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REGULAR ARTICLE

Design of Analysis of a T-Shaped mmWave Antenna on 47 GHz in 6G Application

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This research presents a small T-shaped microstrip antenna that works at millimeter-wave frequencies. It is meant for future 6G wireless communication networks. The antenna is made to pick up signals around 47 GHz and 75 GHz, and these are good frequencies for high-speed limited-range connectivity and dense small-cell deployments in networks that go beyond 5G. The proposed design consists of a T-shaped radiating patch that is stimulated by a microstrip supply line on a minimal-loss dielectric substrate. This creates a basic planar structure that can be easily integrated with RF front-end circuitry. The T-shaped component and the ground plane are formed in a way that makes impedance matching easier and gives you useful bandwidth in the frequency ranges you want. The antenna is still small enough that a single element can be used as a building block in millimeter-wave arrays or Massive MIMO systems needed to meet the throughput and connectivity needs of new 6G scenarios. Full-wave simulations are used to test the design's effectiveness in regards to return loss, voltage standing wave ratio (VSWR), gain, as well as radiation patterns at both working bands. The results show that the suggested antenna has good matching as well as directional radiation properties while taking up less space. This shows that it could be used in small, fast 6G wireless devices and modules.

Keywords: mmWave antenna, T-shaped patch, 47 GHz band, 75 GHz frequency, High gain performance.

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1. INTRODUCTION

The demand for very high rates of data, exceptionally low latency, and a lot of connectivity between devices across a wide range of applications, including immersive communications, smart transportation, as well as automated manufacturing, is driving the rapid progress toward sixth-generation (6G) wireless networks [1]. To achieve these aims, re-searchers are extending beyond standard sub-6 GHz spectrum to millimeter-wave (mmWave) and even terahertz bands, in which very broad neighboring bandwidths are accessible [2]. Functioning in both of these higher frequency bands brings substantial route loss and air absorption, and these makes effective, powerful, and portable antenna layouts a vital feature of upcoming 6G transceivers. Within the mmWave zone, frequency windows between 47 GHz and the 71-76 GHz range have drawn attention for large- capacity backhaul, device-to-device connectivity, and extremely dense small-cell installations [3]. The aforementioned frequency bands can handle multi-gigabit-per-second communications but need highly directed beams and effective beam control to avoid propagation interruptions and interference effects [4]. As a consequence, antenna structures must concurrently offer sufficient gain, wide useable bandwidth, and reliable radiation properties while staying lightweight enough for incorporation in portable or embedded applications. Micro-strip patch antennas are extensively investigated for such applications because that they provide a compact profile, simplicity of production, and uncomplicated integration via RF and hybrid signal circuitry on a single substrate. nevertheless, a basic rectangular patch generally suffers from restricted bandwidth and lower effectiveness at mmWave frequencies, where conductor as well as dielectric losses are more important [5-9]. To solve these restrictions, numerous recent works use curved patches, slots, and parametric components to control the present propagation and produce multiple resonance behavior without dramatically extending the antenna footprint. Within the possible geometries, T-shaped and stub-loaded topologies allow extra several degrees of freedom for impedance alignment and resonance tuning in the higher microwave and mmWave frequencies. By carefully adjusting the parameters of the T-formed arm and therefore position in relation to the feed line, it can be feasible to manage the efficient electrical width and produce

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multiple or widened resonant modes [10-13]. This method can assist with better impedance bandwidth as well as enhanced gain, rendering it desirable for small 6G front-ends, particularly where antenna arrays or multiple-input–multiple-output (MIMO) setups are needed. Present-day literature on mmWave along with 6G antennas includes a broad variety of forms such as slotted, tooth-shaped, as well as hexagonal patches each improving distinct elements such band-width, circular polarization, or as array effectiveness. Regardless, there is a demand for basic one or multiple-element antenna designs that can function around chosen bands, for instance at 47 GHz and across 75 GHz, while offering adequate spectrum gain and radiation functionality suited for incorporation in lightweight user devices or miniature terminals. A T-shaped mmWave microstrip antenna which targets these frequencies can fill this gap by delivering a harmonious equilibrium between structural ease of use and better electromagnetic efficiency for 6G-oriented applications. The proposed design of the antenna is explained with the flowchart representation in the section 2. The design specification and its parameter calculation is detail explained in the section 3. The results and its discussion is explained in detail in the section 4 analysis. The final conclusion of the proposed research is explained in the section 5 in detail.

2. DESCRIPTION OF PROPOSED ANTENNA

2.1 Design Parameter and Its Specification

The mm Wave Patch Array Antenna.

The suggested antenna is depending on a T-shaped micro strip patch designed to function in the millimeter-wave band at roughly 47 GHz and 75 GHz for 6G communication. A lower-loss dielectric barrier substrate like as FR-4 is utilized as the foundation, and a microstrip supply line is attached right away to the T-shaped radiating component to generate the appropriate modes. The arms as well as stem of the T-shape are designed consequently that the efficient electrical length maintains resonance at either desired frequency whereas maintaining the general structure streamlined. By meticulously choosing the substrate size, patching dimensions, and input position, the design seeks to produce good impedance matching, adequate bandwidth, as well as directional radiation patterns in both bands. This single small element can therefore be utilized by itself or as a unit cell in bigger arrays for high-capacity 6G lines.

The flowchart Fig. 1 illustrates a systematic approach for constructing the suggested T-shaped mmWave antenna for 6G operation. The approach begins with establishing design goals, such as dual-band operating at 47 GHz and 75 GHz, small mechanical dimensions, and functionality necessities such as suitable matching and gain. depending on these requirements, a corresponding substrate along with topology are selected here a FR-4 dielectric with a T-shaped microstrip patch fed by a microstrip line. Initial dimensions for the patch and feed are then generated using typical microstrip antenna design equations, offering a beginning point for modelling. The antenna structure is later simulated in a full-wave electromagnetic simulator, during which the substrate, ground plane, T-shaped radiator, as well as supply line are correctly described. Simulation tests are carried out to gather critical outcomes such as S_{11}, VSWR, gain, and radiation patterns throughout the appropriate frequency range. utilizing these outcomes, the design begins an iterative optimization loop in that patch arm lengths, stem arrangement, feed positioning, and ground arrangement are modified to optimize impedance matching as well as radiation properties at both bands. Once the response fulfills the defined requirements, the optimal geometry is finished, and the appropriate parameters, plots, and functionality metrics are recorded for incorporation in the proposed system. Table 1 lists each individual patch component specifications.

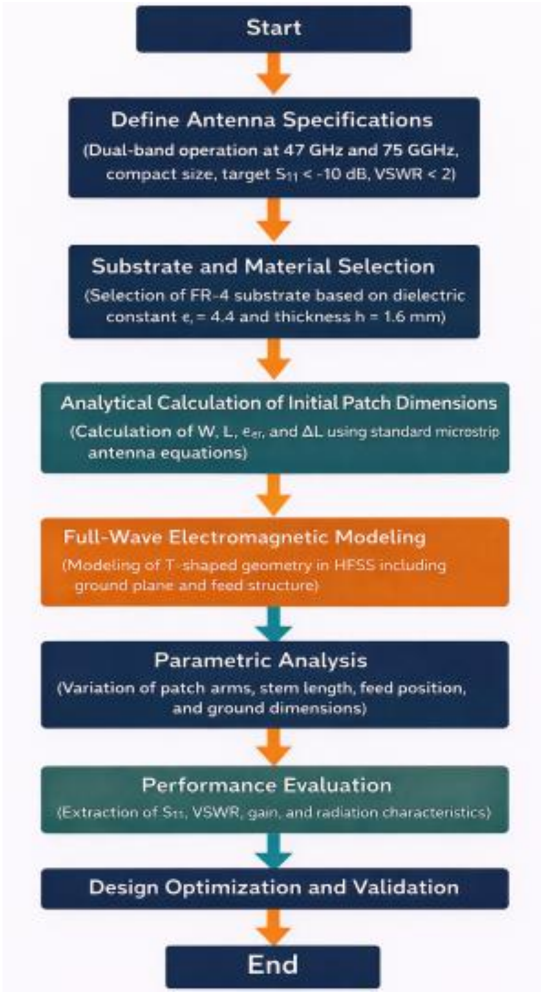

Fig. 1 – Design methodology flowchart for the proposed T-shaped mmWave antenna for 6G applications at 47 GHz

Table 1 – Individual Patch Element Dimensions

Parameter	Value	Unit
Substrate material	FR-4	–
Dielectric constant (εr)	4.4	–
Substrate thickness	1.6	mm
Overall antenna size	22.8 × 22.8	mm
Operating bands	47 / 75	GHz
Min. S11 at 47 GHz	< −10	dB

Min. S11 at 75 GHz	< −10	dB
VSWR at both bands	< 2	–

The selected antenna array setup is predicated on operational frequencies of 47 GHz and 75 GHz. For 6th-generation millimeter-wave MIMO networks of communication requiring fast transmissions and minimal system installations, 75 GHz is a good frequency. The technology was made to get the most gain, effectiveness and beam guiding possible.

The table shows the most important technical and operational factors of the suggested T-shaped mmWave antenna that was made for 6G use. First, it gives a brief overview of the physical setup, such as the FR-4 substrate, its dielectric value, thickness, as well as the size of the antenna as a whole. The operating frequencies around 47 GHz and 75 GHz are then shown, alongside with the fundamental matching targets, which are S_{11} beneath − 10 dB as well as VSWR below two at both resonances. There is also a minimal peak gain amount shown to illustrate which the antenna can send out enough radiation for high-powered communications. At last, the table lists the electromagnetic simulation software that was utilized, which makes it apparent what the design process along with the evaluation environment comprised.

3. TECHNICAL ANALYSIS OF THE ANTENNA

3.1 Patch Antenna Design Principles

The technical analysis of the proposed antenna shows that a T-shaped microstrip patch on an FR-4 substrate can effectively provide dual-band operation around 47 GHz and 75 GHz for 6G applications. The modified T-shaped geometry reshapes the surface current distribution compared to a conventional rectangular patch, allowing dual resonances to be obtained without a significant increase in overall dimensions. Input performance, assessed through return loss and VSWR, confirms good impedance matching, with S11 kept below – 10 dB and VSWR within acceptable limits across both operating bands, indicating efficient power transfer. The far-field radiation patterns exhibit a broadside main lobe with directional characteristics and adequate gain, which is suitable for short-range, high-data-rate millimeter-wave links. Despite the intrinsic loss of FR-4 at such high frequencies, the optimized structure maintains acceptable radiation efficiency and bandwidth, while parametric analysis of the patch arms, stem length, and feed position highlights how these parameters control resonance frequencies and matching, supporting the final optimized design for integration in future 6G front-end modules.

The rectangular conductive patch antenna is centered on the TM_{10} electromagnetic radiation pattern of 47 GHz as well as 75 GHz frequency. The outermost regions of the radiating element are identified by applying standard mathematical methods (1) to (3) that are used to build patch antennas.

3.2 Effective Dielectric Constant (ε_{eff}):

$$\varepsilon_{eff} = (\varepsilon_r + 1)/2 + (\varepsilon_r - 1)/2 \times [1 + 12h/W]^{(-1/2)} \quad (1)$$

For the given parameters:

$$\varepsilon_{eff} \approx 3.44 \text{ (calculated for } W = 15.21 \text{ mm, } h = 1.6 \text{ mm, } \varepsilon_r = 4.4) \quad (2)$$

3.3 Effective Length Extension (Δ*L*):

$$\Delta L = 0.412h \times (\varepsilon_{eff} + 0.3)(W/h + 0.264)/[(\varepsilon_{eff} - 0.258)(W/h + 0.8)] \quad (3)$$

3.4 Resonant Frequency Validation

The propagating element's longitudinal diameter of 11.32 mm translates to almost half of the efficient wave-length at the 75 GHz operational frequency, supporting the designed frequency aim.

4. RESULTS AND DISCUSSION

The efficiency of the suggested T-like mmWave antenna is examined by full-wave modeling, and the important conclusions are provided in this part. The evaluation concentrates on the input properties, like as return loss as well as VSWR, to establish adequate impedance matching for the desired 47 GHz and 75 GHz bands. In furthermore, the electromagnetic performance of the antenna is investigated using 3D patterns along with gain plots to determine its compatibility for 6G millimeter-wave communications. The results generated are contrasted with the basic design objectives to validate that the lightweight structure may offer sufficient bandwidth, gain, and radiation efficiency for futuristic ultra-fast wireless applications.

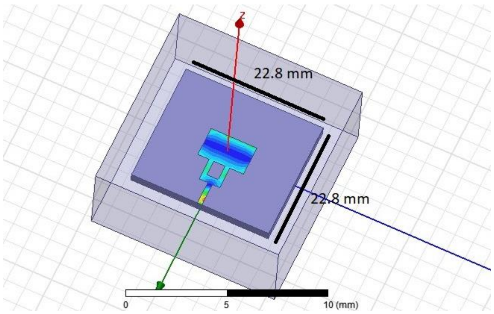

Fig. 2 – Proposed T-Shaped mmWave antenna geometry

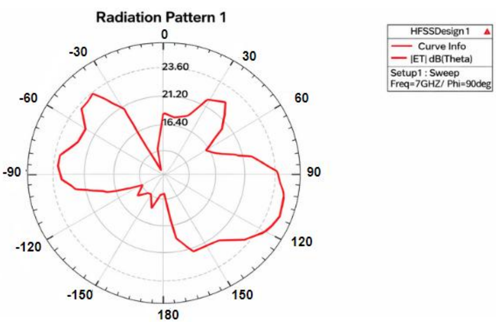

Fig. 3 – Simulated Radiation Pattern

This Fig. 2 depicts the thorough design of the T-shaped microstrip antenna developed for functioning in the 47 GHz and 75 GHz frequency bands. The framework comprises of a T-shaped radiating patch coupled to a microstrip supply line, built on a planar substrate with specified general dimensions. The graphic emphasizes the essential physical characteristics and the configuration of the ground along with patch elements, and this collectively lead to the appropriate electromagnetic efficiency in millimeter-wave applications.

This Fig. 3 illustrates the modeled reflection coefficient (S_{11}) of the suggested T-shaped antenna over a large frequency band. The pronounced peaks in the S_{11} curve correlate to resonant frequencies during which the antenna attains excellent impedance matching, demonstrating optimal functioning near 47 GHz and 75 GHz. The – 10 dB bandwidths surrounding these resonances illustrate the antenna's applicability for broadband 6G communication applications.

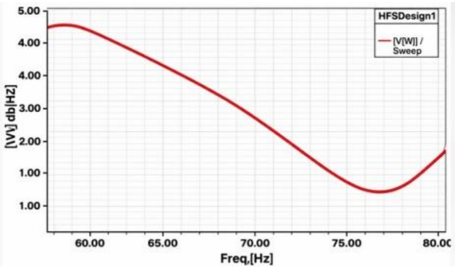

Fig. 4 – Voltage Standing Wave Ratio (VSWR) as a function of frequency

The Fig. 4 depicts the simulated VSWR for the T-shaped microstrip antenna. Results that are near to unity across the intended frequency bands demonstrate that the antenna retains modest mismatch losses at both resonances. The large frequency ranges with VSWR < 2 determine the design's efficient impedance matching over the targeted mmWave band.

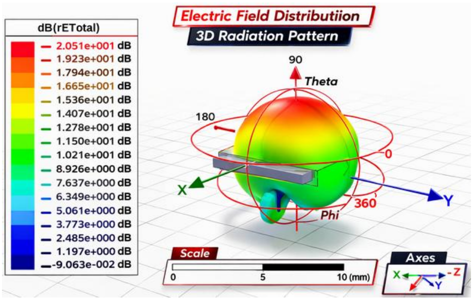

Fig. 5 – 3D radiation pattern at the first resonance

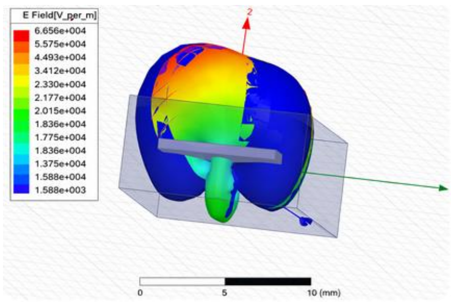

Fig. 6 – 3D radiation pattern at the second resonance

This 3-dimensional graphic depicts the simulated far-field electromagnetic radiation distribution of the antenna at the lowest resonance, around 47 GHz. The radiation segment shape and primary beam direction are displayed in the Fig. 5, exhibiting the antenna's directed operation and demonstrating its possibilities for intended signal transmission in 6G networks.

Similar to the preceding figure, this Fig. 6 depicts the antenna's generated 3D radiation properties at the greater resonance frequency, near to 75 GHz. The design enables the evaluation of directivity and beam-width across both operating bands, emphasizing the structural reliability and appropriateness for multiple-band operations. Similar to the preceding figure, this Fig. 6 depicts the antenna's simulated 3D radiation features at the greater resonance frequency, near to 75 GHz. The configuration enables comparison of directivity as well as beam-width across the two operating bands, emphasizing the structure's reliability and appropriateness for multiple-band operations.

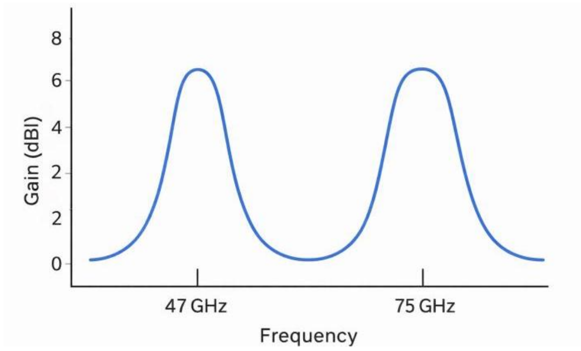

Fig. 7 – Simulated Electromagnetic field antenna gains versus frequency

This Fig. 7 displays the simulated electromagnetic field antenna gain of the suggested T-shaped antenna. The gain stays constant over the two primary operating spectrum bands, producing peak levels adequate for millimeter-wave front ends in sophisticated wireless systems. The efficiency curve underlines the reliability of the layout in generating adequate electromagnetic power for ultra-fast 6G communications.

5. CONCLUSION

The research showed a compact T-shaped microstrip antenna intended to function at 47 GHz and 75 GHz for developing 6G millimeter-wave applications. By employing FR-4 as the substrate and modifying the proportions of the T-shaped patch as well as feed, the suggested structure accomplished satisfactory impedance matching and directional radiation in simultaneously target bands. The simulated findings for return loss, VSWR, along with gain show that the antenna can deliver steady effectiveness while keeping a compact structural footprint, thereby rendering it appropriate for incorporation in dense interface modules. In general, the suggested structure provides a simple as well as scalable technique that may be modified to array setups to fulfill the tremendous data-rate and capacity needs of future 6G wireless systems.

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Розробка та аналіз Т-подібної антени міліметрового діапазону на частоті 47 ГГц у застосунку 6G

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Представлена невелика Т-подібна мікросмужкова антена, яка працює на міліметрових хвильових частотах. Вона призначена для майбутніх бездротових мереж зв'язку 6G. Антена призначена для прийому сигналів на частотах близько 47 ГГц та 75 ГГц, і це хороші частоти для високошвидкісного з'єднання з обмеженим радіусом дії та щільного розгортання малих сот у мережах, що виходять за рамки 5G. Запропонована конструкція складається з Т-подібної випромінювальної ділянки, яка стимулюється мікросмужковою лінією живлення на діелектричній підкладці з мінімальними втратами. Це створює базову планарну структуру, яку можна легко інтегрувати з радіочастотними схемами переднього кінця. Т-подібний компонент і заземлююча площина сформовані таким чином, що полегшує узгодження імпедансу та забезпечує корисну пропускну здатність у потрібних діапазонах частот. Антена все ще достатньо мала, щоб один елемент міг бути використаний як будівельний блок у міліметрових хвильових решітках або системах Massive MIMO, необхідних для задоволення потреб у пропускній здатності та з'єднанні нових сценаріїв 6G. Для перевірки ефективності конструкції щодо втрат на відбиття, коефіцієнта стоячої хвилі за напругою (КСХН), коефіцієнта посилення, а також діаграм спрямованості в обох робочих діапазонах використовується повнохвильове моделювання. Результати показують, що запропонована антена має хороші властивості узгодження, а також спрямованого випромінювання, займаючи при цьому менше місця. Це показує, що її можна використовувати в невеликих, швидких бездротових пристроях та модулях 6G.

Ключові слова: Антена мм-хвиль, Т-подібна візерунка, Діапазон 47 ГГц, Частота 75 ГГц, Високий коефіцієнт підсилення.