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Diversity Antenna for Vehicular Communications in Microwave and mm-Wave Bands

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***Abstract*—A dual band diversity antenna is proposed for vehicular communications. The antenna works at both 5.9 GHz and 60 GHz simultaneously which makes it a suitable candidate for next generation intelligent transportation systems (ITS). High isolation of the two antenna elements with transmission less than -25 dB at both bands guarantees an optimum diversity performance. The theoretical limit of the diversity gain according to the propagation condition is investigated. It is shown that the effective diversity antenna gain (DAG) of the design is 8.7 dB in a uniform propagation scenario which is only 0.04 dB less than the theoretical limit.**

Keywords—Covariance matrix, diversity antenna gain, mean effective gain, vehicular communications.

I. INTRODUCTION

Intelligent transportation systems (ITS) are established for communication between vehicles and road infrastructures at 5.9 GHz. Their main purpose is to enhance the road safety and traffic efficiency [1]. A reliable, high speed link with sufficient capacity is vital in ITS. Applying antenna diversity technique is a promising method to fulfil these requirements [2]. For having links with even higher speed and capacity, it was suggested to adopt mm-wave bands for ITS and devising a network of fifth-generation (5G) communication [3]. Therefore, the vehicle on-board unit should be upgraded to work at both classic ITS band (5.9 GHz) and mm-wave band. It is preferred to have an antenna design capable of working at both bands simultaneously instead of having two different antennas. This is crucial in compact energy efficient systems that employ antenna diversity technique.

The development of 5G technology has motivated the designers to propose multiple antennas working at different bands integrated on the board of the handheld device [4]. However, the number of works in the literature that cover both frequency bands simultaneously with single antenna is limited. The existing works that might be used in ITS application are usually suffering from complicated structures consisting of filters and connections to ground via holes [5]. A diversity antenna system is proposed in this work. The antenna is capable of working at both 5.9 GHz and 60 GHz simultaneously. The simple structure of the antenna along with the high diversity antenna gain (DAG) close to the theoretical limit makes it a suitable candidate for next generation compact ITS on-board units. The structure of the antenna is introduced in the next section and the simulation results are presented. The DAG evaluation of the design at each frequency band is discussed after that and the performance is compared with the maximum possible theoretical limit.

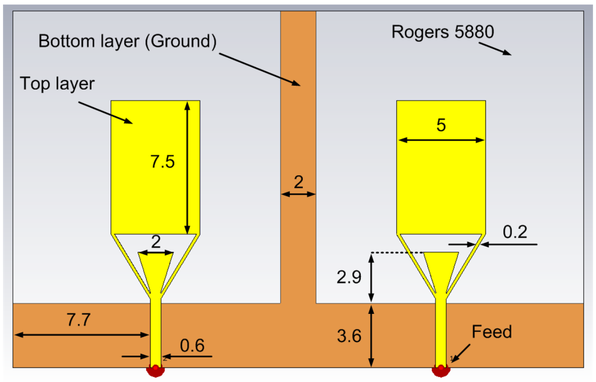

Fig. 1. Structure of the proposed dual-band diversity antenna. All the values are in millimeters.

II. DUAL-BAND DIVERSITY ANTENNA

A. Antenna Structure

The structure of the designed antenna is depicted in Fig. 1. It is comprised of a double-sided Rogers 5880 substrate with 2.2 permittivity and dimensions of 32×20×0.2 mm^3. Two monopole diversity antennas are located on top layer and the T-shaped ground plane on the back of the substrate. The monopole antenna is made of three parts: The microstrip feed line, the trapezoid radiator, and the square radiator. The microstrip feed line conveys the microwave and mm-wave signals to the patches. The length of this line is important for impedance matching particularly at 60 GHz where the line behaves as a periodic filter. This behavior can be controlled by selecting the suitable length and reducing the thickness of the substrate. The trapezoid patch contributes to the radiation at 60 GHz. The square patch radiates at 5.9 GHz. It is connected to the feed line with two thin inductive lines. This not only helps in impedance matching but also prevents the signal of traveling to square patch at 60 GHz.

B. Simulation Results

The structure of the antenna is modeled using CST simulation tool. The frequency response is plotted in Fig. 2. The S-parameters show small reflection coefficient at both frequency bands and high isolation between two antennas as S21 is below -25 dB at both frequency bands. The radiation pattern of the antenna at the two frequency bands is depicted in Fig. 3. The gain of the antenna is 2.5 dBi at 5.9 GHz and 6.9 dBi at 60 GHz. The T-shape ground plane helps in increasing the isolation between the two antenna elements. This is done by altering the surface currents and radiation pattern. The main axis of the torus-shape radiation pattern at 5.9 GHz is deviated from Y axis as can be seen in Fig. 3 (a). Therefore, the field vectors of the two antennas would not coincide on each other. This increases the isolation and

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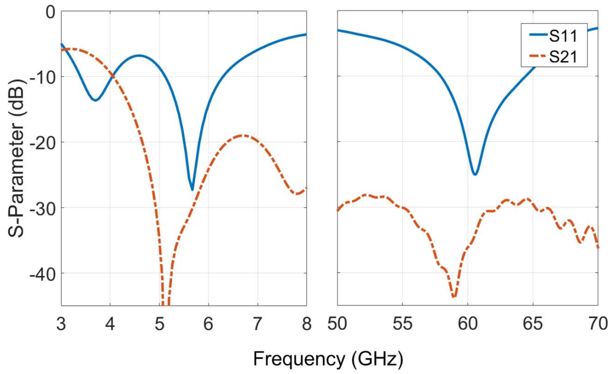
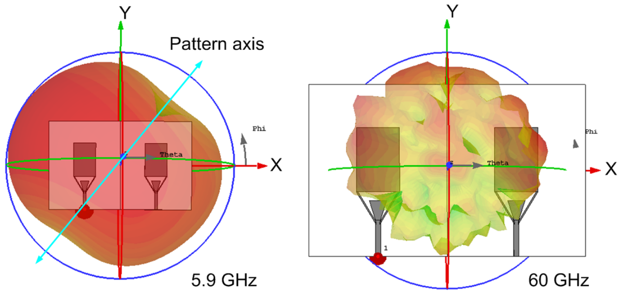


Fig. 2. S-parameters of the antenna at two frequency bands.



(a) (b)

Fig. 3. Radiation pattern of the proposed antenna when a single port is excited. (a) At 5.9 GHz with 2.5 dBi gain. (b) At 60 GHz with 6.9 dBi gain.

reduces the correlation between the two antennas which leads to optimum diversity gain. This is investigated in the next section.

III. COVARIANCE MATRIX AND DAG EVALUATION

The DAG of the antenna in a maximal ratio combining (MRC) scenario is evaluated in this section and compared with the theoretical limit and maximum possible DAG in the certain propagation condition. The DAG can be determined using covariance matrix of the two antennas. The optimum possible covariance matrix for achieving the maximum DAG is studied first and the DAG of the proposed antenna is evaluated after that.

A. *Optimum Covariance Matrix*

MRC is the optimum combining scheme compared with selection combining (SC) and equal gain combining (EGC) in terms of achieving maximum DAG [6]. It is useful to determine the optimum covariance matrix for MRC which leads to the maximum possible DAG among all the practiced combining schemes. The covariance matrix of a diversity system with two antenna elements is traditionally calculated using:

$$\mathbf{\Lambda} = \Gamma_0 \begin{bmatrix} G_{e1} & \sqrt{G_{e1}G_{e2}\rho_e} \\ \sqrt{G_{e1}G_{e2}\rho_e} & G_{e2} \end{bmatrix} \tag{1}$$

where Γ_0 is the average signal to noise ratio (SNR) received by the reference antenna that is an ideal dual polarized isotropic antenna. G_{e1} and G_{e2} are the mean effective gain (MEG) of the two antenna elements and ρ_e is the envelope correlation coefficient (ECC) [7].

An ideal covariance matrix normalized to Γ_0 is a diagonal matrix in fact. The equal diagonal elements represent a maximum received power which is evenly distributed between two ports of the antenna. The non-diagonal elements equal to zero represent a minimum ECC. So, reaching the minimum ECC and maximum possible MEG is the target of designers to get close to the ideal diagonal covariance matrix and consequently maximum DAG. ECC is generally related to the interaction of field pattern of antenna elements and propagation environment. A value less than 0.5 is acceptable in practice according to standard [8]. A well-designed diversity antenna can easily reach this standard. Thus, the main focus here is on MEG which determines the diagonal elements of the matrix. It can be calculated by applying:

$$G_e = \int_0^{2\pi}\int_0^{\pi}\{\frac{XPR}{1+XPR}G_\theta(\theta,\phi)P_\theta(\theta,\phi) + \frac{1}{1+XPR}G_\phi(\theta,\phi)P_\phi(\theta,\phi)\}\sin\theta d\theta d\phi \tag{2}$$

where XPR is the cross polarization factor, G_θ and G_ϕ are the θ and ϕ components of the antenna power gain, and P_θ and P_ϕ are the θ and ϕ components of the angular power distributions of the incoming wave respectively [9].

It is inferred from (2) that MEG is dependent on antenna radiation properties and propagation environment. The maximum possible MEG for each antenna element is equal to the gain of the antenna. For example, the MEG of a half wavelength dipole antenna can never exceed 2.15 dBi. Certain propagation condition is required to achieve this maximum limit. The incoming power needs to be received just from the angle where the maximum antenna gain exists, and the polarization of the propagation environment should be only in the same direction as the antenna. For example, if the antenna is aligned in parallel to Z axis the incident power should be arrived from θ=90 in XY plane and the polarization should be parallel to Z axis. Now, if the angle of arrival is spread symmetrically from two sides of θ=90 with the same polarization, the MEG starts to get less than 2.15 dBi until the point the range of θ is [0, 180] where MEG is equal to 0 dBi which is the gain of the isotropic antenna.

In a uniform propagation environment not only the angle of arrival is uniform but also the XPR=1 which means both horizontal and vertical incident powers exist simultaneously. This propagation environment is important as it is commonly considered in channel analysis and antenna evaluation. The MEG of an arbitrary antenna is equal to 0.5 (-3 dBi) in such a multipath uniform environment [9]. It can be concluded from this discussion that there are two critical values for MEG in practical condition. Firstly, the maximum limit of 1 (0 dBi) in an environment with single polarized uniform incident power. Secondly, the fixed value of 0.5 (-3 dBi) in a dual polarized uniform propagation environment. The corresponding optimum normalized covariance matrix for these two critical values is a unitary matrix and a half unitary matrix respectively. A half unitary matrix is a diagonal matrix with diagonal elements equal to 0.5.

B. *DAG Evaluation*

The covariance matrix of the proposed antenna is determined in this subsection considering a uniform propagation environment with XPR=1. The MEG is equal to 0.5 in this situation as discussed above. Therefore, in a traditional covariance matrix method the diagonal elements of the matrix are fixed to 0.5 and the only determining factor is ECC which is present in non-diagonal elements. The drawback of the traditional covariance matrix method is that the DAG is only depended on ECC whereas the impedance matching of the system also affects DAG in reality. The results of the covariance matrix are only valid for a system with perfect impedance matching. The DAG comparison of different designs would not be fair in this case. In addition, ECC values less than 0.5 would not change DAG significantly. So, the DAG plot of different designs with acceptable standard ECC would be very close to each other.

A novel covariance matrix method introduced in [2] is used in this work which is free from the disadvantages of the classic method. This method relies on the reciprocity principle of the diversity antenna system and uses the effective length of the antenna elements instead of ECC and MEG. The covariance matrix can be calculated using following equations:

$$\mathbf{\Lambda} = \Gamma_0 \frac{\omega \mu_0 k}{\pi Z_0} \mathbf{W} \left(\int_{\Omega} \mathbf{L}_e(\Omega) \mathbf{P}(\Omega) \mathbf{L}_e^H(\Omega) d\Omega \right) \mathbf{W}^H \tag{3}$$

$$\mathbf{W} = \left(\mathbf{I} + \mathbf{Z}^T \mathbf{Z}_L^{-1} \right)^{-1} \tag{4}$$

$$\mathbf{P}(\Omega) = \begin{bmatrix} \frac{\mathrm{XPR}}{\mathrm{XPR}+1} p_\vartheta(\Omega) & 0 \\ 0 & \frac{1}{\mathrm{XPR}+1} p_\varphi(\Omega) \end{bmatrix} \tag{5}$$

where ω is the angular frequency, μ_0 is the free space permeability, k is the wavenumber, Z_0 is the transmission line characteristic impedance which is 50 Ω usually. $\mathbf{L}_e$ is the effective length matrix of the diversity antenna that is calculated using the field pattern of the design. $\mathbf{Z}$ and $\mathbf{Z}_L$ are the impedance matrix of the antenna and termination circuit respectively. The propagation environment is determined by matrix $\mathbf{P}(\Omega)$. In a uniform propagation environment $p_\vartheta(\Omega)=p_\varphi(\Omega)=1/(4\pi)$. For more details see [2].

The validity of the novel covariance matrix method was confirmed in [2] by comparing the results with the classic method which agrees to each other in a perfect impedance matching scenario [2]. Thus, the critical unitary and half unitary covariance matrices discussed in the previous subsection are valid for the novel method as comparison limits as well. The covariance matrix of the proposed antenna is calculated at both working frequency bands using the new method. The field pattern of the antenna is extracted from the simulation result using CST software and $\mathbf{L}_e$ is calculated. The impedance matrix $\mathbf{Z}$ is directly acquired from CST impedance plots. A 50 Ω diagonal matrix is considered for $\mathbf{Z}_L$. The characteristic impedance of the transmission line Z_0 is also set to 50 Ω. A uniform propagation environment where XPR=1 is selected for determining $\mathbf{P}(\Omega)$. The ideal covariance matrix in this condition is a half unitary matrix. The results at the two bands are as follows:

$$\mathbf{\Lambda}_{5.9GHz} = \begin{bmatrix} 0.4953 & -0.0054 \\ -0.0054 & 0.4953 \end{bmatrix} \tag{6}$$

$$\mathbf{\Lambda}_{60GHz} = \begin{bmatrix} 0.4988 & -0.0003 \\ -0.0003 & 0.4988 \end{bmatrix}. \tag{7}$$

The corresponding cumulative distribution function (CDF) of each covariance matrix is determined using [7, eq. (7)] which relates the CDF to the eigenvalues of matrices. The CDF of the dual antenna system at each frequency is plotted in Fig. 4. The effective DAG of the design at 1% outage probability (OP) is 8.7 dB as shown in the figure. The CDF of a uniform dual polarized propagation environment with a half unitary covariance matrix is also plotted in the figure. The effective DAG of the proposed design is only 0.04 dB less than this ideal limit. The covariance matrix of an ideal single polarized propagation environment is a unitary matrix which is twice of the covariance matrix in a dual polarized uniform environment. So, it is expected to have 3 dB difference between the effective DAG of these two conditions which is confirmed in Fig. 4.

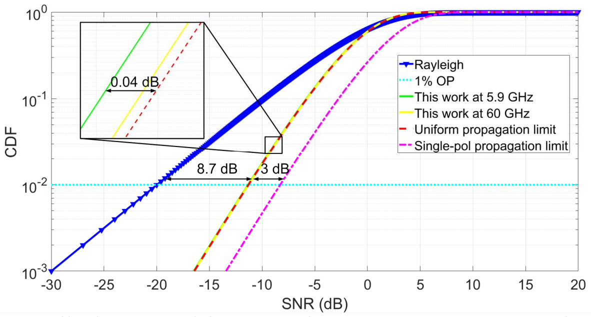


Fig. 4. Effective DAG of the proposed antenna at 1 % OP compared with the limits in dual polarized and single polarized uniform propagation environments for 2 element diversity antenna systems.

IV. CONCLUSION

A diversity antenna system for vehicular communication working at both microwave and mm-wave bands was proposed in this work. The theoretical limit for diversity performance of a two-antenna system was investigated by analysing the classic covariance matrix. The performance of the antenna was evaluated using a new covariance matrix method. It was shown that the diversity gain of the proposed design is close to the theoretical limit.

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