Covariance Matrix Evaluation of a Diversity Slot Antenna for Vehicular Communications

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***Abstract*—A dual-port slot antenna is proposed for vehicular communications. The antenna works at 5.9 GHz in intelligent transportation system (ITS) band. The diversity performance of the design is evaluated using a novel covariance matrix methodology based on reciprocity theorem. The performance evaluation at the early design stage is explained for the first time by relating the radiation pattern of the designed antenna to the effective length matrix. The antenna offers -21 dB of isolation and a minimum gain of 6.5 dB before mounting on the vehicle roof. The evaluated effective diversity gain is 8.6 db.**

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

I. Introduction

Multiport antenna (MPA) elements are an important part of a MIMO system. A well-designed MPA can directly influence the performance of the MIMO system by enhancing the signal to noise ratio which can be evaluated using diversity antenna gain (DAG) metric. It is preferred to evaluate DAG at the early design stage as a cost and time effective approach. This can be achieved using covariance matrix methods [1]. In conventional covariance matrix method the envelope correlation coefficient (ECC) and mean effective gain (MEG) of the MPA are required [2].

A novel covariance matrix method was proposed in [3] which relies on the reciprocity principle of the MPA system. The matrix can be calculated directly using the effective length of the MPA without the need of ECC and MEG. For applying the covariance matrix method at the early design stage, the radiation pattern data of the designed MPA should be acquired from antenna simulation software and certain procedure needs to be followed. However, this was not covered in [3]. In this paper, the procedure for applying the novel covariance matrix methodology at the early design stage is explained and the diversity performance of a dual-port antenna system designed at 5.9 GHz is evaluated using this method. The antenna design is introduced in the next section followed by the covariance matrix calculation and the evaluation results.

II. Dual-Port Slot Antenna

A. Antenna Structure

A dual-port slot antenna is designed at 5.9 GHz for vehicular communications. The vertically polarized structure offers an omni-directional radiation pattern which is required in intelligent transportation systems (ITS) [4]. The antenna structure is depicted in Fig. 1 (a). It is comprised of four slots and a conductive ground bottom. Two of the adjacent slots

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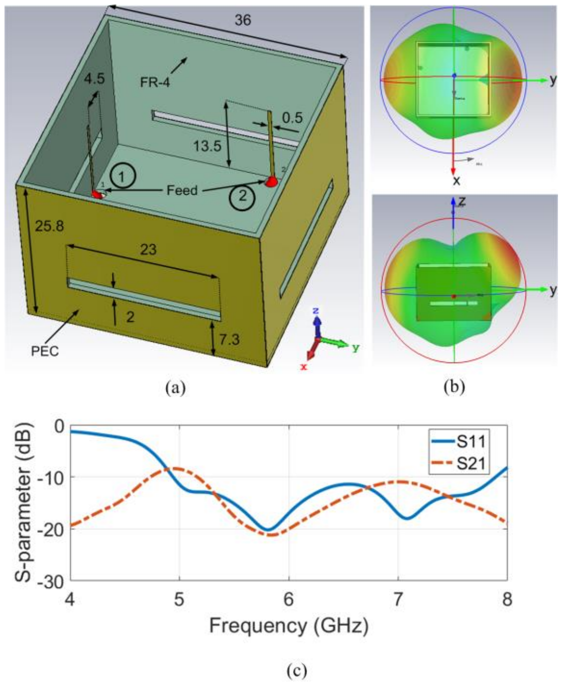

Fig. 1. (a) Structure of the proposed design. All the values are in millimeters. (b) Radiation pattern of port 1. (c) S-parameters of the ports.

are excited by two different ports as can be seen in the figure. There is another slot in front of each port-excited slot at the distance of 3λ/4 at 5.9 GHz. These slots are excited by the traveled wave inside the system. The structure of the antenna is composed of FR-4 substrate with 0.8 mm thickness and permittivity of 4.3. The length of the slot is approximately λ/2 at 5.9 GHz. The asymmetric location of the slots on each wall helps to elevate the radiation pattern according to horizon. This would prevent the increased mutual coupling when the antenna is installed on top of the vehicle. The slots are excited by microstrip lines from inside the structure. The length, width, and location of the microstrip line is optimized for achieving an acceptable bandwidth and impedance matching to 50 ohm port.

B. Simulation Results

The structure of the antenna is modeled using CST simulation tool. The radiation pattern of the antenna when port 1 is excited is illustrated in Fig. 1 (b). The gain of each port is around 6.5 dB. This value would increase by placing the antenna on a large conducting plate such as the car roof. Each antenna port provides two radiation lobes to cover azimuth angles around the car. The S-parameters of the two ports is plotted in Fig. 1 (c). The reflection coefficient and transmission of each port is -19 dB and -21 dB respectively. This confirms a good matching and isolation of the ports.

III. Covariance Matrix and Diversity Evaluation

A. Matrix Calculation Process

The novel covariance matrix method introduced in [3] can be calculated using following equations:

$$\mathbf{\Lambda} = \Gamma_0 \frac{\omega\mu_0 k}{\pi Z_0}\mathbf{W}\left(\int_\Omega \mathbf{L}_e(\Omega)\mathbf{P}(\Omega)\mathbf{L}_e^H(\Omega)d\Omega\right)\mathbf{W}^H \tag{1}$$

$$\mathbf{W} = \left(\mathbf{I}+\mathbf{Z}^T\mathbf{Z}_L^{-1}\right)^{-1} \tag{2}$$

$$\mathbf{P}(\Omega) = \begin{bmatrix} \frac{\text{XPR}}{\text{XPR}+1}p_\vartheta(\Omega) & 0 \\ 0 & \frac{1}{\text{XPR}+1}p_\varphi(\Omega) \end{bmatrix}. \tag{3}$$

Please refer to [3] for more details. The $\mathbf{P}(\Omega)$ matrix is independent from the MPA system as it determines the power density of the received signal. In a uniform propagation environment, XPR = 1 and $p_\vartheta(\Omega) = p_\varphi(\Omega) = 1/(4\pi)$. The $\mathbf{W}$ and $\mathbf{L}_e$ matrices should be determined after designing the MPA as they are dependent to the radiation and impedance characteristics of the MPA. Finding the $\mathbf{W}$ matrix is straightforward. $\mathbf{Z}$ is calculated using antenna simulation software tools and $\mathbf{Z}_L$ is determined by the designer according to the termination condition of the system.

The effective length matrix is comprised of transverse ϑ and φ components. In a two-port MPA system it is defined by:

$$\mathbf{L}_e = \begin{bmatrix} \ell_{\vartheta_1} & \ell_{\varphi_1} \\ \ell_{\vartheta_2} & \ell_{\varphi_2} \end{bmatrix} \tag{4}$$

where each row of the matrix defines the effective length components of a different antenna in the system. According to [5], these components can be related to the antenna far-field radiation vector using:

$$\ell_{\vartheta/\varphi} = j\frac{4\pi r}{k\eta I_{in}}E_{far}(\vartheta,\varphi)e^{jkr} \tag{5}$$

where r is the distance from the antenna, k is the wavenumber, η is the characteristic impedance of the propagation environment, E_{far} is the far-field radiation vector, and I_{in} is the input current to the antenna terminals.

On the other hand, the field pattern data exported from an antenna simulation software tool such as CST is related to the far-field radiation vector by:

$$E_{pattern}(\vartheta,\varphi) = rE_{far}(\vartheta,\varphi)e^{jkr}. \tag{6}$$

Comparing (5) and (6), it can be concluded the effective length components are related to the antenna field pattern by:

$$\ell_{\vartheta/\varphi} = j\frac{4\pi}{k\eta I_{in}}E_{pattern}(\vartheta,\varphi) = j\frac{2\lambda}{\eta I_{in}}E_{pattern}(\vartheta,\varphi) \tag{7}$$

where λ is the wavelength.

After designing the MPA in the simulation software and obtaining the field pattern data, (7) can be applied to determine the effective length matrix. It is important to mention that for obtaining the field pattern data a discrete port of a current source type should be used to feed the antenna in CST software, whereas a S-parameter port is required for calculating the Z matrix. After substituting the matrices in (1), the double integral over solid angle should be calculated. This can be done by applying a numerical solution such as trapezoidal rule. Finally, the covariance matrix is calculated.

TABLE I
Covariance Matrix Comparison

Reference	This work	[6]	[7]
Covariance matrix	$\begin{bmatrix} 0.49 & 0.0063 \\ 0.0063 & 0.49 \end{bmatrix}$	$\begin{bmatrix} 0.43 & 0.0103 \\ 0.0103 & 0.43 \end{bmatrix}$	$\begin{bmatrix} 0.37 & 0.0158 \\ 0.0158 & 0.37 \end{bmatrix}$

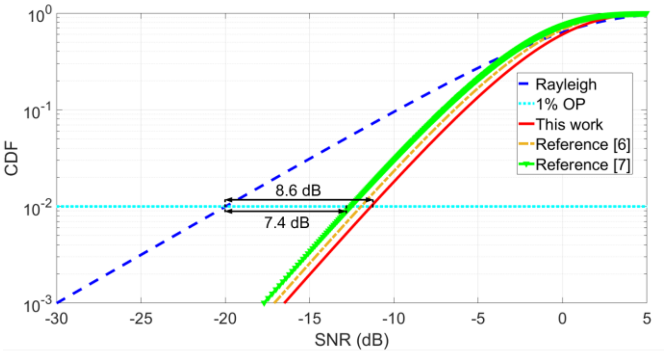

Fig. 2. Effective DAG of the proposed antenna at 1% OP compared with two other works.

B. Evaluation of the Two-Port Slot Antenna

The covariance matrix of the proposed two-port slot antenna is evaluated following the introduced calculation process. A uniform propagation environment is considered for $\mathbf{P}(\Omega)$ and a 50 ohm 2×2 diagonal matrix for $\mathbf{Z}_L$. The antenna design is simulated in CST software and the radiation pattern data is obtained at 5.9 GHz. The covariance matrix of the design is calculated and compared with two other references at the same frequency in Table I. High port isolation and low radiation pattern correlation makes the off-diagonal entries of the matrix close to zero. The CDF of output SNR in an MRC diversity scenario is calculated using [2, eq. (7)] and the result is plotted in Fig. 2 compared with two other references. The effective DAG at 1% outage probability (OP) is also shown in the figure which is 8.6 dB for the designed antenna.

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