency) |
|-----------------------------------|-------------------------------------------------------------|---------------------------------------------------------------|
| Copper (Cu) thickness             | 0.03556 (mm)                                                | 0.03556 (mm)                                                  |
| Triangle side length (L)          | 66.7 (mm)                                                   | 78.0 (mm)                                                     |
| Height (H)                        | 3.87 (mm)                                                   | 2.50 (mm)                                                     |
| Feed offset distance (offs.)      | 9.33 (mm)                                                   | 9.30 (mm)                                                     |
| Dielectric constant, $\epsilon_r$ | 4.80                                                        | 4.95                                                          |
| Ground length                     | 96.707 (mm)<br>4 elements<br>196.414 (mm)<br>8 elements     | 235.500 (mm)<br>4 elements<br>472.500 (mm)<br>8 elements      |
| Ground width                      | 96.707 (mm)                                                 | 235.500 (mm)                                                  |
| Row spacing                       | 90.795 (mm)                                                 | 119.100 (mm)                                                  |
| Column spacing                    | 90.795 (mm)                                                 | 120.100 (mm)                                                  |

Owing to its configuration and the ease with which it can be integrated with microstrip technology, the TMP rectangular array antenna is frequently used as an element in arrays. The typical antenna design radiation pattern, such as the gain, half-power beam width (-3 dB), and minimal sidelobe level, will be optimized via simulations for mechatronics engineering. This reduces the possibility of errors in the designed antenna. A phased-array antenna feeds radiators with different phase shifts. Thus, an electrical signal can be generated via a common antenna design. The electrical steering of the antenna is always more flexible and requires less maintenance than mechanical steering. At zero wavenumber,  $k = 0$ , and azimuth angle  $\theta = 90^\circ$ , the normalized power gain ( $G$ ) of the antenna phased array is

$$G(\theta) = \left| \frac{\sin\left(\frac{Nkd}{2}\right) \cos \theta}{N \sin\left(\frac{kd}{2}\right) \cos \theta} \right|^2, \quad (2)$$

where  $N$  represents the elements and  $d$  is the element distance. With the given value, the length of  $a$  can be calculated for  $f_r = 3.0$  GHz as the center frequency,  $c = 3 \times 10^8$  m/s, and  $\epsilon_r = 4.8$ . On the basis of the simulation results, the triangular side length  $a = 66.69$  mm and height  $L_p = 3.8$  mm of the TMP rectangular array antenna. Equation (2) describes the normalized power gain of the antenna phased array, a critical parameter for determining the antenna's efficiency.

The Standing Wave Ratio (SWR) enables the transmission line to transmit its maximum amount of power. Engineers spend a significant amount of time on efficient impedance matching [24].

$$SWR = \frac{1+|r|}{1-|r|}, \quad (3)$$

where  $r$  is a function of the load impedance.

Near-field measurements are more complex because the amplitude and phase information are highly correlated with the reference signal source. Furthermore, the near field to far-field transient coefficients is added to the calculation of the results. *Figure 6* illustrates the configuration of the measurement antenna eccentricity. The most important range of fields is also indicated. *Figure 3* shows the configuration of the measurement setup, particularly highlighting the antenna eccentricity. This setup is critical for evaluating the mutual coupling between elements, measuring near-field radiation, and calibrating the antenna for real-world applications. The eccentricity allows for more precise measurements by accounting for variations in polarization and signal interference.

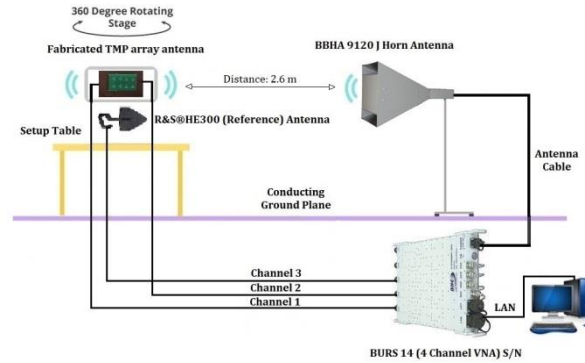


Fig. 3. Configuration of measurement antenna eccentricity

The demonstrated setup was the main platform for measuring the performance of the designed and manufactured TMP array and single antennas. This near-field measurement technique considers the mutual coupling of the antennas, the radiation

patterns of the antenna arrays from the environment, and the implications of the near field, all of which can have a significant impact at a test distance of 2.6 meters. This method of site evaluation is more precise than the Normalized Site Attenuation (NSA) used in far-field Antenna Under Test (AUT) methods because it does not depend on the usage of antenna factors to determine test site performance. The antenna factors used in the ElectroMagnetic Interference (EMI) measurements to calculate the field strength were defined as free-space antenna factors. These antenna factors have single values within each frequency and are not affected by the height of the antenna, its polarization, or its range from the transmitter. However, the in situ reflections have a very high influence on the measurement conditions, which causes difficulties in the evaluation of the test results; consequently, these factors have a greater emphasis on antenna calibration.

An appropriate antenna calibration method is crucial to antenna measurement accuracy. This method depends on the antenna type and the frequency range for a given test platform geometry. The developed PCB TMP array antennas perform through the EMI measurement proceedings and antenna calibration results published in the test and evaluation section. Typically, antenna calibration requires an antenna frame, which can be located either indoors or outdoors. Open-field testing locations are sensitive to the effects of the local climate, whereas indoor ranges have a limited amount of available space. There are a few alternative approaches for antenna calibration. IEEE/ANSI C63.5:2017 [42] provides specifications for the Standard Site Method (SSM).

Different antenna calibration procedures create various Antenna Factors (AFs), and fluctuations are important when a platform must calculate, report, and apply antenna radiation-emission measurement errors. A lower antenna ratio significantly decreased the emission measurement error. Thus, it provides a precise value for EMI measurement.

### 3. Experimental setup

The test environment, calibration, and antenna parameters are presented in this section. The in situ test setup environment, measurement results, and key differences between the theoretical and fabricated antenna performances are also discussed. Near-field measurements are more complicated because the amplitude and phase information must be recorded with a high correlation to the reference signal source. The results also include the near-field to far-field transient coefficients. Far-field radiated emission measurements are required worldwide to prove product compliance with regulations.

In situ measurements assess antenna mutual interference, radiation patterns, and near-field measurement considerations at 2.6 meters. Near-field measurements were also used to evaluate product prototypes, modules, and antenna design changes to ensure product compliance before marketing. An in situ near-field test range was established in the Department of Electrical Engineering and Mechatronics (CPS Laboratory), Faculty of Engineering, University of Debrecen, Hungary, illustrating the measurement antenna eccentricity configuration (*Fig. 4*).

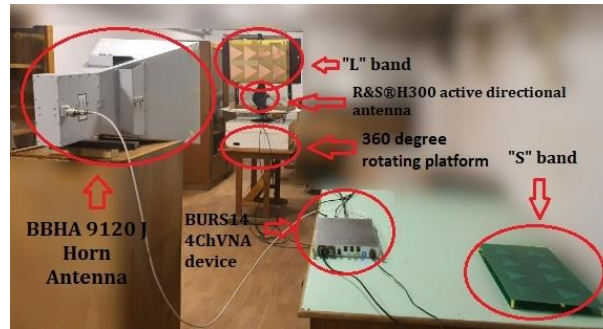


Fig. 4. Test setup environment for antenna measurement

A four-channel Vector Network Analyzer (VNA) has an RF transmitter, four receivers, and L- and S-band antennas. The antenna was tested on a 360°-rotating platform. The BroadBband High gain horn Antenna (BBHA) 9120 J Horn antenna sends a standard signal. The R&S®H300 active directional antenna served as a reference for testing the rotating antenna. Linear cross-polarization is needed. The BURS14 4ChVNA (computer-controlled) collects antenna signals for processing on a personal computer (PC), with PCs connected via LAN cable to control the system and analyze the 4ChVNA data.

#### 4. Results

Table 2 summarizes the amplitude and phase of the fabricated antenna at different frequencies. The performance of the fabricated antenna systems changes, but these changes is within the acceptable range for such measurements.

Table 2. Amplitude and phase of the measured fabricated antenna

| TMP Antenna                              | Phased Array (2×4 elements) |                 |                |
|------------------------------------------|-----------------------------|-----------------|----------------|
|                                          | Channels                    | Amplitude (dBm) | Phase (degree) |
| Frequency                                |                             |                 |                |
| 3.0 GHz                                  | 4V TMP array                | -53             | 40°            |
|                                          | 4H TMP array                | -47             | 150°           |
|                                          | HE300                       | -37             | 190°           |
| 3.1 GHz                                  | 4V TMP array                | -70             | 30°            |
|                                          | 4H TMP array                | -60             | 130°           |
|                                          | HE300                       | -56             | 170°           |
| NRP =1.0 RPM and Number of rotations = 3 |                             |                 |                |
| 2.9 GHz                                  | 4V TMP array                | -53             | 62°            |

|         |                |     |       |
|---------|----------------|-----|-------|
| 3.4 GHz | 4H TMP array   | -46 | -120° |
|         | HE300          | -33 | 30°   |
|         | 4V TMP array   | -51 | 47°   |
|         | 4H TMP array   | -63 | -20°  |
| 3.1 GHz | HE300          | -34 | 80°   |
|         | x-polarization |     |       |
|         | 4V TMP array   | -40 | 80°   |
|         | 4H TMP array   | -45 | 170°  |
|         | HE300          | -45 | 50°   |

As it is illustrated in *Table 2*, the amplitude and phase of the fabricated antenna systems exhibit variations that remain within acceptable limits.

*Table 2* shows that the antenna characteristics were stable and had different frequency bands, and the antenna was ready for calibrated measurements. With the in situ measurement technique, tests for the given TMP array antenna aim to determine the individual element characteristics and defects (amplitude and phase) on the basis of measurements of the global radiation performance. This is one of the objectives of the in situ measurement technique. The in situ measurement setup is shown in the measured performance of the fabricated TMP antenna.

3D radiation patterns were generated at a working frequency of 3.0 GHz to visualize the antenna's far-field performance. These patterns, shown in *Figs 5 and 6*, highlight the gain and directivity in three dimensions, confirming the high performance of the proposed antenna.

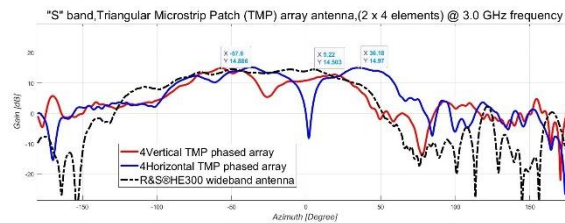


*Fig. 5.* Gain of TMP array antennas with a standard reference antenna

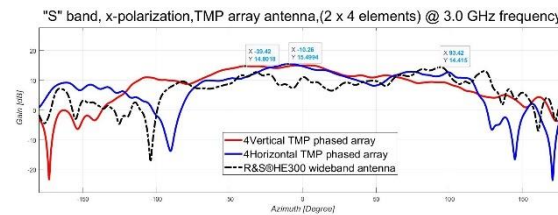


Fig. 6. Gain of TMP array (2×4) antennas with x-polarization

3D radiation patterns enhance the understanding of an antenna's radiation properties through visual confirmation.

After analyzing the fabricated antenna in a near-field test setup environment and calculating various mathematical equations, the following are the performance characteristics of the fabricated antenna. The gain and impedance matching observed in our 2×4 TMP array closely align with the simulated results, as it is shown in *Figs 5 and 6*. The gain margin of 1.3 dB compared with the reference antenna is within an acceptable range, confirming the robustness of our design. However, the phase discrepancies noted during testing suggest the need for further optimization of polarization control, particularly in environments with significant interference.

*Figure 5* shows the radiation pattern of the TMP array antennas with respect to the azimuth. The gain serves as a measure of an antenna's radiation pattern. The assessment findings for the horizontal (*H*) and vertical (*V*) TMP array Cu antennas, which determine the maximum gain in dBi, are determined by analyzing the signal's frequency response, as it was referenced in Eq. (2), at a frequency of 3.0 GHz. By utilizing the measured near-field data, the computed gain results are as follows:

- 4 Vertical (*V*) array elements achieve a gain of 14.886 dBi;
- 4 Horizontal (*H*) array elements yielded a gain of 14.503 dBi;
- The R&S®H300 (reference) antenna attained a gain of 14.97 dBi.

The gain of the fabricated antennas is within a 0.3 dBi margin after the reference antenna and the fabricated antenna patterns are compared. However, phase discrepancies in polarization drifts lead to notches in the patterns.

After applying x-polarization, the evaluation results show nearly identical radiation patterns within the same frequency band. In *Fig. 6*, the x-polarization measurement setup was used for the TMP array antenna measurement.

- 4 Vertical array elements achieve a maximum gain of 14.80 dBi;
- Four horizontal array elements attained a maximum gain of 15.49 dBi;
- The R&S®H300 (reference) antenna attained a maximum gain of 14.41 dBi.

The reference antenna patterns were compared with those of the fabricated TMP array's (2×4 elements) horizontal and vertical antennas, revealing a gain margin of 1.3 dBi. Upon analyzing the measured results of the fabricated phased array antenna, it is evident that the fabricated antennas demonstrate positive outcomes and nearly perfect impedance matching. However, disruptions in performance caused by local interference led to unpredictable amplitude notches.

The antenna array's isolation between radiating elements was calculated. The results indicate minimal mutual coupling, with isolation values greater than 20 dB across the operational bandwidth. Furthermore, the radiation efficiency of the array was calculated to be 92%, further confirming the suitability of the design for high-performance applications. Because there was no anechoic chamber, a standard reference antenna was used to compare the results, and the performances are shown in *Figs 8 and 9* as dotted lines, referred to as R&S®H300 wideband antenna. The radiation efficiency was

calculated and confirmed to be 92%, and its 2D representation was plotted against frequency. This can be visualized as a stable efficiency curve across the operating bandwidth, peaking at the design frequency of 3.0 GHz. It can be determined that the gain of the fabricated antennas is within a 1.3 dB margin by comparing the patterns of the reference antenna and the fabricated TMP array (2×4 elements) horizontal and vertical antennas.

## 5. Discussion

Research has been conducted on TMP (2×4 array elements) antennas. The rectangular array configurations with one element and two rows of four elements exhibited good performance. A handful of triangular patch antennas were purpose-built to conduct accurate analysis. The interferometric radar measurements were also a good fit for each design. While keeping the antennas' sidelobes to a minimum, using array techniques significantly improves the system's gain and directivity.

The novelty of this work lies in the development of a TMP array antenna specifically optimized for in situ testing in CPS environments. Unlike previous designs that predominantly focus on single-element antennas, our study introduces a 2×4 element configuration that enhances performance in terms of gain and impedance matching. Additionally, the in situ measurement methodology offers more precise results than traditional far-field measurements do, providing a more accurate characterization of the antenna's real-world performance.

A single element and array built from different elements of a TMP antenna can be designed and fabricated in the CPS Laboratory. These proposed antennas are suitable for applications operating at approximately 3.0 GHz. The in situ measurement confirmed that both antennas that were fabricated have a high level of performance, high quality and nearly perfect impedance matching. In the future, coaxial feeding techniques may perform better than proximity-coupled feeding techniques in terms of parameter results. The TMP antenna can be tailored to meet the requirements of a given application through the flexible fabrication and design process of the Department of Mechatronics. Extensive testing was conducted on the antennas, revealing their efficient performance across the frequency range of approximately 3.0 GHz. Consequently, these antennas are highly suitable for a wide range of wireless communication systems. The test results obtained from the in situ analysis provided evidence that the antennas produced had outstanding performance characteristics. These include notable attributes, including high gain, minimal loss, and superior impedance matching. Moreover, preliminary observations indicate that coaxial feeding approaches may yield more favorable parameter outcomes than proximity-coupled feeding strategies do, thus potentially facilitating the development of antenna technology.

The most challenging aspect was performing near-field antenna measurements in the test setup environment, which involved the mechanical settings. However, with the assistance of specialized equipment and mast systems, successful test results were obtained from various fabricated TMP antennas (single and array elements). The performances of the fabricated and simulated TMP array antennas were similar. This study demonstrated that a TMP rectangular array antenna could efficiently decrease the

sidelobe level, particularly in  $(2 \times 4)$  array elements in the horizontal and vertical directions.

The findings additionally demonstrated that the TMP rectangular array antenna exhibited a substantial enhancement in directivity and gain compared with single-element antennas. Moreover, this research emphasized the prospective utilization of TMP array antennas in domains requiring superior functionality and minimal sidelobe levels, similar to as radar systems and satellite communications.

Mechatronics engineering with antenna design toolkits provides a comprehensive understanding of the manufacturing process of sensor/radar and communication antennas. It supports IoT sensors and communication efficiency, along with manufacturing technologies, regulatory environments, improved quality, lower error rates, increasing capacity, and improved expert research areas, which identify standard antenna construction [42]. This level of insight is crucial for creating cutting-edge antenna designs that can meet the expanding needs of today's sophisticated communication networks. Furthermore, this study delves into the prospective uses of mechatronics engineering within the field of satellite communications, facilitating progress in worldwide connectivity and data transfer.

## 6. Conclusions

This study successfully designed and evaluated a TMP array antenna for CPS applications, achieving significant performance improvements. The proposed  $2 \times 4$  array configuration demonstrated a gain of 14.89 dBi and an efficiency of 92%, with impedance matching characterized by a return loss of -41.84 dB at an operating frequency of 3.0 GHz. The proposed design is compact, lightweight, and suitable for various wireless communication applications. The findings derived from these evaluations provide valuable insights that can be applied to the development of future designs for TMP array antennas, with the goal of improving their overall performance and utility. This research emphasizes the importance of conducting comprehensive evaluations of antenna performance and deploying phased array designs to increase the capabilities of sophisticated CPS sensors.

The compact size and lightweight design along with the high directivity and wide bandwidth of the antenna prove beneficial for CPSs and other wireless communication systems. The almost perfect agreement between the simulated and measured results confirms the robustness of this design. Subsequent investigations will involve continued optimization of the feed design, pursuit of meta-material improvements, and automated rotation of the antenna platform to improve measurement accuracy.

This research highlights the potential of TMP array antennas to meet the performance demands of modern CPSs, providing a foundation for further advancements in antenna technology. It is necessary to make additional advancements to automate the rotation of antenna platforms in terms of rotation angle, speed, and antenna height. This was presumed to be simple to implement. Ad hoc testing methodologies and near-to-far field mathematical solutions will be the primary focus of future work. Future work will focus on further optimizing the feed mechanism and exploring meta-material enhancements.

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