

A compact flat antenna array based on Wilkinson power divider for radar applications

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ABSTRACT

This paper presents the design, simulation, and achievement of an optimized 64-element antenna array based on Wilkinson power divider operating at 24 GHz. The whole circuit is mounted on a Rogers RO4830 substrate with a thickness of 0.127 mm, copper cladding thickness of 0.018 mm, dielectric constant of 3.24, and a loss tangent of 0.0033. Using advanced design system (ADS) from Keysight, the combiner is meticulously simulated to achieve efficient power combination with minimal insertion loss, excellent impedance matching, and high port-to-port isolation. The design ensures that power from multiple input ports is effectively combined into a single output port, suitable for high-frequency applications. Simulation results at 24 GHz confirm optimal performance, and validation corroborates the accuracy of the ADS-based simulations. The proposed design demonstrates reliability and efficiency for integration into modern communication radar systems operating at millimeter-wave frequencies.

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1. INTRODUCTION

The swift advancement of high-frequency communication technologies, including 5G networks and satellite systems, has heightened the demand for reliable and efficient components to enhance sophisticated antenna arrays. Wilkinson power combiners and dividers play a crucial role in these technologies, as they are capable of delivering accurate power distribution and combination, ensuring excellent impedance matching, and providing significant isolation between ports [1]. These characteristics make them especially effective for millimeter-wave applications, such as those functioning at 24 GHz. At these elevated frequencies, it is essential to maintain low insertion loss, compact dimensions, and thermal stability. The advantages of Wilkinson power combiners are noteworthy. Their high efficiency means that low insertion loss leads to minimal power loss, thereby optimizing system performance [2]. Additionally, proper impedance matching ensures excellent return loss, which reduces signal reflections and enhances power transfer [3]. The use of resistor-based isolation contributes to high isolation, minimizing interference between input ports and preserving signal integrity [4]. Furthermore, Wilkinson combiners can be designed to take up very little

space, making them particularly suited for integration into compact antenna arrays [5]. The Wilkinson power divider [6] is commonly employed in a range of microwave and millimeter-wave circuit applications. While the traditional design utilizing quarter-wave lines is straightforward and effective, it tends to be restricted to operation within a single frequency band [7]. Recently, several new schemes are reported in the literature to achieve the Wilkinson divider operation at two or more frequency bands [8]–[17]. Unlike traditional passive patch antennas that rely solely on their design to achieve the necessary gain and impedance characteristics, active patch antennas incorporate amplification techniques to significantly boost signal strength and enhance coverage area. This capability is particularly advantageous in high-frequency communication systems, where the effectiveness of the antenna plays a crucial role in determining data transfer rates and overall network capacity [18], [19]. Active integrated patch antenna arrays can transmit signals at much higher power levels than their passive counterparts, making them ideal for scenarios that require better signal penetration, reliable connectivity, and faster data transmission [20], [21].

However, the integration of a power amplifier with a patch antenna array adds layers of complexity to the design process. This is especially important for sub-6 GHz 5G applications [22], [23], where it is vital to ensure proper impedance matching between the antenna and amplifier, minimize insertion and radiation losses, and maintain system stability during high-power usage. Additionally, effective thermal management is crucial to avoid overheating, which could otherwise impair system performance or lead to component failure [24], [25].

The 64-element antenna array designed to operate at 24 GHz is tailored for short-range radar applications in both automotive and industrial fields. In automotive advanced driver assistance systems (ADAS), this configuration supports critical safety features such as blind spot detection (BSD), rear cross-traffic alerts (RCTA), parking assistance, and lane change guidance. These functions require high angular resolution and quick beam steering to accurately detect objects within a range of 0.2 to 30 meters. The Wilkinson power divider provides outstanding -60 dB isolation, which is vital for minimizing interference between transmit and receive channels, allowing for effective identification of multiple targets in congested traffic situations. In industrial settings, the array facilitates non-contact level measurements in storage tanks, monitoring the flow of bulk materials, and detecting presence in hazardous areas, where dependable operation in harsh conditions is essential. Additionally, the design supports perimeter security radar for intrusion detection and smart infrastructure monitoring for traffic management.

Figure 1 provides an overview of the architecture for an automotive ADAS that employs 24 GHz radar technology. This diagram illustrates how a 64-element patch array antenna is installed on an RO4830 substrate and linked to a Wilkinson power divider. This design is especially well-suited for automotive radar functions such as BSD, RCTA, and parking assistance, where dependable target recognition, compactness, and sufficient angular coverage are crucial. The 24 GHz radar system can be seamlessly integrated into compact vehicle platforms, including sensors mounted on bumpers and at the rear, thus offering a viable solution for automotive spaces with limited room. The combination of a 64-element array and a compact Wilkinson power divider enhances the ability to tackle the challenges of miniaturizing the system while ensuring effective power distribution among the antenna components. As a result, this architecture shows promise for integration into practical automotive radar modules, especially in scenarios that demand reliable short- to medium-range sensing and restricted installation areas. Furthermore, beyond automotive safety, this compact high-isolation architecture holds strong potential for deployment in 5G backhaul communication networks and industrial sensing, directly contributing to enhanced road safety, vehicle automation, and modern smart infrastructure. Future work will aim to expand this architecture to support multiband functionality, explore its scalability to larger antenna arrays, and further refine its electromagnetic characteristics and feeding network performance concerning insertion loss, isolation, impedance matching, and radiation properties.

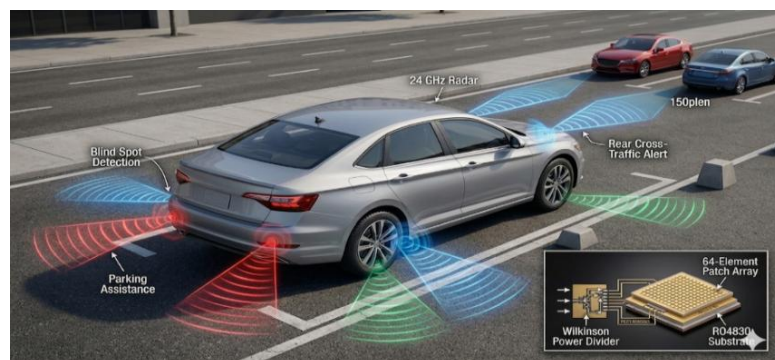


Figure 1. The structure of the Wilkinson power divider

A compact flat antenna array based on Wilkinson power divider for radar ... (Mohamed Lemine El Haidad)

The novelty of this work lies in the development of an optimized hierarchical 64-element Wilkinson power divider network operating at 24 GHz for large millimeter-wave antenna arrays. The proposed architecture ensures uniform power distribution, effective impedance matching, low insertion loss, and high port isolation. It achieves an insertion loss of 3.07 dB, an input reflection coefficient of -14 dB, and port-to-port isolation of approximately -60 dB at 24 GHz. Fabricated on a thin, low-loss Rogers RO4830 substrate (0.127 mm, $\tan\delta=0.0033$), the design provides a compact and efficient solution for advanced 5G/6G communications and millimeter-wave radar applications.

In this study, we introduce the development of an enhanced antenna array consisting of 64-elements, designed to operate at a frequency of 24 GHz and utilizing a Wilkinson power combiner. The circuit is constructed on a RO4830 Rogers substrate, recognized for its minimal loss and consistent dielectric characteristics ($\epsilon_r=3.24$, $\tan\delta=0.0033$), which are essential for achieving optimal performance at millimeter-wave frequencies. We utilize keysight advanced design system (ADS) for simulation and optimization, allowing for precise modeling of the combiner's performance. With its high gain, narrow beamwidth, and effective power distribution, this antenna array is ideal for numerous millimeter-wave applications. These include 5G infrastructure (especially within the n258 band), industrial monitoring radars, short-range automotive sensing systems, high-capacity point-to-point wireless backhaul, and security screening imagers. Consequently, it emerges as a dependable choice for dense urban environments, smart manufacturing facilities, and advanced transportation systems.

2. THEORY

2.1. Wilkinson power divider

Conventional power dividers, such as the lossless T-junction, face challenges due to impedance mismatches at all ports and a lack of isolation between the outputs [26], [27]. On the other hand, while a resistive divider provides matched ports, it is inherently lossy and does not offer isolation either. However, there are lossy three-port networks that can successfully achieve both impedance matching and isolation. One notable example is the Wilkinson power divider, which operates almost losslessly when its output ports are properly matched, only dissipating power that is reflected. Although Wilkinson dividers can be tailored for unequal power distributions, we will focus first on the standard equal-split (3 dB) variant. This design is frequently realized through microstrip or stripline technology, as illustrated in Figure 2, where Figure 2(a) shows the microstrip line form and Figure 2(b) depicts the corresponding transmission line circuit. The analysis will utilize an even-odd mode technique [27], which simplifies the circuit into two segments driven by symmetric and antisymmetric sources at the output ports. This analytical approach will also be relevant for the antenna array. To facilitate the analysis, we will standardize all impedances to the characteristic impedance Z_0 and design the circuit based on Figure 2(b).

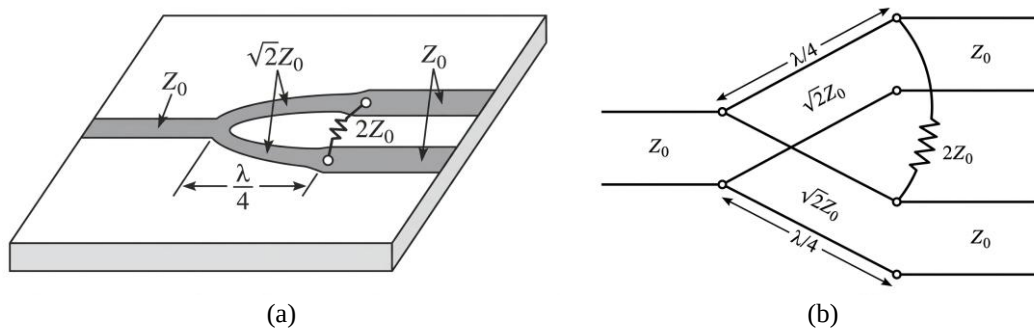


Figure 2. Wilkinson power divider; (a) an equal-split Wilkinson power divider in microstrip line form and (b) equivalent transmission line circuit [25]

The Wilkinson power combiner is designed for effective power combination with minimal losses, ensuring high isolation and excellent impedance matching. These characteristics make it particularly suitable for systems that require integration with extensive antenna arrays. Power combination: in a 64-element antenna array, signals received from the elements are routed through the power combiner to produce a single coherent output signal. Figure 3 shows the frequency response of the equal-split Wilkinson power divider. At f_0 , $|S_{21}|$ is approximately -3 dB, confirming equal power division, while $|S_{11}|$ and $|S_{23}|$ reach about -40 dB, indicating excellent matching and isolation.

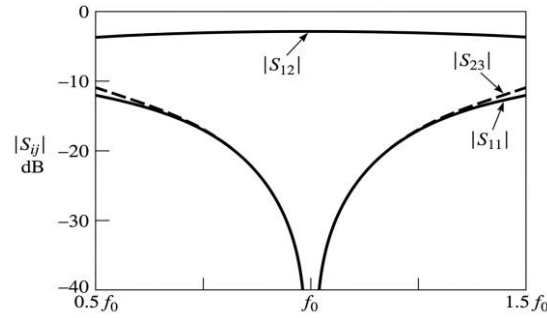


Figure 3. Frequency response of the equal-split Wilkinson power divider

In order to determine the dimensions of the Wilkinson power divider, we have to use (1)-(3) [25]. For quarter-wave transmission line length (l):

$$l = \frac{\lambda_g}{4} = \frac{C}{4f\sqrt{\epsilon_{eff}}} \quad (1)$$

where λ_g is the guided wavelength, C is the speed of light, $f=24$ GHz is the frequency, and ϵ_{eff} is the effective dielectric constant. And to calculate the characteristic impedance (Z_c) of the microstrip lines:

$$Z_c = \sqrt{Z_0 Z_l} \quad (2)$$

Isolation resistor value:

$$R = 2Z_0 \quad (3)$$

For the design, Z_0 is typically set to 50 Ω ; therefore, $R=100$ Ohm.

2.2. Single patch antenna design

To obtain antenna array, we have to start by single antenna, which is shown in the Figure 4, and the Table 1 illustrates dimension of the proposed antenna. To obtain the dimension of an antenna we use (4)-(6):

$$W_p = \frac{C}{2f_0\sqrt{\frac{\epsilon_R+1}{2}}} \quad (4)$$

$$L_p = \frac{C}{2f_0\sqrt{\epsilon_{eff}}} - 0.824h \left(\frac{(\epsilon_{eff}+0.3)(\frac{W}{h}+0.264)}{(\epsilon_{eff}-0.258)(\frac{W}{h}+0.8)} \right) \quad (5)$$

$$\epsilon_{eff} = \frac{\epsilon_R+1}{2} + \frac{\epsilon_R-1}{2} \left[\frac{1}{\sqrt{1+12(\frac{W}{h})}} \right] \quad (6)$$

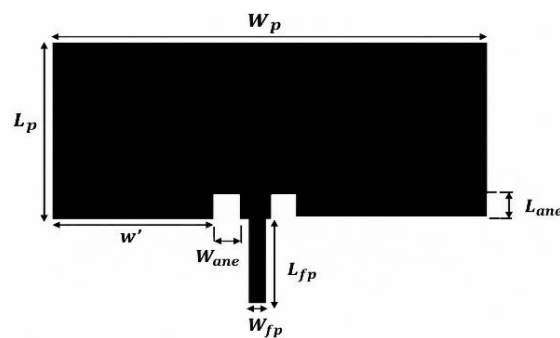


Figure 4. Single antenna parameters

Table 1. Dimension of the proposed antenna

Parameters	Value (mm)	Parameters	Value (mm)	Parameters	Value (mm)
Wp	4.29	Wfp	0.1	W100	0.2
Lp	3.4	Lfp	2.06	Wanc	0.17
W'	1.83	L100	2.7	Lanc	0.48

3. DESIGN PROCEDURE AND RESULTS DISCUSSION

3.1. Wilkinson power design

After calculating the different power divider elements, we have conducted the simulation using ADS as presented in Figure 5. This Wilkinson divider was simulated and tested previously with very good results. Simulations with ADS momentum. Figure 6 illustrates the performance, where Figure 6(a) shows the input return loss, Figure 6(b) displays the output return loss, Figure 6(c) presents the insertion loss, and Figure 6(d) demonstrates the isolation.

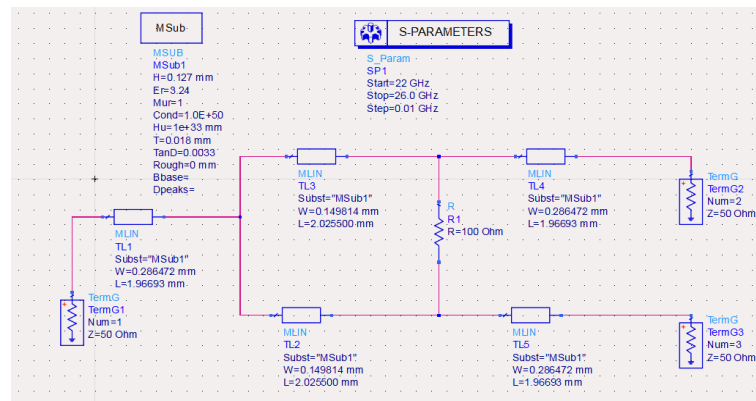


Figure 5. The structure of the Wilkinson power divider

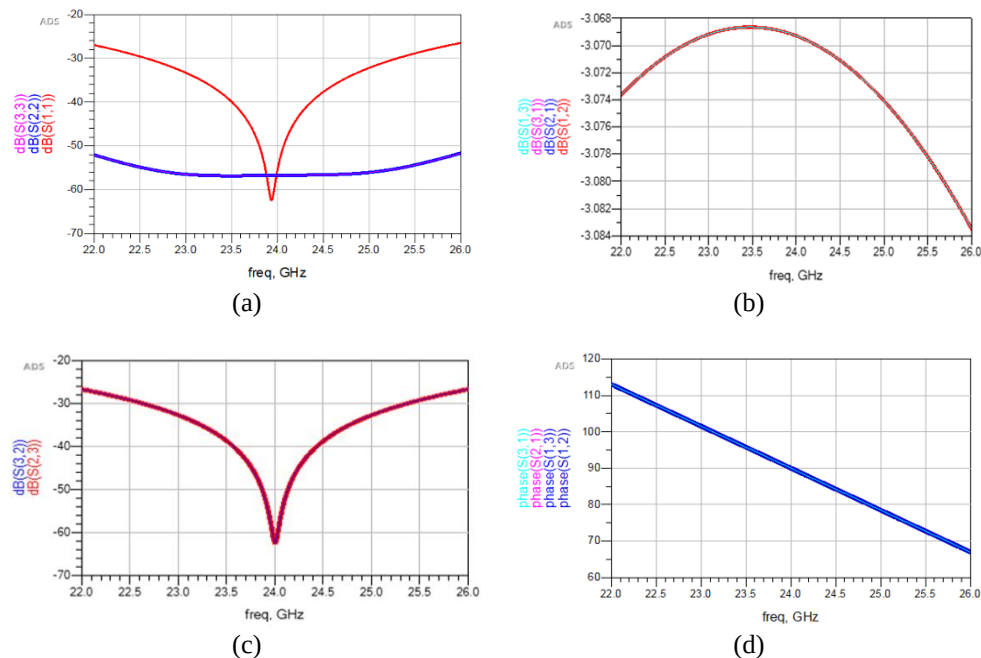


Figure 6. Simulated S-parameters and phase response versus frequency; (a) input/output return loss, (b) transmission coefficient, (c) inter-port isolation, and (d) transmission phase distribution

Impedance matching and port return loss (S11, S22, S33):

- The input reflection coefficient (S11) demonstrates an exceptional resonance at 24 GHz, reaching a null deeper than -60 dB, this indicates near-perfect impedance matching to the $50\ \Omega$. Similarly, the output port return losses (S22 and S33) remain below -50 dB across the 22–26 GHz band. Such high return loss values ensure that any back-reflections from the antenna elements are effectively suppressed, maintaining the stability of the RF chain.
- Transmission coefficients and insertion loss (S21, S31): the transmission magnitude plots reveal a highly efficient power transfer. Magnitude: at 24 GHz, both S21 and S31 are measured at approximately -3.07 dB. Loss analysis: an ideal lossless 1-to-2 divider typically results in a -3 dB output, while the additional 0.07 dB accounts for the overall insertion loss, which includes both dielectric and conductor losses.
- Power balance: the close alignment of the S21 and S31 curves indicates an even distribution of power. This symmetry is essential for the 64-element array, as it guarantees consistent aperture illumination and helps avoid any distortion in the beam pattern.
- Output port isolation (S32, S23): the degree of isolation between the output ports is crucial for minimizing mutual coupling in large arrays. The simulation results indicate an isolation peak that surpasses -60 dB at the designated frequency. This level of isolation ensures that each antenna element within the 64-way corporate feed network functions independently, significantly lowering the likelihood of "scan blindness" or any degradation of the radiation pattern caused by internal coupling.
- Phase response and linearity: the phase response demonstrates a linear trend throughout the frequency spectrum. At 24 GHz, the phase difference between the two output ports is minimal. For a large-scale feed network, comprising six stages for 64-elements, it is vital to maintain this phase coherence to enable accurate beam forming and high directivity.

Figure 7 depicts the configuration of the Wilkinson power divider with resistor using ADS. The layout shown depicts a microstrip Wilkinson power divider created using ADS. This configuration features a $50\ \Omega$ input port alongside two $50\ \Omega$ output ports, which are interconnected via quarter-wavelength transmission lines that have a characteristic impedance of approximately $70.7\ \Omega$ ($\sqrt{2} Z_0$). To provide effective isolation in cases of impedance mismatch, a $100\ \Omega$ isolation resistor is placed between the output paths. The use of a circular design helps optimize size while still ensuring the necessary electrical length is achieved. This design guarantees an even distribution of power, effective impedance matching, and minimal insertion loss, making it well-suited for high-frequency applications, including feeding networks for antenna arrays operating at 24 GHz. The main parameters of the Wilkinson power divider are presented in Table 2.

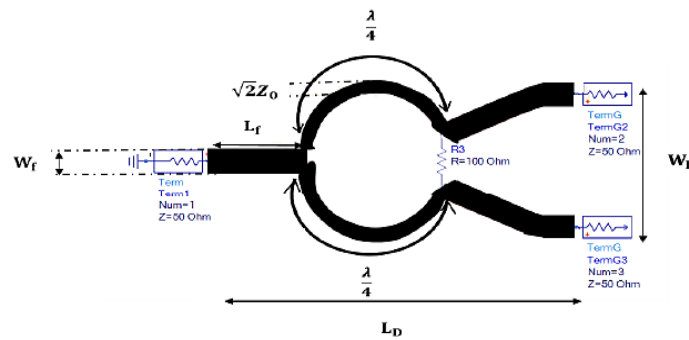


Figure 7. The layout of Wilkinson power divider with resistor

Table 2. The parameters of Wilkinson power divider

Parameters	Value (mm)
L_D	4
W_D	2.66
W_f	0.286
L_f	1

3.1.1. Co-simulation antenna array 2 elements design

Figure 8 displays the proposed co-simulation setup and layout for the 2-element antenna array:

- In Figure 8(a), the proposed design illustrates a co-simulated integration of a Wilkinson power divider along with a two-element microstrip patch antenna array intended for operation at 24 GHz. The Wilkinson divider plays a crucial role in providing equal power distribution to the two radiating elements and ensures that proper impedance matching is maintained at the input port. By incorporating a $100\ \Omega$

isolation resistor between the output branches, the design enhances isolation and reduces mutual coupling effects, thus contributing to the overall stability of the system. The microstrip feed lines are meticulously crafted with equal electrical lengths to ensure phase coherence between the antenna elements, which is vital for achieving a uniform and controlled radiation pattern. Additionally, the co-simulation method facilitates precise modelling of the interactions between the feeding network and the antennas, considering real impedance variations and electromagnetic coupling effects. This integrated design showcases high efficiency and is particularly well-suited for millimeter-wave applications, such as 5G communication systems and radar technologies.

- Figure 8(b) illustrates the simulated return loss (S_{11}) of the proposed structure across the 18–27 GHz frequency band. The results demonstrate a distinct dual-band operating characteristic. While the response remains highly reflective at the lower and upper extremities (18–22 GHz and 25–27 GHz), with a notable anti-resonance peak observed near 22–23 GHz, the circuit exhibits excellent impedance matching at the targeted frequencies. Specifically, two sharp resonance dips are achieved within the 23.5–24.5 GHz range, reaching a minimum return loss of approximately –20 dB. These deep troughs indicate that less than 1% of the incident power is reflected, thereby validating the effectiveness of the matching network for the desired dual-band application.

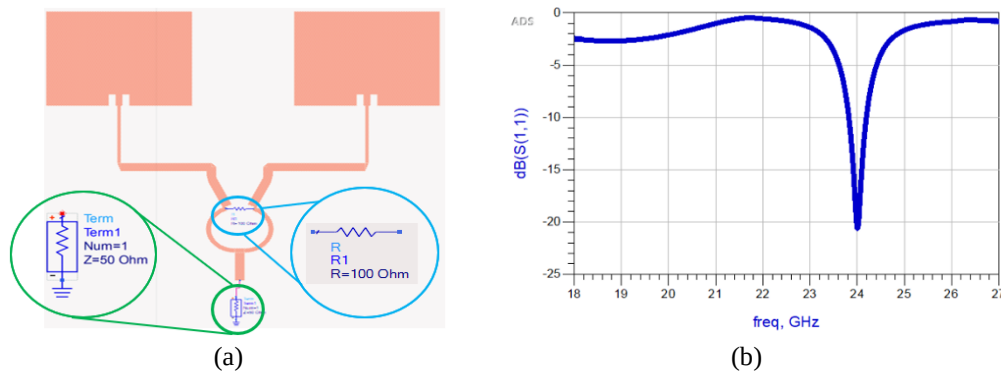


Figure 8. Two-element antenna array system; (a) co-simulation layout and schematic setup and (b) simulated reflection coefficient S_{11} response

3.1.2. 64-elements antenna array design with Wilkinson divider

Figure 9 depicts the completed co-simulation framework for the 64-element antenna array, which incorporates a Wilkinson power divider. This design aims to achieve the most efficient power distribution among all elements. The elements are positioned with a minimum separation of 0.5λ [28] to reduce interference and coupling effects, thus improving the array's overall performance. The configuration of the antenna array is organized in an 8×8 format, consisting of 8 elements per block.

The structure outlined here depicts a corporate feed network intended to energize a multi-element antenna array. This network utilizes a cascaded Wilkinson power divider arrangement, which guarantees equal power distribution and strong isolation among its branches. The input signal is systematically divided through several stages, leading to consistent amplitude and phase excitation across all antenna components. The microstrip transmission lines are meticulously crafted to ensure phase consistency and maintain impedance at 50Ω . Such a setup facilitates high gain and well-defined directional radiation patterns, making it appropriate for high-frequency uses like millimeter-wave antenna arrays. Nevertheless, the design must take into account factors such as insertion losses, fabrication tolerances, and the complexity of the layout, particularly at elevated.

The block of Wilkinson divider achieves uniform power distribution across all 64-elements with minimal losses and excellent impedance matching, even with resistors.

- Compact design: the hierarchical structure significantly reduces the layout complexity and maintains a compact footprint, making it suitable for high-density antenna arrays.
- Scalability and practicality: the modular approach allows scalability for larger arrays or higher-frequency applications, and the use of Rogers RO4830 substrate ensures low loss and high thermal stability at 24 GHz.
- Performance metrics: simulations validate the system's high efficiency, with low return loss ($S_{11} < -10$ dB).

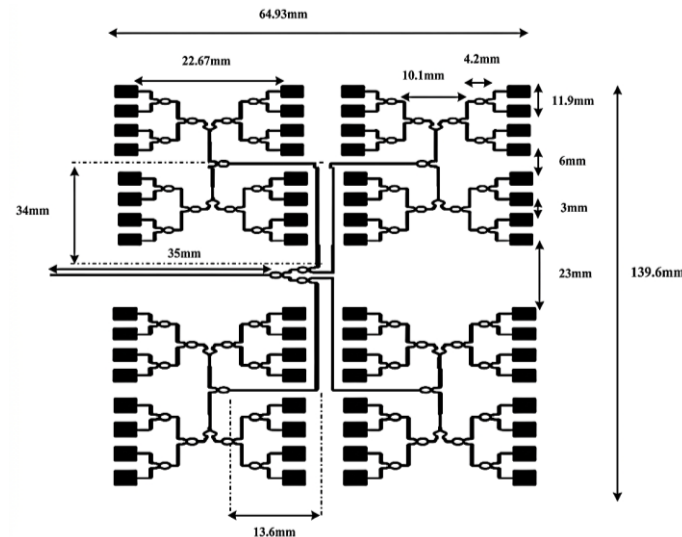


Figure 9. The geometry of the proposed antenna array 64-elements at 24 GHz

Figure 10 presents a comparison of the reflection coefficient (S_{11}) derived from ADS simulation alongside another electromagnetic solver across the frequency spectrum of 23 to 25 GHz. The results from both methods display a largely similar pattern, reinforcing the credibility of the proposed design. Notable alignment is seen in the location of the primary resonances, especially near 24 GHz, where both graphs reveal a significant return loss, suggesting effective impedance matching. Nevertheless, minor variations in magnitude and shifts in frequency are evident, potentially resulting from distinctions in the numerical techniques, meshing strategies, or boundary conditions employed by the two solvers. In summary, this comparison illustrates dependable performance and supports the validity of the simulation methodology.

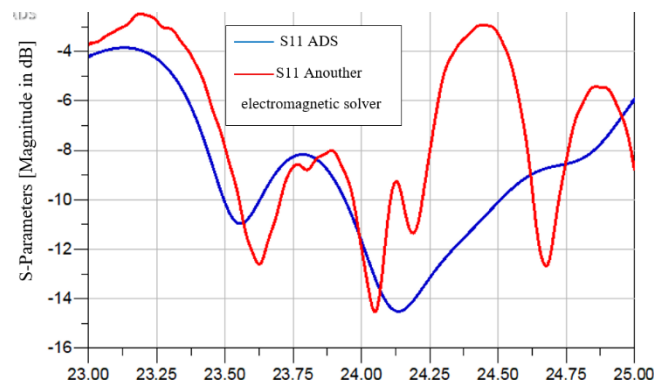


Figure 10. Cross-verification of the simulated S_{11} response using two distinct EM solvers across 23–25 GHz

The analysis comparing the S_{11} results from both ADS and CST simulations provides valuable insights into the proposed design's performance and accuracy at 24 GHz. In the ADS simulation, the reflection coefficient shows a relatively stable response, achieving a minimum of about -14 dB close to the target frequency. This suggests a satisfactory impedance matching with minimal reflected power. This characteristic primarily stems from ADS's circuit-based modelling approach, which assumes ideal transmission lines and lumped components while overlooking more complex electromagnetic effects. On the other hand, the CST results exhibit a slightly altered and more erratic S_{11} response, with minimum values ranging from -12 to -14 dB in the vicinity of 24–24.2 GHz. This variation arises from another electromagnetic solver full-wave electromagnetic modelling, which accounts for realistic factors such as parasitic coupling, radiation losses, discontinuities, and substrate influences. As a result, another electromagnetic solver offers a more precise depiction of the physical implementation, revealing additional losses and impedance mismatches that ADS fails to capture. The minor frequency shift observed between the

two outcomes is thus anticipated and underscores the influence of layout-specific effects and mutual coupling within the design. Overall, while both simulations indicate that the design functions close to the desired frequency band, the difference underlines the importance of full-wave validation to ensure dependable performance in real-world applications. To achieve better impedance matching ($S_{11} < -20$ dB) and enhance the system's overall efficiency, further refinement of the geometry and matching network is necessary.

The performance of the proposed Wilkinson power-divider-based antenna array is compared with recently published designs operating in the millimeter-wave frequency range, as summarized in Table 3. The comparison shows that recent studies [29] have mainly focused on improving the bandwidth, reducing the physical size, suppressing harmonics, or implementing compact Wilkinson power dividers for mmWave applications. For example, Saeed *et al.* [30] demonstrated a compact six-element antenna array operating at 28 GHz using an integrated Wilkinson-like power divider, while Wang *et al.* [31] reported a multi-stage Wilkinson power divider covering a wide frequency range that includes the 24 GHz region. Other recent works [32] have investigated large-scale phased-array architectures at frequencies close to the proposed operating frequency. In comparison, the proposed design operates at 24 GHz and employs an 8×8 hierarchical Wilkinson power-divider network to feed 64 planar antenna elements. The simulated results provide an input reflection coefficient of approximately -14 dB, an insertion loss of approximately -3.07 dB, and an output-port isolation of approximately -60 dB. Although some recently reported designs achieve lower return loss or lower insertion loss, they generally employ different architectures, technologies, or array configurations. The main advantage of the proposed design is therefore the combination of a 24 GHz operating frequency, a relatively large 64-element planar array, and a hierarchical Wilkinson feeding architecture while maintaining good impedance matching and very high port isolation. This comparison demonstrates the scalability and suitability of the proposed feeding network for compact mmWave radar and beamforming applications.

Table 3. Comparative analysis of Wilkinson power divider performance

Reference	Frequency (GHz)	S_{11} (dB)	Insertion loss (dB)	Isolation (dB)	Remarks
[29]	28	NR	-3.2	-19.21	Tapered 2-way Wilkinson divider for 5G/mmWave applications; simulated bandwidth 23.5–37.9 GHz.
[30]	28	≈ -20.7 measured	≈ -3	NR	Six-element mmWave antenna array with integrated Wilkinson-like divider; Rogers 3003; 5G application.
[31]	18.6–33.6	< -12	< 0.7	> 20	Broadband multi-stage Wilkinson power divider/combiner; covers the 24-GHz region.
[32]	26–32	> -11.8	< -0.85	> -18.7	4-way CMOS Wilkinson divider; compact mmWave phased-array application.
This work	24	≈ -14	≈ -3.07	≈ -60	64-element planar antenna array using an 8×8 hierarchical Wilkinson power-divider network for radar applications.

4. CONCLUSION

The 64-element antenna array, driven by an 8×8 hierarchical Wilkinson power divider functioning at 24 GHz, serves as a highly effective and adaptable solution for millimeter-wave applications, including 5G communications, radar technologies, and satellite communications. By employing a hierarchical design that breaks down the overall network into eight sub-networks, each supplying eight antenna elements, the approach significantly alleviates the complexity found in a traditional 64-way power divider. This organized method not only streamlines the manufacturing process and layout but also aids in reducing insertion loss while ensuring proper impedance matching throughout the network.

Moreover, the hierarchical Wilkinson setup guarantees even power distribution while maintaining phase coherence, which is crucial for precise beamforming. When combined with the antenna array, this system can generate high gain and well-defined radiation patterns, facilitating accurate directional transmission and reception. Such attributes are particularly vital in millimeter-wave systems, where high propagation losses necessitate effective energy focusing. Another significant benefit of this design is its compactness and modularity. The implementation of repeated 8-element blocks simplifies optimization, testing, and the potential for scaling up to larger arrays. Although the current setup already exhibits strong performance, future enhancements could involve the addition of isolation resistors within the Wilkinson branches to improve port-to-port isolation and mitigate unwanted coupling effects. Exploring advanced optimization strategies, such as electromagnetic tuning or artificial intelligence-based design approaches, could further enhance efficiency and bandwidth. This research holds particular significance for applications operating in the vicinity of 23.6 GHz and 25.2 GHz, where precise impedance matching and consistent performance are essential. These frequency ranges are commonly utilized in contemporary wireless

communication systems, automotive and surveillance radar, as well as high-frequency sensing technologies. In summary, the proposed design lays a solid foundation for next-generation high-frequency systems by effectively balancing performance, scalability, compactness, and manufacturability.

While the proposed 64-element antenna array utilizing a Wilkinson power divider at 24 GHz demonstrates low insertion loss (~ 3.07 dB) and excellent isolation (~ 60 dB), it also presents several design challenges. One major limitation of this research is its dependence on full-wave electromagnetic simulations, indicating that future efforts will prioritize the physical construction and experimental testing of the prototype. Additional obstacles include the complexity of fabrication, the expense associated with ultra-thin substrates (0.127 mm Rogers RO4830), and the sensitivity to variations in dielectric constant tolerances. Moreover, although the dual-band functionality provides flexibility for multi-band radar and communication applications, achieving stable patterns across larger arrays necessitates careful phase control. To build upon these findings, future research will pursue concrete avenues for system enhancement, including the integration of active components (such as power amplifiers) to boost output power, further structural miniaturization for portable radar devices, and the extension of the feeding network toward multi-band operations. In summary, this study offers a methodologically sound and reproducible approach for advancing millimeter-wave and 5G/6G antenna systems.

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C : **C**onceptualization

M : **M**ethodology

So : **S**oftware

Va : **V**alidation

Fo : **F**ormal analysis

I : **I**nterpretation

R : **R**esources

D : **D**ata Curation

O : **O**rganizing - **O**riginal Draft

E : **E**ditorial - **E**ditorial Review & **E**ditorial

Vi : **V**isualization

Su : **S**upervision

P : **P**roject administration

Fu : **F**unding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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