Low Profile Dual-Band Shared Aperture Array for Vehicle-to-Vehicle Communication

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ABSTRACT In this paper, we present a non-standalone dual-band shared aperture antenna array that operates at both the current Dedicated Short Range Communications (DSRC) band (viz. 5.9 GHz) and the future 5G millimeter-wave (mm-wave) band (viz. 28 GHz) allocated for vehicle-to-vehicle (V2V) communications. The design consists of a 2x2 differentially fed patch array operating at 5.9 GHz, co-printed with a 1x2 series fed array operating at 28 GHz on a single layer substrate. In particular, the shared aperture array operates from 5.84-5.94 GHz (DSRC band) with a 100 MHz impedance bandwidth and from 27.75 - 28.47 GHz (5G mm-wave band) with a 720 MHz impedance bandwidth. Gain improvement of ∼1.44 dB at 28 GHz is observed as a result of the higher order modes generated by the 5.9 GHz array. The shared aperture array was fabricated and measured showing a gain of ∼9.97 dBi at 5.9 GHz and ∼12.3 dBi at 28 GHz. The ports of the array are highly isolated with measured isolation >55 dB at the DSRC band and >33 dB at the 5G mm-wave band.

INDEX TERMS Shared aperture array, DSRC, 28 GHz, millimeter-wave, vehicle-to-vehicle communication, higher order mode

I. INTRODUCTION

Globally, road accidents claim 1.3 billion lives per year [1]. Particularly in the US, road accidents result in 38 thousand deaths per year [2]. Improving the safety of the drivers is one of the primary goals of the intelligent transportation system. The Federal Communications Commission (FCC) allocated the 5.85-5.925 GHz Dedicated Short Range Communications (DSRC) band in the intelligent transport system (ITS) radio for vehicular communications [3]. This enabled the development of a virtual traffic light (VTL) algorithm to reduce traffic congestion using vehicle-to-vehicle communication (V2V) and internet of things (IoT) technologies. The role of the algorithm is to collect data such as speed, acceleration, and direction of the vehicle from nearby vehicles as well as to control traffic without using physical traffic lights. Field trials conducted in Pittsburgh [4-5] showed that VTL can effectively reduce 1) road accidents at the intersections by 70%, 2) carbon emissions, and 3) commute time from 30.7 to 18.3 minutes. Currently, the US Department of Transportation and various automobile industries use the 5.9 GHz safety band for automatic toll collection, traffic congestion control, emergency vehicle warning, and intersection movement warning [6].

However, due to bandwidth restriction in the DSRC band, high data rate communications, such as video streaming, are quite difficult to achieve. Therefore, the trend is to move towards the millimeter-wave (mm-wave) spectrum for higher speed communications of >1 Gbps with wider bandwidth and reduced interference [7]. In addition, the radios at mm-wave are smaller in size and require low power consumption, implying inconspicuous integration on the vehicular platforms. However, mm-wave spectrum suffers from large propagation and atmospheric losses as well as attenuation due to rain and severe weather conditions [7-8]. These losses can be compensated by using high gain antenna arrays. Importantly, we need a system capable of switching between the 5G mm-wave band, for high speed communications, and well-established the DSRC band to meet the required communication link.
quality of service during severe weather conditions.

Radios that can operate in the traditional low frequency bands and the new mm-wave bands are called non-standalone devices [9]. The main challenge is implementing these devices in a single compact package when the two frequency bands are widely separate with a band ratio > 2:1. These dual-band systems offer high jamming, and interference protection, as well as improvement in the channel capacity by making use of frequency diversity [10]. Traditionally, dual-band radios employ antennas designed using two separate single-band antennas or a single structure that resonates at both bands. Various works have been reported of multi-band antennas using a single feed. For instance in [11], two U shaped patch antennas operating at 1.9 GHz and 2.6 GHz are integrated together with multistub feed structure. Additionally, the upper band patch is designed in such a way that it is also used as feed structure for a lower band patch. In [12], two different frequency patches operating at 12.1 GHz and 17.4 GHz are integrated together using sequential rotation feeding technique for dual-band operation. However, these single feed dual-band antennas require additional RF components in the front-end for separate multiband operation.

A more efficient design for multiband operation is to use separate feed network for each operating frequency bands by adopting a single or multilayer design. Multilayer shared aperture array is designed for C (5.0-6.2 GHz) and X (7.2-8.9 GHz) bands in [13], and each band is designed on different substrates with a foam layer sandwiched between them. However, the isolation between C and X bands is just 15 dB and 20 dB, respectively. Multilayer L (1.07-1.24 GHz) and X (8.3-10.3 GHz) band antennas with parasitic patches, driven patches, and complex feeding network are designed on separate substrates in [14]. The array provides a port-to-port isolation >30 dB and cross-polarization >17 dB and >20 dB at the L and X bands, respectively. However, these results come at the expense of a large array height (0.927λi). The main drawback of these designs are the multilayer fabrication technique that is expensive and increases the size of the array. One of the simple, and easy fabrication technique is using a single layer Printed Circuit Board (PCB). The implemented PCB shared aperture array operates at dual band with highly isolated ports and provides gain improvement at upper band by utilizing the higher order modes of the lower band array.

In this work, a low profile non-standalone, dual-band, shared aperture antenna array with gain improvement is designed for V2V communication. The array consists of 4 patch antennas operating at 5.9 GHz (DSRC) with a differential coax feed network and 2 patch antennas operating at 28 GHz (5G mm-wave) with a series coax feed network, as shown in Fig. 1. The array provides a dual-band operation with high gain, high port-to-port isolation, and high efficiency, as displayed in Table I. The radiation pattern of the arrays with and without shared aperture design was analyzed, showing that the implemented design does not affect the radiation pattern of the individual arrays. Furthermore, a gain improvement at 28 GHz is achieved due to the higher order modes generated by the 5.9 GHz array.

The paper is organized as follows: In Section II, the configuration and design procedure of the shared aperture antenna array is explained along with a comparison of its performance and the individual antenna array. In Section III, the fabricated array is measured, tested, and compared to the performance of other shared aperture arrays. Finally, Section IV concludes the paper.

II. DESIGN PROCEDURE OF THE DUAL-BAND SHARED APERTURE ANTENNA ARRAY

A. CONFIGURATION OF THE SHARED APERTURE ANTENNA ARRAY

Patch antennas are widely known for their low profile and design simplicity. Two patch antenna arrays operating at the fundamental mode TM10 are designed at two different frequency bands. Fig.1 depicts the configuration of the implemented dual band shared aperture antenna array. The shared aperture antenna array is designed on Rogers RT/duroid 5880 substrate with thickness 0.52 mm, dielectric constant εr = 2.2, and loss tangent tanδ=0.0009. The design and optimization of the shared aperture array is carried out using Ansys HFSS software. The lower band array consists of four inset fed patch antennas resonating at the fundamental mode. The spacing between the 5.9 GHz patch antennas is maintained at a distance of 0.5λi to avoid grating lobes. The upper band array consists of two series fed 28 GHz patch antennas. The

| TABLE 1. Specifications of the dual-band shared aperture array |
|-------------------------------------------------------------|
| **Frequency** | 5.9 GHz | 28 GHz |
| **Impedance Bandwidth** | 100 MHz | 720 MHz |
| **Number of elements** | 4 elements | 2 elements |
| **Inter-element spacing** | 0.5λh | 0.55λh |
| **Polarization** | Linear polarization |
| **Port isolation** | >55 dB | >33 dB |
| **Peak gain** | 9.97 dBi | 12.3 dBi |
| **Cross-polarization level** | >16 dB | >20 dB |
| **HPBW** | 53°/47° | 29.9°/60° |

**λi** = Wavelength of the lower DSRC band array corresponding to fi=5.9 GHz  
**λh** = Wavelength of the higher mm-wave band array corresponding to fh=28 GHz  
HPBW = Half power beamwidth
28 GHz array is placed in between the 5.9 GHz array, as shown in the Fig.1, thus saving the extra space.

The surface current distribution of the shared aperture antenna array at 5.9 GHz and 28 GHz is shown in Fig. 2. To analyze the current distribution of the array at 5.9 GHz, the lower band array (i.e., Port 1) is excited and Port 2 is terminated, as depicted in Fig. 2(a). It shows that the presence of 28 GHz array does not affect the current distribution in the 5.9 GHz array, resulting in highly isolated ports. At 28 GHz, when Port 2 is excited and Port 1 is terminated, higher order modes are generated in the nearby 5.9 GHz array, as shown in Fig. 2(b). The lower band array acts as a parasitic patches and increases the gain of the array at 28 GHz.

### B. DESIGN OF 5.9 GHZ DIFFERENTIALLY FED ARRAY

Fig. 3 represents the design of the lower band differentially fed patch antenna array. Four inset fed 5.9 GHz patch antennas are designed covering DSRC band. The length and the width of the patches are calculated using [15]. The total dimensions of the lower band array is 75 mm × 100 mm × 0.52 mm (W × L × h) with \( L_{\text{patch}} = 16.7 \text{ mm} \) and \( W_{\text{patch}} = 19 \text{ mm} \). The resonant frequency of the various TM\( mn \) modes of patch antennas is estimated using [15]

\[
\begin{align*}
  f_{mn} &= \frac{k_{mn} c}{2\pi \sqrt{\varepsilon_r}} \\
  k_{mn} &= \sqrt{\left(\frac{m\pi}{L}\right)^2 + \left(\frac{n\pi}{W}\right)^2}
\end{align*}
\]

Where \( f_{mn} \) resonant frequency at TM\( mn \) modes, 
\( c \) is the speed of the light in free space,
\( \varepsilon_r \) is the dielectric constant,
\( k_{mn} \) is the wave number,
\( L \) and \( W \) is the length and width of the patch, respectively.

The elements are placed at a center-to-center spacing of 0.5\( \lambda \) (see Table I). We note that the elements are excited using differential corporate feed network, in order to provide center gap for designing higher band array, as shown in Fig. 3. The feed network consists of a 180° phase shifter, and three power dividers. The feed network provides 0° and 180° outputs to feed differential pair of single-ended patches, as shown in Fig. 3. To achieve 180° phase difference, a half-wavelength transmission line is designed on one arm of the feed network.

Fig. 4 shows that the simulated array operates from 5.86 GHz to 5.94 GHz considering a 50Ω impedance matching.
C. DESIGN OF 28 GHz SERIES FED ANTENNA ARRAY

Next, a $1 \times 2$ patch array operating at 28 GHz is designed with inter-element spacing of $0.65\lambda_h$, as shown in Fig. 5 and in Table I. The series feed network is chosen to avoid microstrip line losses and for design simplicity. The width and length of the patches are 3.5 mm and 3.25 mm with total dimension $25 \text{ mm} \times 25 \text{ mm} \times 0.52 \text{ mm} (W \times L \times h)$. The 28 GHz patches are inset fed for $50\Omega$ impedance matching and the width and length of the feed line are 0.3 mm and 0.12 mm, respectively. Fig. 6 shows that the simulated array alone is $50\Omega$ impedance matched from 27.46 to 28.4 GHz with $S11<-10$ dB.

D. PERFORMANCE OF SHARED APERTURE ANTENNA ARRAY

The differentially fed lower band array and series fed higher band array are co-printed on a single layer substrate, as depicted in Fig. 7. Notably, no additional space is required for the placement of the upper band array. The upper band array...
is placed a distance of $0.08\lambda_l$ from edges of the 5.9 GHz patches whereas the center-to-center spacing of the lower band array is maintained at $0.5\lambda_l$. The total dimensions of the array is dictated by the lower band array, viz. $75\text{ mm} \times 100\text{ mm} \times 0.52\text{ mm} (W \times L \times h)$. The position of series fed antenna array is optimized for better antenna performance. Fig. 8 displays the simulated active S11 of the shared aperture array when Port 1 is excited and Port 2 is matched loaded, showing that the lower band array operates from 5.84-5.94 GHz with 100 MHz bandwidth. When Port 2 (upper band array) is excited and Port 1 is matched loaded, simulations show that the array operates from 27.75-28.47 GHz, as depicted in Fig. 9. Further, simulations show that the when both the ports are excited, ports of the upper band and lower band array are highly isolated with isolation $>55$ dB at DSRC band and $>38$ dB at 5G mm-wave band, as shown in Fig. 10.

Next, the radiation patterns of the shared aperture array (see Fig. 7) are compared to the patterns of the individual 5.9 GHz array (see Fig. 3). Full-wave simulations show that the radiation patterns of the shared aperture array and the individual 5.9 GHz array remain the same in both the E and H planes, as displayed in Fig. 11. The realized gain of
TABLE 2. Simulated and measured realized gain (dBi) of the shared aperture antenna array

|                     | 5.9 GHz (DSRC band) | 28 GHz (5G mm-wave band) |
|---------------------|----------------------|--------------------------|
|                     | E plane              | H plane                  | E plane              | H plane                  |
| Simulated gain (dBi)| 10 dBi               | 9.92 dBi                 | 11.85 dBi            | 11.85 dBi                |
| Measured gain (dBi) | 9.97 dBi             | 9.85 dBi                 | 12.3 dBi             | 11.7 dBi                 |

The shared aperture array almost remains the same as the individual 5.9 GHz array at the DSRC band, as depicted in Fig. 12.

Similarly, the radiation pattern of the shared aperture at 28 GHz (see Fig. 7) was compared to the radiation pattern of the individual 28 GHz array (see Fig. 5). Fig. 13 shows that the patterns of the shared aperture array are comparable to that of the series fed 28 GHz array with an increase in the gain at boresight. When exciting the 28 GHz array, the nearby 5.9 GHz patches act as parasitic patches for the upper band array and introduces higher order modes at 28 GHz. As a result, the shared aperture array provides an additional ∼1.44 dB improvement in gain at 28 GHz due to the higher order modes of the 5.9 GHz array, as illustrated in Fig. 14.

III. FABRICATED AND MEASURED ARRAY PROTOTYPE

The designed dual-band shared aperture antenna array is fabricated and measured. Fig. 15 (a) displays the top and bottom view of the fabricated prototype. The lower band 5.9GHz array is measured at Port 1 using probe-fed SMA connector. The series fed upper band 28GHz array is measured at Port 2 using probe-fed 2.4mm connector. Fig. 15 (b) displays the scattering parameter measurement at DSRC 5.9 GHz band (left) and radiation pattern measurement setup at 28 GHz band (right). The S parameters of the array are measured using a Vector Network Analyzer and the radiation patterns are measured in the anechoic chamber (see Fig. 15(b)).

A. MEASUREMENTS AT DSRC 5.9 GHZ BAND

The measured and simulated S parameters of the designed shared aperture antenna array are shown in Fig. 16. Results in Fig. 16 show that when Port 1 is measured, the fabricated prototype operates from 5.87-5.99 GHz with 120 MHz bandwidth, hence covering the DSRC band. Notably, the array provides a high measured isolation of >55 dB in the DSRC band (viz. 5.87-5.99 GHz). A small frequency shift in the measured result is due to the fabrication error.

The normalized radiation pattern of the shared aperture array at 5.9 GHz in both E and H plane is shown in Fig. 17. The radiation pattern at 5.9 GHz is measured by exciting Port 1 and terminating Port 2 using 2.4mm 50Ω RF load. The measured patterns agree well with the simulated ones. Table II shows the simulated and measured peak gain (dBi) values in both bands and in the E and H planes. Table II demonstrates that the array provides a measured gain of about
9.97 dBi in the E plane and 9.85 dBi in the H plane at 5.9 GHz. At 5.9 GHz, the fabricated array provides a measured cross-polarization level of < -16 dB in both the E and H planes with a HPBW of 53° in the E plane and 47° in the H plane, as shown in Fig. 17. The measured and simulated gain of the lower band array at DSRC band is shown in Fig. 18. The radiation efficiency of the antenna was estimated using

$$\eta = \frac{G}{D}$$

where G and D are the gain and directivity of the antenna. Fig. 18 shows that the lower band array provides a maximum efficiency of about 86% at 5.9 GHz.

### B. MEASUREMENTS AT MILLIMETER-WAVE 28 GHZ BAND

Fig. 16 shows the measured and simulated S-parameters at the 28 GHz band. When Port 2 is measured, the fabricated...
prototype operates from 27.8-28.65 GHz with 850 MHz operating bandwidth. Fig. 16 also shows that the array provides a high measured port-to-port isolation of >33 dB in the 5G mm-wave band (viz. 27.8-28.65 GHz).

The radiation pattern measurements at 28GHz is carried out by exciting Port 2 and terminating Port 1 with 50Ω SMA load. The normalized radiation patterns of the shared aperture array at 28 GHz are shown in Fig. 19. The shared aperture array provides a realized gain of about 12.3 dBi in the E plane and 11.7 dBi in the H plane at 28 GHz. Fig. 19 shows that the array provides a measured cross-polarization level of <20 dB at 28 GHz in both E and H planes with a HPBW of 29.9° in the E plane and 60° in the H plane.

The measured gain (dBi) and simulated radiation efficiency (%) curves at the 5G mm-wave band is displayed in Fig. 18. A high gain value of 11.85 dB is observed at 28 GHz due to the higher order modes produced by the lower band array. Additionally, the upper band array provides a radiation efficiency of >96% at 28 GHz.

C. COMPARISON WITH OTHER STATE-OF-THE-ART SHARED APERTURE ARRAYS

Table III summarizes other state-of-the-art shared aperture antenna arrays and their performances. Array in [14] provides low mutual coupling between the ports, but it requires multilayer fabrication technique which is quite expensive, and it also increases the thickness of the antenna. Single layer shared aperture antennas are presented in [12], [16], [24-25], but our design provides higher isolation between the ports compared to the other designs. Notably, our design utilizes the higher order modes from the lower band array. Clearly, the shared aperture presented in this paper provides improvement in gain, higher radiation efficiency, and improved port-to-port isolation with a low-profile and design simplicity.

IV. CONCLUSION

This paper presented a single layer shared aperture antenna array for V2V communications. The non-standalone array operates at both the current DSRC band and the future 5G mm-wave band. The shared aperture array consists of a series fed upper band array co-printed with a lower band differentially fed array. The fabricated lower band array operates from 5.87-5.99 GHz with gain of 9.97 dBi. The upper band array operates from 27.8-28.65 GHz with gain of 12.3 dBi. The designed array provides 1) high gain by utilizing higher order modes; 2) improved port-to-port isolation at both the frequencies of >55 dBi at 5.9 GHz and >33 dB at 28 GHz, respectively; 3) a low-profile single layer design and very simple structure; 4) a maintained inter-element spacing of 0.5X; and 5) a low-cost and easy fabrication with standard PCB.

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TABLE 3. Performance comparison between the implemented array and other shared-aperture antenna arrays

| Operating bandwidth (GHz) | Frequency ratio | Number of arrays | Dimensions (λ₀/2 × λ₀/2 × λ₀/2) | Port isolation (dB) | Gain (dBi) | Radiation efficiency (%) | Cross-polarization level | Configuration |
|--------------------------|-----------------|-----------------|----------------------------------|---------------------|------------|--------------------------|--------------------------|--------------|
| [12] 9.5-12.6 GHz/15.5-19.04 GHz | 1.43 | 4 × 4/4 × 4 | 2.87 × 2.58 × 0.032 | - | 17.43/18.26 dBi | - | >19 dB | Single layer |
| [13] 3.0-6.4 GHz/7.2-8.9 GHz | 1.54 | 2 × 2/4 × 4 | 1.94 × 1.94 × 0.081 | >15 dB/20 dB | 13.51/17.3 dBi | - | >19 dB/20 dB | Multi layer |
| [14] 1.07-1.24 GHz/8.3-10.3 GHz | 8.26 | 1/8 × 8 | 0.88 × 0.88 × 0.099 | >30 dB | 6.9/24.1 dBi | - | >17 dB/20 dB | Multi layer |
| [15] 3.12-3.42 GHz/9.2-9.36 GHz | 2.906 | 1/12 elements | 1.06 × 1.06 × 0.017 | >25 dB | 8.5/11 dBi | - | >28.1 dB/19 dB | Single layer |
| [16] 2.94-2.96 GHz/9.8-9.98 GHz | 3.3 | 4 × 8/1 × 2 | 1.81 × 1.04 × 0.018 | >25.3 dB | 18.3/9.5 dBi | - | >17 dB | Multi layer |
| [17] 2.05-2.70 GHz/23-29 GHz | 10 | 2/16 elements | 0.56 × 0.48 × 0.003 | >20 dB | 4.5/12.3 dBi | - | >56% | Single layer |
| [18] 1.9-3.2 GHz/25.7-30.50 GHz | 11.2 | 2 × 0/8 elements | 0.95 × 0.54 × 0.006 | >15 dB/25 dB | 59.9 dBi | - | >65% | Single layer |
| [19] 5.44-6.57 GHz/29.2-30.9 GHz | 5 | 1/1 element | 1.6 × 1.6 | - | 4.5/9.37 dBi | - | >10 dB | Multi layer |
| **This work** | | | | | | | | | |
| 5.84-5.94 GHz/27.75-28.47 GHz | 4.74 | 2 × 2/1 × 2 | 1.47 × 1.96 × 0.01 | >55 dB/ >38 dB | 10 dB/11.85 dB (Sim.) | >86%/96% | >23 dB/25 dB (Sim.) | Single layer |

λ₀ = Wavelength of the center frequency of the lower frequency band

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