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REGULAR ARTICLE

Design and Optimization of Millimeter-Wave Antenna at 27/34 GHz for Next-Generation Communication Systems

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Design and simulation of a compact Millimeter-wave (mm-Wave) antenna is presented for next-generation wireless communication systems applications. The proposed antenna is designed on a FR4 substrate with a relative permittivity of 4.4 and a thickness of 1.6 mm, ensuring reduced dielectric loss at higher frequencies. The antenna structure is optimized to operate at 27/34 GHz, a key band for 5G NR applications, while maintaining a compact size of 5 × 4 × 1.6 mm³. Simulation studies were carried out using HFSS soft-ware, focusing on achieving wide impedance bandwidth, and stable radiation performance. The designed antenna achieves a reflection coefficient (S_{11}) < – 10 dB over the operating frequency range and which is operating under dual bands, offering an impedance bandwidth of 3 GHz (26.43-29.43 GHz) under band 1 and 1.8 GHz (33.82-35.62 GHz) under band 2. The antenna provides a peak gain of 3.6 dB and a good radiation efficiency, making it highly suitable for energy-efficient transmission. The compact geometry and optimized performance make the proposed antenna a promising aspirant for integration into modern 5G cellular networks to provide high speed and low latency data transmission, Internet of Things (IoT) modules, and high-data-rate mm-Wave communication systems. This study highlights the importance of compact antenna structures that achieve high performance without compromising bandwidth, gain, or efficiency, enabling re-liable deployment in 5G, 6G, IoT, V2V, V-I communication and high-speed wireless LANs applications.

Keywords: Compact, mm-wave, Reflection-coefficient, 5G, Dual band, Resonating frequency.

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1. INTRODUCTION

The continuous advancement of the mobile communication sector has led to the development of innovative handset designs aimed at aligning with future market demands. Modern smartphones are now capable of supporting multimedia applications, video streaming, and high-speed internet browsing features primarily enabled by the Long-Term Evolution (LTE) or 4G standard. The widespread adoption of 4G technology has resulted in portable electronic devices such as tablets, notebooks, and laptops operating across LTE frequency bands, specifically 700 MHz, 2400 MHz, 2600 MHz and 3400 MHz although several LTE antenna configurations have been proposed in recent studies [1], many of them lack the flexibility required to adapt to newly emerging lower-frequency operational ranges. With the rapid growth of multimedia applications, there is a growing need for higher data rate communication systems, supported by progress in Nano electronic components that provide improved computational power. However, the heavy utilization of lower frequency bands by multiple communication systems has caused significant congestion. Consequently, industry and research communities are exploring alternative spectral resources. Among these, the unlicensed Ultra-Wideband (UWB) range between 3.1 and 10.6 GHz has attracted attention, especially for indoor wireless scenarios due to its short-range characteristics [2]. UWB antennas are increasingly recognized in both academia and industry for their wide bandwidth and efficiency in wireless communication systems. A wide variety of antenna designs and methodologies have been proposed to improve bandwidth performance and achieve reliable operation across the UWB range [3]. Despite this advantage such as broad bandwidth, low power consumption, and high data rates the majority of UWB antennas still operate within limited frequency ranges, typically between 700 and 2600 MHz [4]. These designs often lack the flexibility to extend their functionality beyond this band. As the communication industry transitions toward the fifth generation (5G) of mobile networks, new challenges and expectations have emerged. Future communication paradigms are anticipated to support not only faster mobile broadband but also massive machine-type communication and real-time tactile internet services. These demands will require

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systems capable of extremely high data capacity, minimal latency, and robust reliability.

Current 4G networks, which were initially optimized for moderate to high data rates, are insufficient to handle the vast diversity and volume of upcoming traffic. It is projected that cellular systems will need to deliver up to a thousand times more capacity than existing infrastructures, pushing conventional systems to their limits. To meet these requirements, expanding the available spectrum becomes crucial, as traditional capacity enhancement strategies can yield only incremental improvements. Consequently, the 5G standardization efforts are focusing on the utilization of higher frequency spectra, specifically within the millimeter-wave (mm Wave) range from 20 to 300 GHz, where substantial unused bandwidth exists. The mm Wave spectrum has been identified as a fundamental component of 5G networks, capable of supporting multi-gigabit data rates necessary for advanced applications such as high-definition and ultra-high-definition video streaming [5]. From both regulatory and technological standpoints, initial 5G spectrum allocations are expected to fall within the 24-57 GHz range, with the 25.25-29.5 GHz and 36-40.5 GHz bands being prioritized as primary targets for deployment [6]. Realizing efficient 5G implementation will, therefore, necessitate the design of compact yet highly efficient antennas [7]. To address these evolving requirements, this work re-engineers a conventional printed monopole antenna design, introducing an optimized wideband configuration aimed at improving bandwidth, efficiency, and minimizing interference in the mm Wave region [8]-[16]. The proposed compact monopole antenna exhibits superior performance within the 5G frequency band, aligning with the ranges identified by the World Radio Communication Conference 2019 [9], making it a promising candidate for Next-generation applications.

Millimeter wave wireless communication characters a significant advancement in wireless technology for ultra-fast, low latency, high capacity 5G/6G, high frequency, high bandwidth, large scale connectivity and compact size. Millimeter technology is very crucial for high data rate by yutao yang et.al [17]

2. ANTENNA CONFIGURATION

The Fig. 1 illustrates the dimensions of the proposed mm-wave antenna. Fig. 1 (a) shows front view and Fig. 1 (b) shows back view of the proposed model. The configuration employs one circular planar radiator, which having a patch radius (r) of 1.6 mm, excited through line feeding with parameters: feed width (F_W) = 0.75 mm, and feed length (f_L) = 1.65 mm. The radiating element is mounted on an FR-4 substrate characterized by a dielectric constant of 4.4, loss tangent of 0.02, and a thickness of 1.6 mm. The substrate dimensions are defined as length (S_L) = 5 mm, width (S_W) = 4 mm, and height (H) = 1.6 mm, while the partial ground plane measures of $2.5 \times 4 \times 1.6$ mm^2. The length of the ground plane $G_L = 5$ mm and width of the ground plane $G_w = 2$ mm as given in the below Fig. 1. To achieve improved impedance matching, the elements are carefully optimized and arranged symmetrically. The resulting design provides a bandwidth with $|S_{11}| \leq -10$ dB.

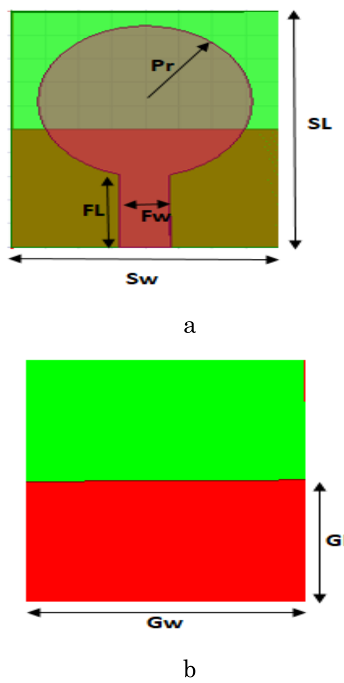


Fig. 1 – Proposed antenna geometry: (a) Front view (b) Back view

3. DESIGNIG METHODOLOGY AND STUDY

The design process of the proposed antenna with the analysis of a single radiating element configuration. Insights obtained from the single-element study were instrumental in achieving an optimized overall design. In the one element system, the radiator is positioned optimally to enhance bandwidth. With this configuration, the antenna operates efficiently across dual band frequencies, band 1 resonates at 27.93 GHz and offering a substantial bandwidth of 3 GHz and band 2 is resonating at 34.75 GHz with 0.75 GHz. This wideband coverage includes the 5G high-band spectrum/ mm-wave (24-40 GHz) and 6G spectrum, delivering strong signals with adequate gain at port. The simulated results confirm optimized performance tailored for wireless communication. As illustrated in Fig. 2, the reflection coefficient ($|S_{11}| \leq -10$ dB) demonstrates expanded bandwidth that successfully covers two mm-wave bands and one 5G high-band, ranging from 26.43 GHz to 29.43 GHz under band1 and ranging from 33.82 GHz-35.62 GHz under band 2. Within this range, the 5G high band and 6G band are fully supported, making the design particularly effective for 5G high-band applications.

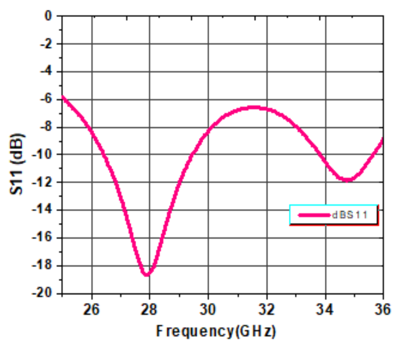


Fig. 2 – *S*-Parameter variations of antenna

Additionally, the antenna achieves improved reflection coefficient of – 18.64 dB and – 11.84 dB across the operating band 1 and band 2 respectively. Overall, the antenna operates across three frequency bands, ensuring compatibility with 5G, 6G, and 5G high-band applications. The supported spectrum is vital not only for advanced 5G but also for emerging high speed, smart city deployments, short range wireless communications, radar, airport security scanners, high power microwave applications for practical accelerators and other next-generation wireless technologies.

Table 1 – Simulated antenna parameter values at port 1

Antenna Parameters	**Resonating Frequency (27.93 GHz)**	**Resonating Frequency (34.75 GHz)**
Bandwidth (GHZ)	3	1.8
Return loss (dB)	– 18.64	– 11.84
Gain (dB)	3.5	3.6

Table 1 presents the simulated results of the proposed mm-wave antenna. The antenna is well operating and it is providing good bandwidth of 3 GHz under band 1 and 1.8 GHz under band 2. So, it is highly suitable for 5G NR cellular networks to provide high speed and low-latency data transmission.

3. RESULTS AND DISCUSSION

Using HFSS software, the proposed mm wave antenna has been carefully designed and optimized. The structural layout of the antenna is presented in Fig. 1, and the simulated *S*-parameter outcomes are shown in Fig. 2. The results confirm that the antenna achieves a wide operating bandwidth, effectively covering the 5G band and extending across 6-8 GHz, which encompasses 5G/6G Wi-Fi frequencies for next-generation wireless communication. This demonstrates its suitability for 5G/6G applications.

Another key metric for evaluating mm-wave antenna performance is the VSWR of the antenna, illustrated in Fig. 3. The results show excellent agreement, with the good impedance matching and the value is varying from 1-2 during the operating frequency. The calculation is done by using the given Eq. 1 as fallows

$$VSWR = 1 - |\Gamma|/1+|\Gamma| \quad (1)$$

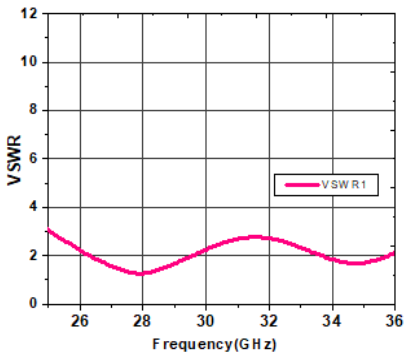


Fig. 3 – Simulated VSWR of proposed mm-wave antenna

The main metric for evaluating mm-wave antenna performance is the gain of the antenna, the total gain of the antenna is illustrated in Fig. 4. The results show excellent agreement, with the adequate gain and it is varying from 3.5 to 3.6 dB during operating frequency. The calculation is done by using the given equation 2 as given below.

$$\text{Gain (G)} = \eta \times D \quad (2)$$

The gain of the system depending on the directivity and the antenna radiation efficiency of the radiating element.

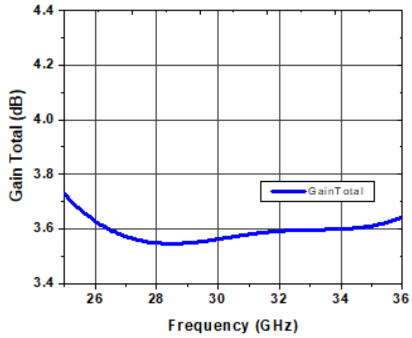


Fig. 4 – Simulated Total Gain of mm-wave antenna

Directivity measures how well antenna focuses the energy in one particular direction compared to the isotropic antenna. If the antenna shows more directivity, then the gain of the antenna will also increase. So, both are directly proportional to each other. Along with directivity, radiation efficiency is also play a good role to improve the system gain.

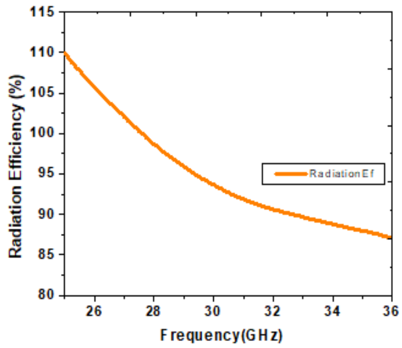


Fig. 5 – Simulated radiation efficiency of proposed radiator

The radiation efficiency of the proposed mm-wave antenna as illustrated in Fig. 5. The maximum efficiency of the system is more than 87.5 % during the operating band 1 and band 2.

The simulated 2D radiation patterns are presented in Figs. 6, 7. When $\Phi = 90°$, the mm-wave antenna exhibits stronger radiation along – 180°. For $\Phi = 0°$, maximum radiation is observed at – 120° and – 150° while nulls occur at 0°. The 3D radiation distribution at the resonant frequency of 33.75 GHz, shown in Figs. 6, 7, demonstrates a broadside pattern. Fig. 8 shows the 2D radiation patterns of designed antenna at $\Phi = 90°$ and $\Phi = 0°$. It is also observed that the peak radiation is directed at $\theta = -150°$ and – 180°. Such radiation characteristics confirm the antenna's suitability for next-generation wireless communication applications. Additionally, the radiation pattern indicating bidirectional beam formation.

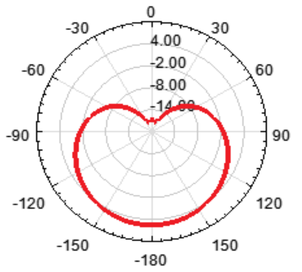


Fig. 6 – 2D Radiation pattern of mm-wave antenna at $\Phi = 90°$

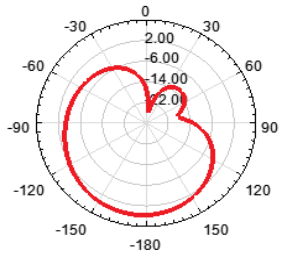


Fig. 7 – 2D Radiation pattern of mm-wave antenna at $\Phi = 0°$

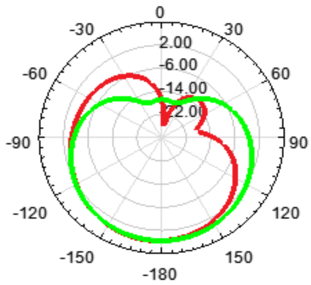
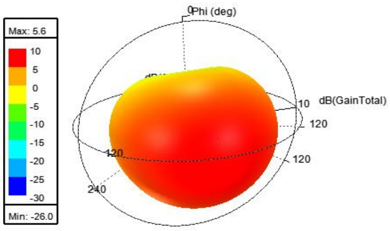
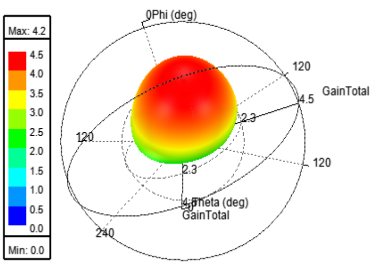


Fig. 8 – 2D Radiation pattern mm-wave antenna at $\Phi = 0°$ and $\Phi = 90°$



a



b

Fig. 9 – 3D Radiation pattern of mm-wave antenna (a) at 27 GHz, (b) 34 GHz

The simulated 3D radiation pattern of the designed mm-wave antenna is illustrated in Fig. 9, showing good radiation at port. The 3D radiation plots indicate that the peak radiated power is mainly oriented along the negative *X*-axes as well as the positive and negative *Y*-axes. The maximum gain is 5.6 dB achieved at 27 GHz. The maximum gain is 4.2 dB attained at 34 GHz.

Table 2 provides a comparative assessment of the proposed mm-wave antenna with other reported designs, considering antenna size, parameters, and key mm-wave performance metrics.

Table 2 – Comparison table proposed (PD) with Existed method

Ref.	Size mm^2	B.W. (GHz)	Gain (dB/dBi)
[14]	6 × 6	1.3	–
[15]	8 × 8	2.3	6.6
[16]	14 × 12	2.6	1.27
P.D.	5 × 4	3 1.8	3.5 3.6

The proposed antenna received more bandwidth and is 3 GHz under operating band1 and 1.8 GHz under operating band 2 and the gain of the antenna is 3.5 dB and 3.6 dB under operating band 1 and band 2 respectively compared to the existing methods. The size of the antenna is also reduced as compared to the existing methods taken at table references. The proposed antenna is compact as well as high bandwidth for high data transmission.

4. CONCLUSION

This study presents the design and analysis of an mm-wave antenna intended for next-generation wireless communication systems. The antenna was modeled and optimized in HFSS using a line-feeding configuration. Experimental results confirm a measured bandwidth of 3 GHz under operating band1from 26.43-29.43 GHz, with maximum return loss of 18.64 dB across the band1 and obtained 1.8 GHz from 33.82-35.62 GHz, with return loss of 11.84 dB during band 2 operating frequency. The proposed design is simple to implement, provides efficient feeding, and demonstrates excellent mm-wave characteristics. These findings validate the antenna's suitability for in 5G, 6G, IoT, V2V, V-I communication and high-speed wireless LANs applications. The future scope of proposed mm-wave antenna is used for massive data transmission, smart cites, automation and AI integration.

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Проєктування та оптимізація міліметрової антени на частоті 27/34 ГГц для систем зв'язку наступного покоління

Varakumari Samudrala[1], Ch. Aparna[1], B.T.K. Chaitanya[1], V. Amrutha[1], G. Nikhil Babu[1], B. Prasanna[1], Sai Sandeep B[2]

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Представлено компактну антену міліметрового діапазону (мм-Wave) для застосування в системах бездротового зв'язку наступного покоління. Запропонована антена розроблена на підкладці FR4 з відносною діелектричною проникністю 4,4 та товщиною 1,6 мм, що забезпечує зменшення діелектричних втрат на вищих частотах. Структура антени оптимізована для роботи на частоті 27/34 ГГц, ключовому діапазоні для застосувань 5G NR, зберігаючи при цьому компактний розмір 5 × 4 × 1,6 мм^3. Моделювальні дослідження проводилися з використанням програмного забезпечення HFSS, зосереджуючись на досягненні широкої смуги пропускання імпедансу та стабільних характеристик випромінювання. Розроблена антена досягає коефіцієнта відбиття (S11) < – 10 дБ у робочому діапазоні частот і працює в двох діапазонах, пропонуючи смугу пропускання імпедансу 3 ГГц (26,43-29,43 ГГц) у діапазоні 1 та 1,8 ГГц (33,82-35,62 ГГц) у діапазоні 2. Антена забезпечує пікове підсилення 3,6 дБ та хорошу ефективність випромінювання, що робить її дуже придатною для енергоефективної передачі. Компактна геометрія та оптимізована продуктивність роблять запропоновану антену перспективним кандидатом для інтеграції в сучасні стільникові мережі 5G для забезпечення високошвидкісної передачі даних з низькою затримкою, модулів Інтернету речей (IoT) та високошвидкісних систем зв'язку міліметрового діапазону. Це дослідження підкреслює важливість компактних антенних структур, які досягають високої продуктивності без шкоди для пропускної здатності, коефіцієнта підсилення або ефективності, що дозволяє надійно розгортати її в застосунках 5G, 6G, IoT, V2V, V-I зв'язку та високошвидкісних бездротових локальних мережах.

Ключові слова: Компактний, мм-хвиля, Коефіцієнт відбиття, 5G, Дводіапазонний, Резонансна частота.