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Design of an Integrated mm-Wave and Sub 6GHz Antenna for 5G Mobile Devices

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In 5G applications, the antenna system plays a vital role to maintain the efficiency of the signal coverage during transmission. The millimeter-wave (mm-wave) and sub-6 GHz bands are integrated into the new antenna system which is suggested for the 5G handheld devices. The suggested antenna is a single antenna system that covers a 32.4 GHz bandwidth from 5.8 GHz to 38.2 GHz. The intended antenna structure has been obtained by introducing T-Shaped slots in the patch along with presence of parasitic elements on either side. The antenna's FR-4 substrate is developed with dimensions of 30 × 28 × 1.6 mm^2. The gain varies between 5 and 32 dBi across the operating frequency. The parasitic components are designed and connected with the patch to support the patch's ability to radiate with multiple resonances over a wide operating band. The optimal antenna includes six resonant frequencies 11 GHz, 18.2 GHz, 20.3 GHz, 21.7 GHz, 23.2 GHz, and 27 GHz. During the entire working frequency, the Voltage Standing Wave Ratio (VSWR) is obtained below 2, which signifies well impedance matching. The antenna maintains an efficiency of at least 65 % throughout, making it a strong candidate for 5G devices. The novel antenna geometry with compact size, wide operating band with multiple fruitful resonant frequencies, high gain, good radiation efficiency, omnidirectional stable radiation patterns are the major findings reported in this article.

Keywords: Millimeter wave, SUB-6 GHz, 5G, Mobile devices, MIMO antenna, Wideband.

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1. INTRODUCTION

Nowadays, the Sub-6 GHz frequencies primarily work in the wireless system, because there is more lack of a frequency band to bring out the requirements in the wireless services. The high-frequency mm-Wave band is perceived as important for maintaining the effectiveness of bandwidth and the potential for widespread use of multi-antenna communications. Nevertheless, mm-Wave communication is inherently unreliable with chances of congestion, high path loss, and channel scanning. Theoretically, it can increase the capacity of Enhanced Mobile Broadband (eMBB) network service and decreases the transmission delay for quieter operation. Therefore, it would be ideal to seamlessly combine the flexibility of the microwave networks with the capacity of mm-Wave networks to provide Ultra – Reliable and Low Latency Communications (URLLC) and high-speed wireless access [1]. Millimeter wave (mm-Wave) communications are of much research interest because of the sheer amount of available bandwidth, potentially at rates of several gigabits per second per user [2]. Massive Multiple Input Multiple Output (mMIMO) was originally developed for frequencies below 6 GHz and is suitable for millimeter wave frequency bands covering the 30 to 300 GHz (mm-Wave) range [3]. The efficient design and utilization of antenna is very crucial for mm-wave communication. Many antenna structures are proposed in the literure. The mm-Wave MIMO antenna system reported in ref. [4] has an in-built bandwidth of 3.8 GHz with high gains of 5.28 and 8.67 dBi, while the presented study shows an operating bandwidth of 2.73 GHz. It has the dimensions of the antenna board as 151 × 72 mm corresponding to the smartphone dimensions. The combination of 6 GHz and mm-wave antenna systems are designed by two capacitive corner-coupled elements (CCEs) and four 28 GHz mm-Wave arrays [5]. The ultra-wideband (UWB) microstrip is proposed for the integration of MIMO antenna with a single patch for 5G applications. It is replaced by two different structures to create notches in other bands or to create a multi-band structure [6]. A multi-branch driven strip and three parasitic ground strips form a simple planar antenna for sub-6 GHz applications without lumped elements or 3D structures. The antenna has

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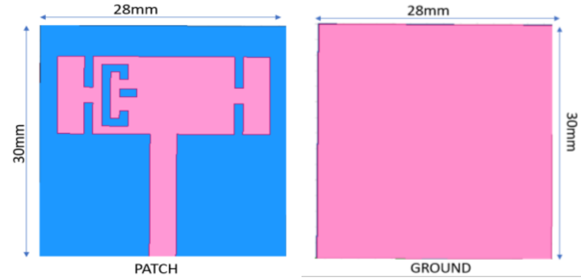
a small footprint of 40150.8 mm^3 and impedance bandwidth of 705-965 MHz and 1610-5500 MHz [7]. The antenna has four 4 × 4 square patches and operates at 3.5 GHz. The antenna has a three-layer structure, and the overall size is 269 mm × 269 mm × 12.5 mm. It is built on a Rogers RO4003C substrate with a dielectric constant of 3.55 and a substrate thickness of 0.8 mm. Results show that the 4 × 4 array has 10 dB bandwidth from 3.3 to 3.8 GHz, 14.9 dB maximum gain at 3.5 GHz [8]. The antenna with H-shaped slot in the patch, and E-shaped patch has a minimum port isolation of 28 dB and resonates at two separate mmWave frequencies, 28 GHz and 38 GHz. The average efficiency is suggested, and the measured average gain is 7.1 dBi at 28 GHz and 7.9 dBi at 38 GHz [9]. Any of two sub-6 GHz antennas fed by four 28 GHz mm-Wave arrays with two capacitive corner coupling components and adjustable radiation pattern (CCE). Two sub-6 GHz bands, 0.79-0.95 GHz and 1.75 GHz were realized in a prototype mm-Wave array [10]. In ref. [11], an integrated antenna design combines dipole and conical slots and it operates in multiple bands including sub-6 GHz at 3.5 GHz and mm-Wave at 28 GHz. Compact dual-function antenna for 5G mobile applications operating at 3.5 GHz and mm-Wave (28 GHz) with frequency reconfiguration technology is reported in [12]. The desired antenna size is significantly reduced to 15.3 mm × 7.2 mm × 0.508 mm by using meander line. For mm-Wave applications, an innovative microstrip antenna is used, the patch consisting of an octagonal annular ring structure and a degraded ground plane. This antenna has excellent performance at 43.5 GHz with a reflection coefficient of -26 dB and it is designed to fit in small electronic devices. [13]. A brand new slotted hexagonal patch antenna with a modified ground plane and overall dimensions of 25 mm × 20 mm is proposed for use below 3.5 GHz [14]. It can be observed from the literature survey that both the required sub-6 GHz and mm -wave bands are not covered by a single antenna element. Therefore, from the literature, it is inferred that there is a necessity to suggest an antenna design that can be able to cover both sub-6 GHz and mm-wave 5G application bands by using a single antenna. The proposed antenna achieves good gain when compared with the literature survey covering both the sub-6 GHz and mm-wave band. This is achieved by implementing full ground plane.

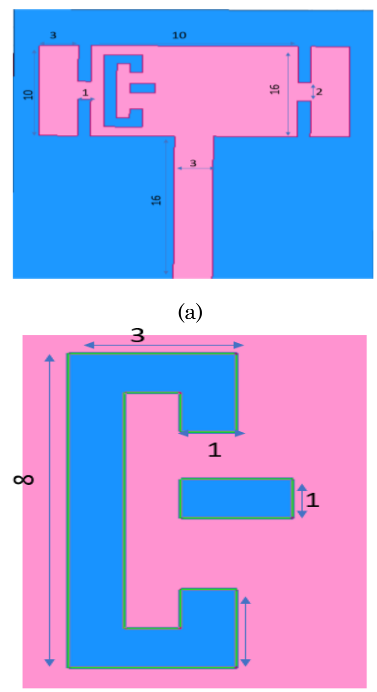
2. INTEGRATED MM-WAVE & SUB 6 GHZ (I-MM W & 6G) ANTENNA

In this work, a single antenna element with a measurement of 30 × 28 × 1.6 mm^3 is proposed. The integrated MIMO antenna system has been structured, and simulated with standard tools called High-Frequency Structure Simulator (HFSS). The compact dimension is compatible with handheld devices. The FR-4 substrate is used to design the suggested antenna. Figures 1 (a) and 1 (b) show the patch and ground structures of the optimized design. In order to resonate the antenna for the sub-6 GHz frequency, T-shaped slots are installed in the patch and the center feed is designed into the antenna. Parasitic elements are constructed and combined with the patch which is made of the resonator to work at both mm-wave and sub-6 GHz frequency ranges. Figures 2 (a) and 2 (b) show the detailed dimensions of the antenna. The whole ground is retained in the design to prevent back-radiation, which must be avoided in handheld devices.



(a) (b)

Fig. 1 – Proposed antenna structure (a) front view (b) rear view



(b)

Fig. 2 – (a) Dimensions of the antenna (b) projected view of incorporated slot with dimensions

3. DESIGN STEPS OF THE ANTENNA WITH ANALYTICAL EQUATIONS

The antenna is designed using the following equations

Width of the Patch,

$$W = \frac{c}{2f}\sqrt{\frac{2}{\varepsilon_r+1}}, \text{ with } \varepsilon_r = 4.4$$

Length of the patch,

$$L = L_{eff} - 2\Delta L, \text{ Where, } w = \text{width of the patch}$$

C = Velocity (3×10^{11}mm), f = Resonant frequency, L = length of the inner patch and ε_r = Substrate's dielectric constant, L_{eff} = Effective length, and it is given by, $L_{eff} = \frac{c}{2f\sqrt{\varepsilon_{reff}}}$

The antenna substrate length and width are formulated by further,

$L_g = L + 6h = 30$ mm

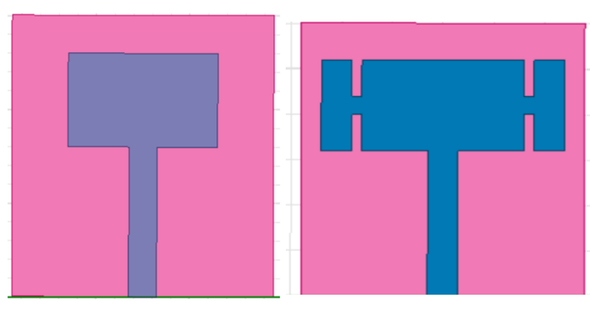
$W_g = W + 6h = 28$ mm

Where Lg and Wg are length and width of substrate, and 'h' is given by $h = \frac{0.0606\lambda}{\sqrt{\varepsilon_r}}$

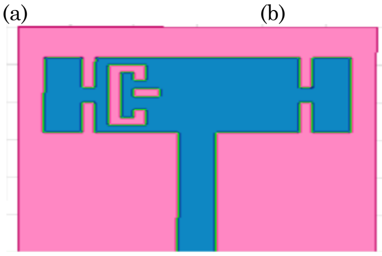
Feed length is calculated using $(L_f) = \frac{\lambda_g}{4} = 16$ mm

Where λ_g is wavelength and it is given by, $\lambda_g = \frac{\lambda}{\sqrt{\varepsilon_{reff}}}$.

The parametric analysis, which includes the development stages is shown in Figs. 3 (a-c). An easy microstrip patch antenna is designed and simulated initially. The simulated results appeared to radiate at frequencies below 6 GHz and in the C-band. Next, after designing and combining the parasitic parts with the patch, the resonance frequencies cover mm-wave bands. Slots are added to improve the impedance matching and hence the return losses at each resonance, which is seen to be greater than 15 dB. High gains are achieved as 17 dBi at 11 GHz, 20.7 dBi at 18.2 GHz, 23.2 dBi at 20.3 GHz, 29.1 dBi at 21.7 GHz, 13.2 dBi at 23.2 GHz, and 20 dBi at 27 GHz, due to the suggested modifications in the patch and by implementing whole ground plane.



(a) (b)



(c)

Fig. 3 – Development stages of the intended antenna: (a) 1st stage (b) 2nd stage (c) Final stage (proposed)

4. RESULTS AND DISCUSSION

We need to examine the improvements in major characteristics parameters such as return loss, gain, and radiation efficiency along with radiation patterns due to the prescribed changes in the antenna geometry. The antenna suffers from poor impedance matching without the presence of any slots within it, while with slots included, it is seen to be much higher than – 15 dB at each resonance. The visual depiction of S_{11} (dB) vs frequency (GHz) is shown in Fig. 4. It can be seen that the radiator operates from 5.8 GHz to 38.2 GHz with multiple resonance at 11 GHz, 18.2 GHz, 20.3 GHz, 21.7 GHz, 23.2 GHz, and 27 GHz and the impedance bandwidth under at – 10 dB level is recorded as 32.4 GHz, which measures 147.27 % fractional bandwidth. The gain and radiation characteristics are displayed in Figs. 5 and 6, respectively. The maximum gains are noted as 17 dBi at 11 GHz, 20.7 dBi at 18.2 GHz, 23.2 dBi at 20.3 GHz, 29.1 dBi at 21.7 GHz, 13.2 dBi at 23.2 GHz, and 20 dBi at 27 GHz. As per Fig. 6, the antenna maintains radiation efficiency of above than 60 % throughout the entire band of operation [5.8 to 34.2 GHz]. The radiation patterns at different resonant frequencies are omnidirectional as shown in Fig. 7 (a-b).

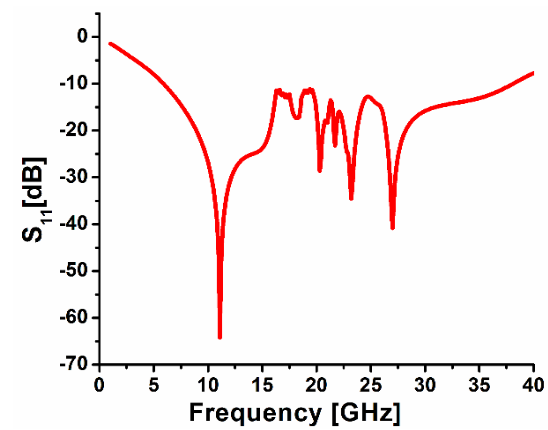


Fig. 4 – Scattering Parameter of Antenna

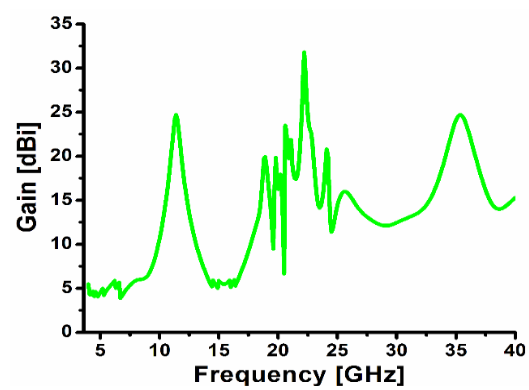


Fig. 5 – Gain Parameter of Antenna

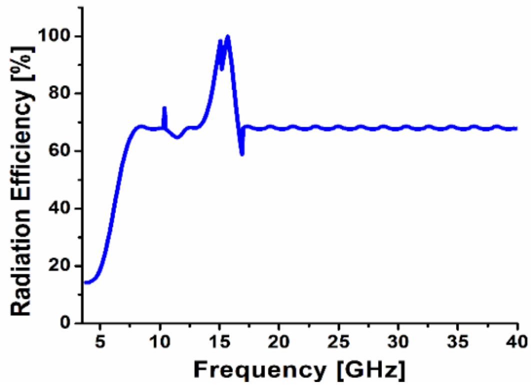


Fig. 6 – Radiation efficiency parameter of antenna

5. CONCLUSION

An integrated mm-wave and sub-6 GHz antenna is designed which operates at multiple frequencies with (11, 18.2, 20.3, 21.7, 23.2, and 27 GHz) covering a huge 32.4 GHz bandwidth from 5.8 to 38.2 GHz. The VSWR is maintained < 2 and the obtained gains are high with radiation efficiency maintained to be above 60 % throughout. The presented antenna can be a good candidate for handheld devices which is validated as follows,

– Implemented with a compact size of 30 × 28 × 1.6 mm^3.

– Full Ground is implemented which avoid backward radiation when the antenna is imprinted in 5G Handheld devices.

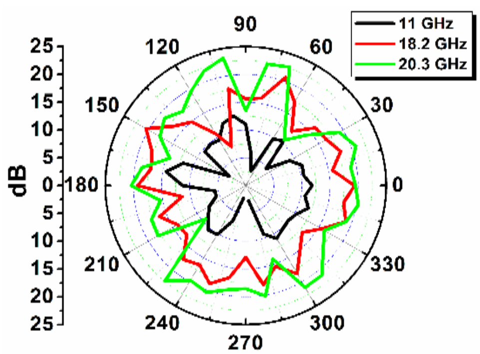
– A High Gain of about 29.1 dBi is obtained by implementing parasitic elements.

– Wide Bandwidth of about 32.4 GHz is achieved which proves the novelty of proposed antenna.

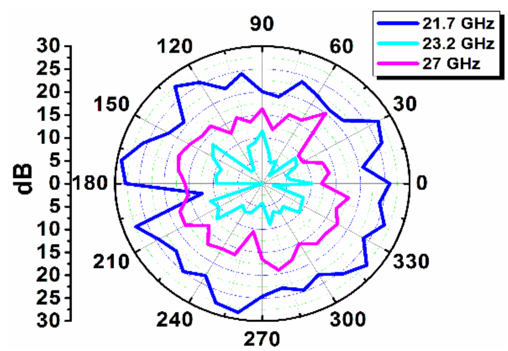
– The antenna maintains radiation efficiency above 60% through the whole band of interest.

– The antenna operates at six distinct resonant frequencies (11, 18.2, 20.3, 21.7, 23.2, and 27 GHz) with VSWR less than 2.

Due to the above-mentioned novel characteristics, the proposed antenna is suitable for mm-wave & sub-6 GHz 5G wireless communication systems.



(a)



(b)

Fig. 7 – Radiation patterns at (a) 11, 18.2, and 20.3 GHz (b) 21.7, 23.2, and 27 GHz

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Конструкція інтегрованої антени мм-хвиль і суб-6 ГГц для мобільних пристроїв 5G

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У додатках 5G антенна система відіграє важливу роль для підтримки ефективності покриття сигналу під час передачі. Діапазони міліметрового діапазону і суб-6 ГГц інтегровані в нову антенну систему, яка пропонується для портативних пристроїв 5G. Запропонована конструкція з однією антеною, яка охоплює смугу частот 32,4 ГГц від 5,8 ГГц до 38,2 ГГц. Передбачувана структура антени була отримана шляхом введення Т-подібних прорізів у накладку разом із присутністю паразитних елементів з обох боків. Підкладка FR-4 антени розроблена з розмірами 30 × 28 × 1,6 мм². Коефіцієнт підсилення змінюється від 5 до 32 дБі на робочій частоті. Паразитні компоненти розроблені та з'єднані з патчем для підтримки здатності патча випромінювати з кількома резонансами в широкому робочому діапазоні. Оптимальна антена включає шість резонансних частот 11 ГГц, 18,2 ГГц, 20,3 ГГц, 21,7 ГГц, 23,2 ГГц і 27 ГГц. Протягом усієї робочої частоти коефіцієнт стоячої хвилі напруги (КСХВ) становить менше 2, що означає добре узгодження імпедансу. Антена має ефективність щонайменше 65 %, що робить дає змогу використовувати її для пристроїв 5G. Нова геометрія антени з компактним розміром, широка робоча смуга з кількома ефективними резонансними частотами, високий коефіцієнт підсилення, хороша ефективність випромінювання, всенаправлена стабільна діаграма спрямованості є основними перевагами даної конструкції, що представлена в цій роботі.

Ключові слова: Міліметрова хвиля, SUB-6 ГГц, 5G, Мобільні пристрої, MIMO антена, Широкосмуговий діапазон.