A Dual Circularly Polarised Contrawound Quadrifilar Helix Antenna for Land Mobile Satellite MIMO Terminal

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***Abstract*— A dual circularly polarised Contrawound Quadrifilar Helix Antenna (CQHA) is proposed for land mobile satellite MIMO systems. The CQHA is combination of two QHAs with opposite winding rotation where one is positioned inside of the other. Low return loss and isolation of the CQHA elements is achieved by varying the radius of the outer QHA while the inner QHA is fixed. Preliminary evaluation of its MIMO capability is done by calculating the mean effective gain and analysing the polarisation correlation of each QHA. A deployment configuration of two CQHAs for land mobile satellite /DVB-SH vehicular rooftop antenna is also proposed in this paper. Mean effective gain of the CQHA configuration for a complete azimuth plane is calculated by considering Gaussian Angle of Arrival model for the angular distribution of the incident waves.**

I. Introduction

Multiple-input Multiple-output (MIMO) antenna techniques have become one of the fundamental technologies in the future wireless communication systems due to its significant capacity increase without additional bandwidth. The implementation of MIMO in land mobile satellite (LMS) systems is more restrictive compared to the terrestrial because of the different characteristics of the propagation channel (e.g. scattering environment and free space path loss). Polarization multiplexing has been shown to nearly double the theoretical capacity of LMS systems where a single satellite is equipped with two orthogonal polarised antennas transmitting to a receiver with a dual-polarised antenna [1].

As MIMO techniques are being adapted for mobile satellite communication, a compact antenna for the LMS MIMO terminal is needed to realise such a system. The quadrifilar helix antenna (QHA) is the most popular handheld terminal antenna for LMS systems due to its hemispherical/cardioid radiation pattern, good axial ratio, wide circular polarised beam and low manufacturing cost [2]. Polarisation of the QHA depends on the winding direction of the elements. The direction of the co-polarised radiation pattern depends on the feeding phase of the QHA. Complete reference on the QHA design for land mobile satellite systems can be found in [3].

To cater for the LMS MIMO system requirement, a multifilar helix antenna has been chosen as the basic structure of the dual-polarised antenna. In this paper, a dual circularly polarised contrawound quadrifilar helix antenna is proposed for the LMS MIMO receiver terminal. High frequency simulation using CST Microwave Studio is utilised to optimize the CQHA design. Validations of the simulation results are done by fabricating a prototype of the CQHA and its radiation and impedance properties are measured.

Its MIMO capability is evaluated by analysing the complex cross correlation between the CQHA and also its mean effective gain (MEG). Finally, a configuration of two CQHAs is proposed for a vehicular rooftop antenna and its mean effective gain is evaluated.

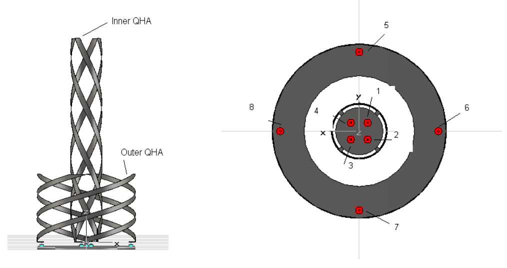
II. CQHA Design

Proposed design of the CQHA with dual polarization is based on the combination of two QHAs with opposite windings. The structure of CQHA is such that one QHA is inside of another QHA as shown in Fig. 1. The limitation of this design is the strong mutual coupling between the antennas due to the close distance, which will reduce the antenna radiation efficiency. In order to decrease the mutual coupling, the distance between the antennas needs to be increased. This can be done by increasing the radius of the outer QHA while keeping the radius of the inner QHA fixed. However the distance is limited by the maximum radius achievable by a QHA with 0.75 wavelength element length.

The axial length of the CQHA, L_x can be calculated based on the equation below [3]

$$L_x = N\sqrt{\frac{1}{N^2}\left(L_{element} - 2r\right)^2 - \left(2\pi r\right)^2} \quad (1)$$

where N is the turn, r is the radius of the QHA and $L_{element}$ is the element length of the QHA.

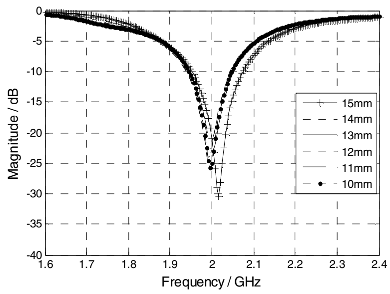


(a) (b)

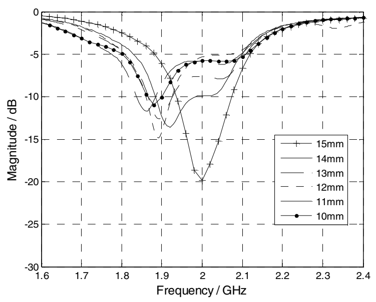
Fig. 1 a) Dual polarised Contrawound Quadrifilar Helix Antenna and b) port numbering of the CQHA

III. Simulation and Measurement

A parametric study to find the most optimum distance between inner and outer QHA at 2GHz operating frequency was conducted by electromagnetic simulation using CST Microwave Studio. The inner QHA radius is fixed at 7mm while the radius of the outer QHA is varied from 17mm to 22mm. Radius of inner QHA is fixed at 7mm due to its beam pattern that only realisable at minimum radius. This variation of outer radius corresponds to separation distance from 0.067λ to 0.1λ at 2GHz frequency. Several performance parameters of the CQHA simulation are return loss of the antenna elements, mutual coupling between antenna elements and co-polar and cross-polar radiation patterns of each QHA. Fig. 2 shows the effect of the outer QHA variation from 17mm to 22mm on the return loss of element 1 and element 5 on the CQHA. It can be concluded from the return loss result that the minimum separation distance of 15mm or 0.1λ at 2GHz frequency between the inner and outer QHA is required for the CQHA to radiate efficiently.



(a)



(b)

Fig. 2. Return loss of a) element 1 and b) element 5 on the CQHA with the difference between radius of inner and outer QHA from 10mm to 15mm.

Based on the simulation results, a CQHA with the distance of 0.1λ at 2GHz frequency between the inner and outer QHA has been chosen for prototype fabrication. Table I details out the physical parameters of the simulated and fabricated CQHA operating at 2GHz frequency. The axial length of the CQHA is calculated using equation (1). The CQHA is designed so that the inner QHA radiates a left hand circular polarisation while the outer QHA radiates the orthogonal polarisation. Its radiation and impedance properties were measured and its comparison with simulation is discussed in sections below.

TABLE I
Physical Parameters of the CQHA

Parameter	CQHA with 0.1λ separation distance between inner and outer QHA	
	Inner QHA	Outer QHA
Turn, N	1	0.75
Element length	0.75λ	0.75λ
Axial length (mm)	90	30
Radius (mm)	7	22

A. Return Loss and Isolation

Return loss and isolation of each CQHA element were measured and its results are compared with simulation. In this paper, only the results of element 1 on the inner QHA and element 5 on the outer QHA are shown as the results are also applicable to other elements due to CQHA rotational symmetry (element is numbered based on its port numbering). Fig. 3 shows the simulated and measured return loss of element 1 and 5 of the CQHA. The measured return loss of element 5 is significantly less than the simulated data because of fabrication imperfection of the QHA with bigger radius and its feeding network.

The mutual coupling between CQHA elements can be categorised into 2 components: 1) intra coupling which indicates the mutual coupling between elements in the same QHA and 2) inter coupling which shows the mutual coupling between elements in inner QHA and the outer QHA. With the same reasoning as return loss, only the analysis of the simulated and measured isolation of the element 1 and 5 are shown in this paper.

The mutual coupling between element 1 and element 2 (intra coupling) and element 5 (inter coupling) is shown in Fig. 4 and mutual coupling between element 5 and element 6 (intra coupling) and element 1(inter coupling) is shown in Fig. 5. The inter coupling for both elements is below -15 dB at 2GHz which is significantly good for a separation distance of 0.1λ [12]. As expected, intra coupling in both QHAs is higher compared to inter coupling due to the close proximity of elements in the same QHA.

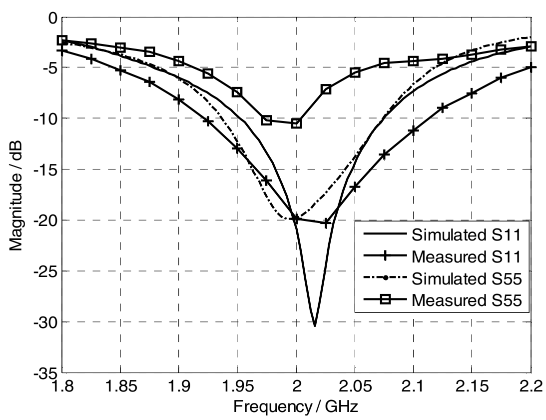


Fig. 3. Return loss of the element 1 on the inner QHA and element 5 on the outer QHA.

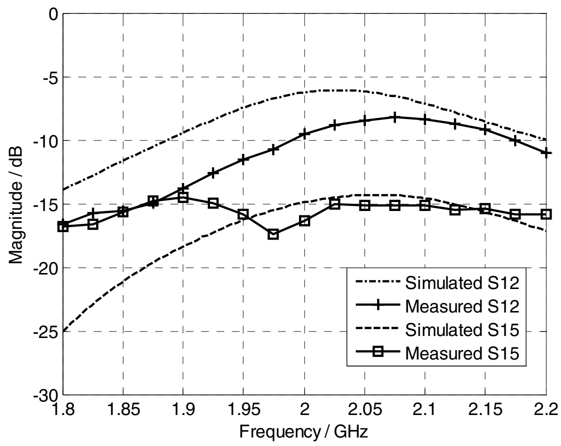


Fig. 4. Isolation between element 1 on the inner QHA with element 2 on the inner QHA and element 5 on the outer QHA.

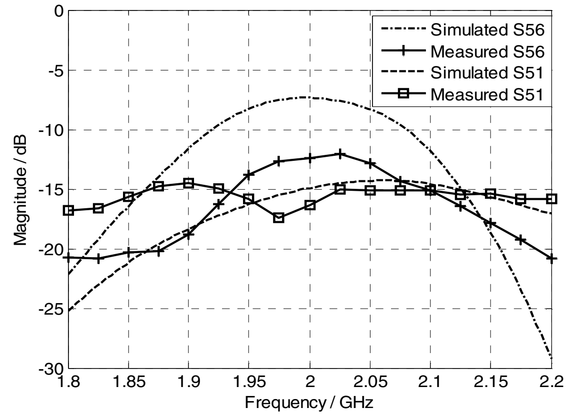


Fig. 5. Isolation between element 5 on the outer QHA with element 6 on the outer QHA and element 1 of the inner QHA.

B. Radiation Pattern

Radiation patterns of the CQHA for both polarisations are measured and compared with the simulated patterns. It is important for the CQHA radiation to have the same pattern as an isolated QHA for land mobile satellite systems. Fig. 6 and 7 show the elevation cut of co-polar and cross polar radiation patterns of the inner and outer QHA. As mentioned earlier, the inner QHA radiates left hand circular polarisation while the outer QHA radiates the orthogonal polarisation.

There are several significant differences between the measured and simulated co-polar and cross polar patterns. The first is the measured co-polar patterns have back lobe for both QHAs. Meanwhile, the measured cross polar patterns show a significant decrease in the backward direction but higher side lobes at one side of the upper hemisphere for both QHAs. One probable explanation for this discrepancy is the effect of the external feeding network of the CQHA in the measurement setup which has not been included in the simulation.

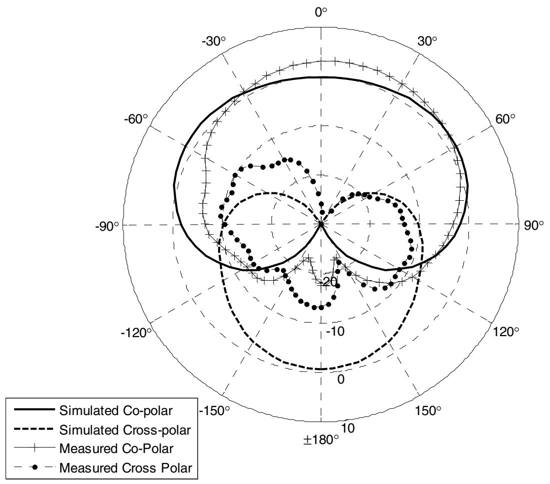


Fig. 6. Radiation pattern of the inner QHA (dBi).

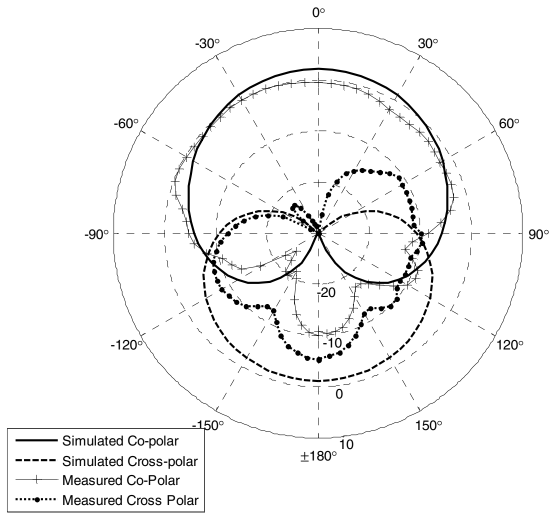


Fig. 7. Radiation pattern of the outer QHA (dBi).

IV. MIMO Evaluation of CQHA

A. Mean Effective Gain

Mean effective gain (MEG) of an antenna is defined as the ratio of the average received power by an antenna over a random route to that received by an isotropic antenna [4]. In terms of multiple antenna system, MEG of an antenna is used to determine the branch power ratio of the antenna compared to other antennas. Based on Taga's formulation [4], the MEG value is dependent on two important parameters of the channel which are the cross polar ratio, XPR and the Angle of Arrival (AOA) distribution of the incident waves. In order to evaluate CQHA, the XPR and AOA distribution of LMS channel need to be characterised accurately. XPR value has been extensively researched and is widely available in the literature [5], [6] however there is little published on the AOA distribution of LMS channel. Therefore, two assumptions are made to approximately model the AOA distribution in the MEG evaluation of a single CQHA. Firstly, the azimuth distribution is uniform for both polarisations due to the random orientation of the receiver terminal and scatterers [4] and the second assumption is the elevation distribution for both polarisations is Gaussian with varying mean from 20° to 60° depending on LMS satellite position [7]. 3-D simulated radiation pattern of the CQHA is then used in the MEG calculation.

Fig. 8 shows the MEG of the inner and outer QHA with XPR from -20 dB to 20 dB and mean of elevation distribution from 20° to 60° and standard deviation (std) of 20°. One important result is the difference in MEG value between both QHAs is less than -3 dB, which is acceptable for MIMO systems.

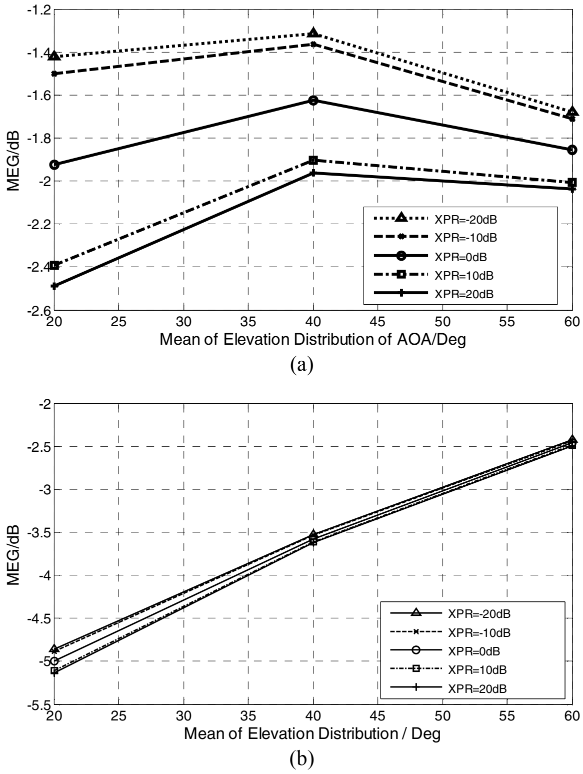


Fig. 8. MEG of a) inner QHA and b) outer QHA with varying XPR and mean of elevation distribution of the AOA.

B. Polarisation Correlation Analysis

Correlation between antennas determines the impact of the antennas on the realistic performance of the MIMO systems, aside from branch power ratio. In LMS MIMO system, the polarisation correlation of the antennas has to be evaluated so that polarisation multiplexing can be implemented. The closed form of polarisation correlation expression is given in [8]. To calculate the polarisation correlation, ρ_{12} of the CQHA which radiates circular polarisation, the equations in [8] are modified to include the phase difference of the antenna theta/phi field pattern, $\psi_{\theta 1}-\psi_{\theta 2}$ and $\psi_{\phi 1}-\psi_{\phi 2}$ as shown in (2).

$$\rho_{12}=\frac{\int_0^{\pi}\int_0^{2\pi}\left(XPR.\frac{|A_{\theta 1}||A_{\theta 2}|e^{j(\psi_{\theta 1}-\psi_{\theta 2})}}{\sqrt{\left(|A_{\theta 1}|^2+|A_{\phi 1}|^2\right)\left(|A_{\theta 2}|^2+|A_{\phi 2}|^2\right)}}p_\theta(\theta,\phi)+\frac{|A_{\phi 1}||A_{\phi 2}|e^{j(\psi_{\phi 1}-\psi_{\phi 2})}}{\sqrt{\left(|A_{\theta 1}|^2+|A_{\phi 1}|^2\right)\left(|A_{\theta 2}|^2+|A_{\phi 2}|^2\right)}}p_\phi(\theta,\phi)\right)\sin\theta d\phi d\theta}{\sqrt{\left(\int_0^{\pi}\int_0^{2\pi}\left(XPR.\frac{|A_{\theta 1}|^2}{|A_{\theta 1}|^2+|A_{\phi 1}|^2}p_\theta(\theta,\phi)+\frac{|A_{\phi 1}|^2}{|A_{\theta 1}|^2+|A_{\phi 1}|^2}p_\phi(\theta,\phi)\right)\sin\theta d\phi d\theta\right)\times\left(\int_0^{\pi}\int_0^{2\pi}\left(XPR.\frac{|A_{\theta 2}|^2}{|A_{\theta 2}|^2+|A_{\phi 2}|^2}p_\theta(\theta,\phi)+\frac{|A_{\phi 2}|^2}{|A_{\theta 2}|^2+|A_{\phi 2}|^2}p_\phi(\theta,\phi)\right)\sin\theta d\phi d\theta\right)}}$$

where

$A_{(\theta,\phi)n}$ = antenna n theta /phi field pattern

$\psi_{(\theta,\phi)n}$ = phase of antenna n theta/phi field pattern

$p_{\theta,\phi}(\theta,\phi)$ = elevation/azimuth distribution of AOA

Table II gives the value of polarisation complex correlation between two QHAs in the CQHA with the same environment characteristics as in MEG analysis. It is clearly shown that the polarisation correlation between the inner and outer QHA is nearly zero as both antennas radiates orthogonal polarisation with nearly the same radiation pattern. It is known from [8], [9] that polarisation correlation of antennas is inherent within angular correlation and two purely orthogonal polarized antenna with the same pattern will have zero angular and polarisation correlation. Therefore, it is expected of the CQHA to also have very low angular correlation. Table III shows the angular correlation coefficient between the inner and outer QHA in the same environment as polarisation correlation analysis.

TABLE II
POLARISATION COMPLEX CORRELATION OF THE CQHA

XPR / dB	Mean of Elevation Distribution / Deg		
	0	30	60
0	0.0089+j0.0064	0.0143+j0.0067	0.0164+j0.0066
6	0.0095+j0.0048	0.0142+j0.0061	0.0163+j0.0066
10	0.0097+j0.0042	0.0142+j0.0059	0.0163+j0.0065
20	0.0099+j0.0036	0.0142+j0.0057	0.0163+j0.0065

TABLE III
ANGULAR COMPLEX CORRELATION OF THE CQHA

XPR / dB	Mean of Elevation Distribution / Deg		
	0	30	60
0	0.0104+j0.0072	0.0162+j0.0065	0.0173+j0.0069
6	0.01+j0.0044	0.0139+j0.0057	0.0159+j0.0063
10	0.0098+j0.0032	0.0136+j0.0053	0.0157+j0.0062
20	0.0097+j0.0023	0.0134+j0.0050	0.0156+j0.0061

V. Deployment For Vehicular Rooftop

A deployment configuration of two CQHAs is proposed for land mobile satellite / DVB-SH [10] vehicular rooftop antenna as shown in Fig. 9. Both antennas are 30° tilted and positioned back-to-back in the horizontal plane so that the antennas are directed to the average elevation angle of LMS systems [11] and can complement each other by antenna selection for different azimuth orientation. The number of CQHA in the configuration is limited to 2 in order to have a balance between feeding complexity and azimuth plane coverage. To ensure the radiation and impedance properties of the CQHAs are not being distorted by the ground plane, the antennas is placed 50mm above the vehicular rooftop.

To analyse the MEG of the proposed configuration, the azimuth and elevation distributions of the AOA are characterised as Gaussian with varying mean and fixed standard deviation. Result of the MEG analysis with the mean and std of 30° for elevation distribution and varying mean and std of 30° for azimuth distribution is shown in Fig. 10. Using antenna selection method, the MEG of the inner and outer QHA will always be above -2.4 dB and -4.4 dB for the complete azimuth plane.

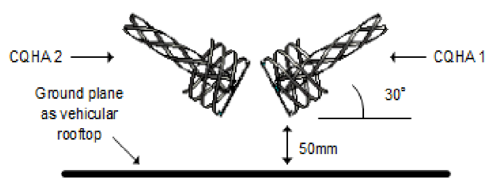


Fig. 9. Proposed deployment configuration of two CQHAs for vehicular rooftop antenna

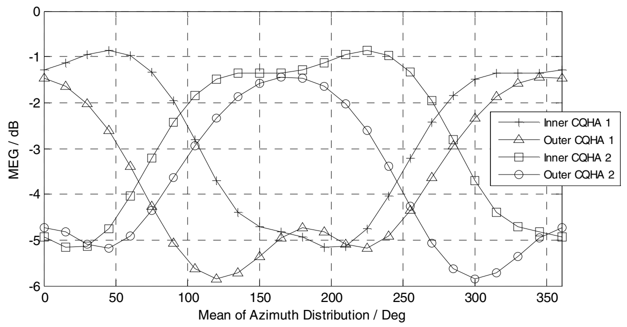


Fig. 10. MEG value of the CQHA configuration for vehicular rooftop antenna.

VI. Conclusion

The radiation and impedance characteristics of the proposed dual polarised CQHA has been simulated and measured to evaluate its performance for LMS MIMO terminal. Calculated mean effective gain and complex correlation coefficient of the CQHA indicate that it can be effectively used in LMS MIMO system. The proposed configuration of CQHA has been evaluated in terms of its MEG value and the result shows that by using antenna selection, the complete azimuth plane can be effectively covered by this configuration. The next step of this research will be to evaluate the MIMO theoretical capacity of the CQHA using simulation and also field measurement to validate the simulated result.

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