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Dual Band 1x4 Linear Metamaterial Bowtie Antenna Array for Autonomous Vehicle in Public Safety Band Communications

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Abstract— This research presents the design, simulation, and fabrication of a dual-band 1x4 linear metamaterial bowtie antenna array for applications in 5G wireless systems and public safety band communications. The single-element antenna is a compact dual-band structure with a complementary split-ring resonator (TCSRR) element, and it exhibits resonant frequencies of 3.5 GHz and 4.9 GHz, covering the sub-6GHz 5G spectrum and the public safety band. The antenna aray design is optimized for impedance matching and radiation efficiency. The 1x4 linear antenna array is designed with a quarter-wave transformer feed network and carefully controlled mutual coupling to enhance gain and directionality. Simulated and measured results confirm the performance of the array, with a reflection coefficient within -10 dB from 3.2 GHz to 3.85 GHz and from 4.55 GHz to 5.95 GHz and 3.45 GHz to 3.75 GHz and 4.45 GHz to 5.7 GHz, respectively. The array exhibits a peak realized gain of up to 8.7 dBi and efficient radiation patterns. This work offers promising insights into the development of antenna systems for advanced wireless communication applications and vehicle-to-vehicle communication in public safety band.

Keywords- Metamaterial (MTM), Complementary split-ring resonator (CSRR), Antenna array, Vehicle to Vehicle communications, Public safety band

I. INTRODUCTION

According to the 2022 survey, the total number of global deaths due to vehicle crashes was approximately put around 1.35 million [1]. Hence, the great need to impose certain systematic driving forces that promote road safety thereby drastically reducing vehicle crashes and road accidents with the help of autonomous vehicles is paramount. Besides, it was asserted that autonomous vehicles [2] in their own right can do away with more than 85% of vehicle crashes without the intervention of humans; indeed, the report has it that most traffic accidents are prompted by human errors.

However, the present study takes this opportunity and reflects on efforts invested related to the conception of AV. The very first concept was introduced by General Motors back in 1939 which highlighted the importance of research and development in this sector. This inception attracted scientists and researchers and consequently in 1950 General Motors and Radio Corporation of America Sarnoff Laboratory launched a joint venture in this regard. More interestingly, in the last three decades of the 19th century, a range of Research and Development (R&D) programs were operational globally covering America, Europe, and Asia. We name some of the projects such as Tsukuba Mechanical Engineering Lab, Bundeswehr Universität München, Pan-European PROMETHEUS Project (famously known as the longest AV project ever done), CMU Navlab, AHS Demo'97. Some of these were individual based and many were joint ventures funded by either governments or academia. Above mentioned contributions resulted in many laureates however, people witnessed more than 20 fully auto-mated vehicles first time on highways in San Diego, California. We now consider efforts and contributions made by many in the first two decades of the 20th century. More specifically in the first decade of the 20th groups like CARSENSE, AHSRA Demo 2000, HAMELEON, DARPA Demo III, ARCOS, CarTALK 2000, INVENT, PREVENT, DARPA Grand Challenge II & III, etc in the true spirit made a remarkable difference by making maneuvering of AV ensuring many safety features. In the second decade, we start with Google which started its efforts in 2009 and in 2017 WAYMO by Google was successfully driven in four states covering almost 3 million miles. Another Tech Giant TESLA announced in 2014 that AV designed by them will capture 90% of the market and currently existing models by TESLA remarkably offer self-driving capability fulfilling their claim and making them leading in this regard. Also, other famous brands including Nissan, Mercedes-Benz, Audi, and BMW are venturing to launch their AV in the market by 2020. All these efforts were aimed at developing automated vehicles and corresponding smart systems. For further enlightenment, we suggest these texts [3,4,5,6]. Summing up [7], it is surprising that still there exist no "fully autonomous vehicles", rather all available AVs operate using:

a) Range of sensing and capturing tools such as sensors, lasers, ultra-sonic radars, cameras, etc.

b) Information acquired through these senses is processed using software to generate guided maps of their surroundings.

c) This finally serves as new instruction for car navigation systems such as steering and braking.

Therefore, these contemporary solutions require further improvements to curtain the already portrayed limitations in order to fully have the benefit of the type of AVs; more particularly, its swift communication feature that makes dependable decisions satisfying [8, 9]. In addition, a prognostic lively front steering control system was initiated in [10] for AVs, upon which a finite distance is identifiable with every given trajectory at each time step. Further, the expected front steering angle at utmost entry speed is revealed with regard to the governing trajectory, more particularly for slippery roads. Furthermore, a 2D low-cost laser scanner was utilized in [11] to link the lane-keeping assistant and forth-coming AVs via the application of a map-free lane method. Remarkably, some of the contributions of this method are exclusively summarised below:

1) Sharp curves detections in the lane using a 2D laser scanner;

2) Development of algorithm offering efficiency and reliability using raw data generated by 2D laser scanner;

3) Using local lane fitting smooth path generation and reliable forecasting is achieved;

4) Development of a unique in-built drive-by-wire system for electronic vehicles.

We now consider another outstanding contribution that is associated with connected vehicles, known as integrated positioning [12]. Positioning availability and accuracy were enhanced particularly for town canyons using unified cooperative positioning, through the utilization of a short-range communication mechanism that is rooted in raw data from GPS receivers and inertial sensors from the road trajectories. Moreover, an advanced lane-keeping assistance system (famously abbreviated as LKAS) was proposed in [13]. Certainly, LKAS mainly acts as an assistant to switch lane departure prevention and lane-keeping co-pilot modes. For further technical details and implementation of such a system, readers are encouraged to consult [13] in detail. Continuing further, an efficient and reliable photovoltaic LIFI communication system, which is called the intelligent transportation system and is applicable to vehicles and road infrastructure (V2RI) and AVs was developed [14]. In fact, this submission greatly outperformed the classical communication system, which uses radio frequency (RF). In addition, LIFI gained popularity because of salient features such as highly secure, high precision, low cost, reliable connectivity, etc. Nonetheless, it was applicable to indoor applications which means traditional LIFI receivers did not work properly under sun illumination. This major limitation was removed by Sunpartner Technologies by replacing traditional LIFI detectors with specific photovoltaic surfaces enabling them to be used as outdoors offering high-speed LIFI communication. This brought in a new pool of potential features such as energy harvesting and adaptation of the communication angle to the application needs through the photovoltaic surface sizing. It is indeed noteworthy to emphasize here that the RF-based communication system that was introduced in [15] covered the range of 20 kHz to 300 GHz, and was further based on the alternation rate of voltage and electric current.

In this regard, it is pertinent to stress the huge relevance of both the antennas and their operating frequencies in vehicular communication systems. Undoubtedly, highly advanced attributes associated with the transmission management systems and traffic could be achieved with regard to vehicular communication systems upon paying considerable attention to both the antennas and their operating frequencies.

Hence, the making consideration of the design and construction of antennas for vehicular communication systems, a durable and flexible microstrip antenna [16] was de-signed particularly for the automotive industry that operates a frequency of 5.9 GHz. These antennas are of various shapes and can further work under the directional and om-nidirectional radiating conditions, respectively. In addition, small-sized wide-beamwidth patch antennas, which are circularly polarized (CP), were designed for detecting blind spots. These antennas can easily be put on aerodynamic wireless devices, thereby capturing signals from the entire azimuth range and wide elevation angles among others [17]. Yet, a promising approach that takes into consideration sensor nodes (low-cost) with complexity requirements and stern power utilization was devised in [18] for effective communication via the application of directional far-field functions infused in multiple low-cost antennas. This approach further affirms that the placement of the antenna has nothing to do with either the far-field functions or the optimum phase slopes.

In the same vein, we make mention of the symmetric pattern radiating antennas [19] that were designed, tested, and analyzed; indeed, these types of antennas were found to be appropriate for ITS processes. Equally, circular array antennas were in 2009 to enhance the recital of communication correlated with ITS [20]; read also [21], where microstrip phased array antennas were designed for blind spots of an ITS and operating with frequencies of 5.88 GHz. Furthermore, the transmission for improved recital antennas, located at various positions in a car offered an all-inclusive wide coverage, however, less than a pair of antennas situated in a bumper or on the roof of the vehicle [22]; interested readers can equally read [23] and [24] for the design and fabrication of circular polarized (CP) and multi-band CP antennas, respectively, where the CP antenna was hemispherically transmitted at a frequency of 4.9 GHz. Equally, a dual-band double-sided bowtie antenna for high gain ITS communications was designed, simulated, and fabricated in the 4.9 GHz public safety bands [25]. Additionally, a wide-band CP antenna was designed in [26] and further found its relevance in front-end radiation for ITS processes; see [27] and [28] also for various designs with the impedance bandwidths operating at different frequencies ranging from 8.8 and 11.2 GHz and 5.2 and 5.8 GHz, correspondingly. Besides, the peak gain values in [27] and [28] were estimated to be around 5.04 and 5.01 dBi, and 3.23 and 4.38 dBi, respectively. Moreover, in [29] a novel complementary split-ring resonator (CSRR) metamaterial (MTM) based hexagonal bowtie antenna for a high gain V2V communication was designed, the proposed antenna achieved a gain and bandwidth of 1.6 dBi / 6 dBi and 100MHz/ 800MHz at 2.4GHz /3.5GHz, respectively, which ascertain their cost-efficiency in comparison to many other antennas.

This research paper discusses the comprehensive design and analysis of a dual-band 1x4 linear metamaterial (MTM) bowtie antenna array. Section 2 briefly describes the sin-gle-element MTM antenna, highlighting its dual-band characteristics. Section 3 provides a detailed discussion of the design of the 1x4

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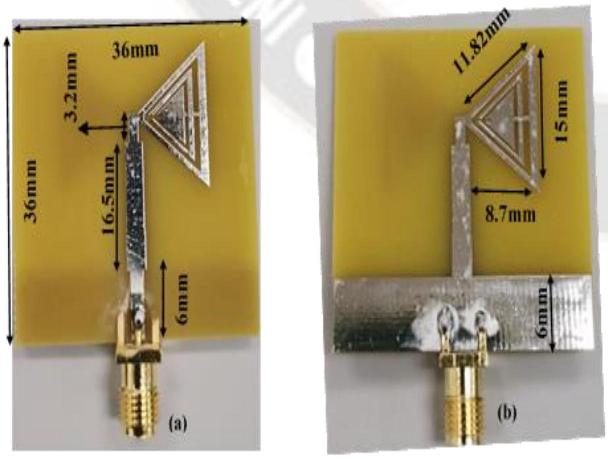
linear MTM antenna array, emphasizing its significance in 5G and public safety applications due to its high directionality, gain, and resonant bandwidth. Additionally, it addresses the critical role of the feed network in controlling the array's performance and discusses the issue of mutual coupling. The results of simulation and measurements, including reflection coefficients, realized gain, and radiation patterns, are briefly presented, demonstrating the efficient operation of the proposed antenna systems.

II. ANTENNA DESIGN

The antenna array design begins with a single element antenna. This antenna is a compact, dual-band, double-sided triangular bowtie antenna with a triangular comple-mentary split-ring resonator (TCSRR) element. It is fed by a 50Ω microstrip line and is printed on an FR4 substrate with a thickness of 1.6 mm, permittivity of 4.4, and loss tan-gent of 0.018. The antenna structure includes a radiating bowtie-shaped patch on the top and bottom layers, a partial ground plane, a modified feedline, and a triangular-shaped split ring resonator (SRR) etched from the radiating patch. This SRR provides the antenna with TCSRR metamaterial properties. The optimized dimensions of the SRR and single element antenna are provided in detail in a referenced article [30]. The dual-band antenna is then fabricated based on the optimized design parameters. The simulation and meas-ured results of the S-parameter and 2D radiation pattern characteristics are presented and explained in the referenced article [30]. The fabricated prototype of single element antenna shown in Fig.1(a-c) and the S-parameter result of single element antenna shown in Fig.2. The dual-band fabricated antenna operates at two frequency ranges: 3.45GHz-3.85GHz and 4.65GHz-5.4GHz. The initial resonant frequency of the proposed antenna is 3.5 GHz, and it also operates at a second frequency of 4.9 GHz. These frequencies cover the sub-6GHz 5G spectrum and the public safety band, respectively. It has a band-notched re-gion between 3.85GHz and 4.65GHz. Experimental measurements using a Keysight Technologies FieldFox N9916B Vector Network Analyzer confirmed these results. Addi-tionally, the antenna's measured bandwidth is 400MHz for the 5G band and 750MHz for the public safety band.



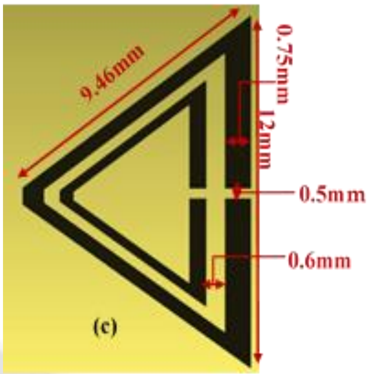


Fig. 1. Fabricated prototype of single element proposed antenna (a) Front View (b) Back View (c) Triangular-shaped split ring resonator (SRR)

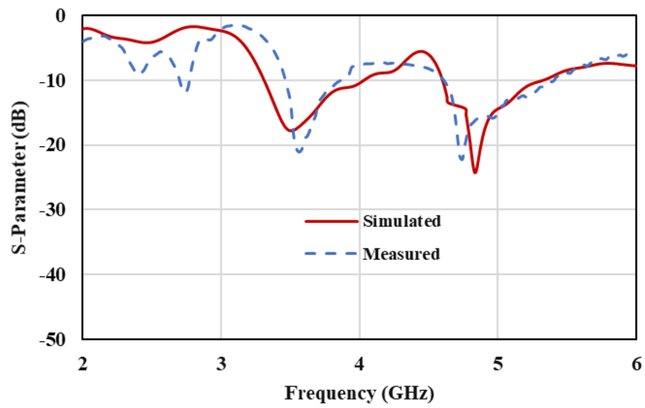


Fig. 2. Simulated and measured S-parameter result of single element proposed antenna.

III. 1×4 LINEAR METAMATERIAL BOWTIE ANTENNA ARRAY

In this section, we have designed, simulated, and fabricated a 1x4 linear metamaterial bowtie antenna array shown in Fig 3 (a-d). Antenna arrays with multiple elements are crucial for applications such as currently deployed 5G wireless systems, and public safety band for vehicle-to-vehicle communications, as they provide high directionality, gain, and resonant bandwidth. The total field of the 1×4 linear Metamaterial Bowtie Antenna Array is obtained by multiplying the single-element field at the origin with a factor known as the array factor.

When constructing an array, the design of the feed network plays a crucial role. The feed network is responsible for controlling the amplitude and phase of the radiating elements within the array, allowing for control of the beam scanning properties [31]. Therefore, the selection and optimization of the feed network are critical in the array design process. Various types of feed networks are available, including parallel feed, T-split power divider, quarter-wave transformer, and metered bend feed [32]. Each of these feed network de-signs serves the purpose of regulating the signals and power distribution among the radiating elements in the array. In this design, quarter-wave transformer was used a feeding network to achieve better impedance matching.

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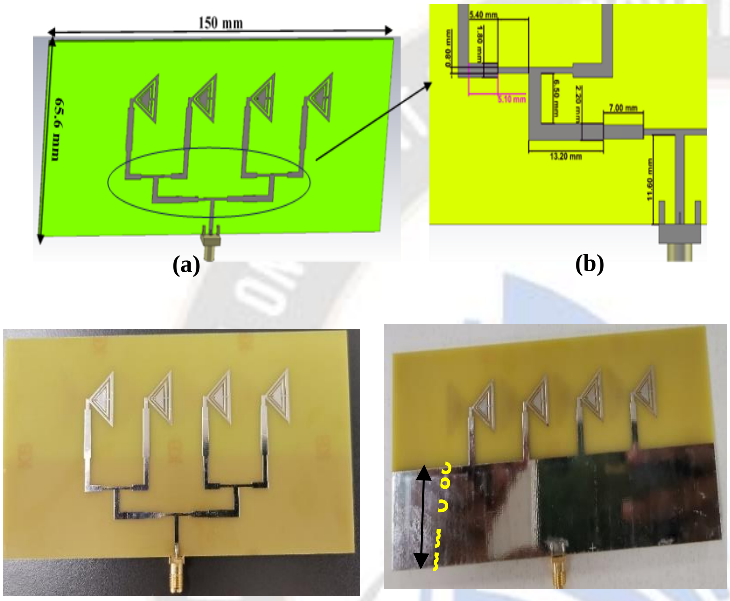
A. Mutual Coupling

A crucial aspect of array design is mutual coupling, which is the amount of energy acquired by nearby antenna. Stronger mutual coupling can affect the array's gain and the main beam's radiation efficiency [33]. In order to obtain the optimum matching and radiation pattern for the designs, a precise distance of 25.3mm has been selected through a parametric analysis. Ideally, the distance between the centres of two elements should fall between λ /2 and λ. As seen in Fig.4, when four antenna elements are positioned side by side to evaluate their mutual coupling, this distance equates to 0.6λg at a frequency of 3.5 GHz.



(c) (d)

Fig. 3. Simulated and fabricated a 1x4 linear metamaterial bowtie antenna array (a) Top-layer (b) feeding network (c) fabricated top-layer (d) bottom-layer

IV. RESULTS AND DISCUSSION

In Fig.4, the reflection coefficient for the 1×4 linear antenna array is depicted through both simulation and measurement. The -10 dB simulation reflection coefficient is operating from 3.2 GHz to 3.85 GHz and from 4.55 GHz to 5.95 GHz. The measured dual frequency band is observed from 3.45 GHz to 3.75 GHz and 4.45 GHz to 5.7 GHz, where the -10 dB reflection coefficient is achieved as well.

Fig. 5 illustrates the simulated peak realized gain of the linear array, which varies between 2 dBi and 8.7 dBi. Notably, the gain increases towards the end of the frequency band, which aligns with expectations, as it occurs when the distance between the elements exceeds the wavelength (λ).

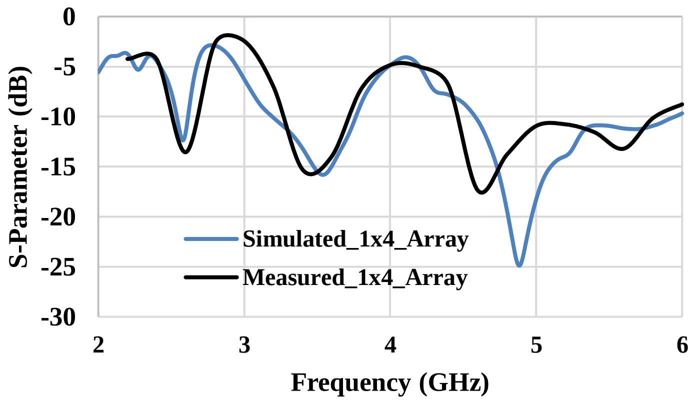


Fig. 4. Reflection coefficient for the proposed 1×4 linear antenna array

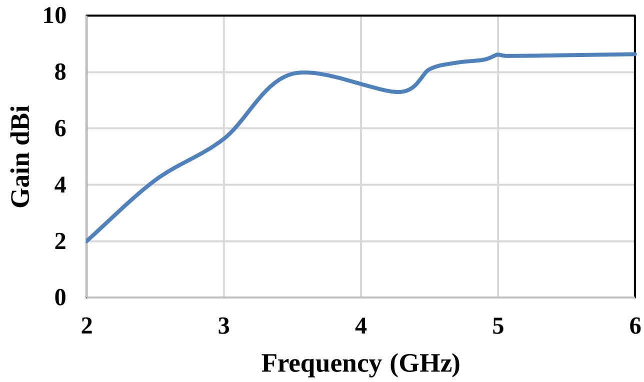


Fig. 5. Simulated peak realized gain of the linear array.

The simulated radiation fields for the E-plane and H-plane at 3.5 GHz and 4 GHz are shown in Fig.6 (a-b). The main function of these radiation patterns is to show the antenna's strength of radiation at various angles. It is clear from reviewing these radiation patterns in Fig.6 (a-b) that the proposed antenna operates in an efficient manner that is comparable to that of traditional printed monopoles.

In Fig.6 (a), the simulated radiation patterns in the E-plane at 3.5 GHz and 4.9 GHz show a peak gain of 7.8 dBi and 8.8 dBi, respectively, occurring at an angle of 90 degrees. Meanwhile, in Fig. 6(b), the maximum simulated gain for the H-plane at 3.5 GHz is 7.6 dBi, and at 4.9 GHz, it reaches 8.7 dBi at an angle of 0 degrees. Although the radiation patterns at 3.5 and 4.9 GHz appear similar, they exhibit different gains and angles. Fig.7 (a-b) illustrates the proposed antenna's 3D radiation pattern at 3.5GHz and 4.9GHz.

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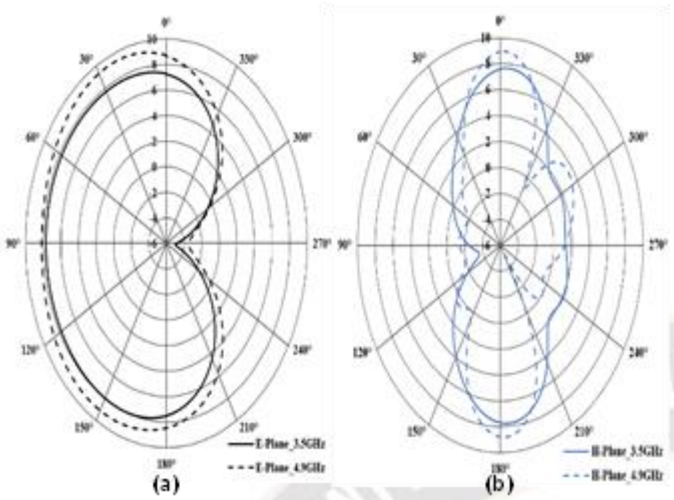

Fig. 6. Simulated radiation fields at 3.5 GHz and 4 GHz (a) E-Plane (b) H-Plane.

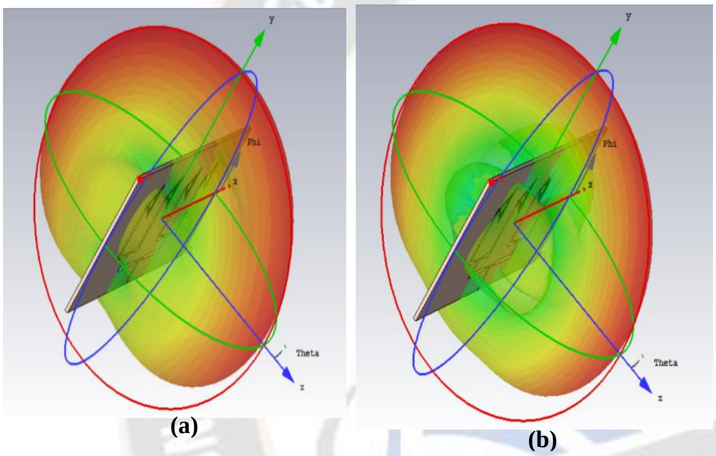

Fig. 7: 3D Radiation patter of proposed 1×4 linear antenna array (a) 3.5GHz (b) 4.9GHz.

Table.1 below provides a comparison between the proposed 1x4 linear antenna array and existing array antenna systems. Most of the articles listed in the table have focused on enhancing either the gain, broadening the bandwidth, or reducing the size of the array system. Notably, the proposed system aimed to achieve improvements in all of these aspects simultaneously. In article [3281], the gain was elevated to 16.5dBi, but this accomplishment required the use of 10 elements, resulting in a significant increase in the size of the antenna array. In contrast, the proposed antenna array utilizes low-cost materials compared to other articles that employed RT duroid substrate for higher gain. It's important to note that the gain of the proposed 1x4 linear MTM antenna array has the potential for further enhancement through the utilization of high-end materials like Rogers.

V. CONCLUSION

In this study, we have successfully designed, simulated, and fabricated a dual-band metamaterial bowtie antenna and a 1x4 linear metamaterial bowtie antenna array. The single-element antenna exhibits excellent performance, with dual resonant frequencies at 3.5 GHz and 4.9 GHz, covering the crucial sub-6GHz 5G spectrum and the public safety band. The design ensures an impedance-matched structure with a band-notched region between 3.85 GHz and 4.65 GHz.

The 1x4 linear antenna array is carefully designed with a quarter-wave transformer feed network, which allows for precise control of amplitude and phase among the radiating elements. Mutual coupling is minimized through strategic element placement, enhancing the array's gain and radiation efficiency. Simulated and measured results validate the array's performance, with a reflection coefficient below -10 dB over the desired frequency bands and a peak realized gain of up to 8.7 dBi.

The radiation patterns of the proposed antenna array show strong performance, comparable to traditional printed monopoles. This research contributes valuable insights into the development of antenna systems for 5G and public safety applications, offering high gain, directionality, and efficient radiation patterns. These achievements pave the way for enhanced wireless communication systems in various scenarios, including 5G networks and vehicle-to-vehicle communications in the public safety band.

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TABLE. 1. Proposed MTM 1 x 4 linear antenna array comparison with the existing design

Ref	Operating Frequency (GHz)	Size	Bandwidth (MHz)	Gain (dBi)	Material	No of elements
[34]	2.1/3.5	-	400/700	8.5/9.2	RO4003C	4
[35]	2.1/3.5	2.14λ_o x 1.56λ_o	50/70	11.1/6.6	RT/Duroid	4
[36]	3.5/4/4.22	1.79λ_o x 81λ_o	25	6.4/6.8/7.25	FR4	4
[37]	3.5	5.25λ_o x 1.63λ_o	140	16.5	RO4003C	10

[38]	3.5	2.76λₒ x 0.75λₒ	400	13.5	-	-
Our Work	3.5/4.9	1.75λₒ x .76λₒ	650/1500	8.7	FR4	4

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