Exploitation of Elliptical Polarization for Improved Orthogonal Static Links

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Abstract— Orthogonal static or fixed links with polarization multiplexing can be formed by using dual polarized antennas with a low cross coupling from one polarization to the other. This is limited by the level of achievable polarization purity of two orthogonal dual polarized antennas. Any practical antenna is inherently elliptically polarized, resulting in either circular or linear polarization impurity. This work exploits such impurity where simple semi directional elliptically polarized antennas are designed to have minimal cross coupling. Results show a dual polar static link can reach the capacity limit using elliptical polarization, which is not reached with linear polarization. Channel measurements both in free space and indoor environments were carried out from 2.2 to 2.4 GHz using a derived cross polar ratio to quantify the impact of multipath scattering on static links.

Index Terms—Elliptical polarization, MIMO, Polarization Multiplexing

I. INTRODUCTION

STATIC or fixed links including a line of sight have utilized multiple input multiple output (MIMO) technology to substantially enhance the data rate within the same spectrum bandwidth, which has been useful in backhaul or fronthaul links [1]-[4], while they may also have benefit in nomadic links that are temporarily static [5]. Traditionally, MIMO exploits the rich multipath in a non line of sight environment while in a line of sight environment, multiple element antennas can achieve improved throughput by use of array or beamforming gain. If elements are sufficiently spaced, they can use spatial multiplexing though this requires substantially wide spacing between the antenna elements [6]. Therefore, multiplexing techniques that avoid this necessity and enable the antenna elements to be closer or co-located can be achieved by exploiting other degrees of freedom, such as the angular pattern, field and polarization in the case of mobile terminals with wide angles of arrival [7]-[9].

For static links with a line of sight, key candidate technologies researched in recent years for multiplexing data are orbital angular momentum (OAM) and polarization. Multiplexing via OAM is achieved by creating modes of differing phase changing radially around the direction of

propagation [10][11]. Though OAM has the potential to create several modes, it has two major drawbacks notably that the radiation pattern disperses over distance requiring spatially and radially separated receiver elements or lens correction at the transmitter, which makes it vulnerable to errors from multipath. Polarization multiplexing is therefore favorable in scenarios where directional antennas can be built to be resilient to depolarization in fixed links [12][13].

In line of sight polarization multiplexing, the antennas are designed to have either linear or circular polarization. Linear polarization has been more evident in fixed mmWave links [14] with almost free space propagation and highly directional antennas since scattering can easily de-polarize such channels. Circular polarization multiplexing has been a popular alternative particularly at lower frequencies showing more resilience to scattering [15] while for satellite communications it avoids effects of Faraday rotation [16][17] and it can also offer polarization diversity in non line of sight environments [18]. The polarization multiplexing in a line of sight depends upon the low scattering, directional antennas but also antenna polarization purity quantified by a high co to cross polar ratio.

Linear polarized antennas based on patch structures [19] [20] typically achieve a co to cross polar ratio of 20-30 dB while crossed dipole wire structures can achieve up to 40-50 dB [21] but a high precision feed structure and thin radiating elements are required. More typically their cross polarization is similar to a patch especially where wideband planar radiating elements are used [22].

The benefits of circular polarization over linear polarization in diversity and multiplexing have been studied in [23] to show the resilience to tilt angle around the axis of propagation, while this is studied further in [24] but also analyzing the three dimensional angular effects, spatial separation and axial ratio of the left and right hand circular polarized antennas. While these works show the benefit of circular polarization over linear polarization to improve diversity, polarization multiplexing relies on minimizing the polarization cross coupling at the boresight of the antenna. Circular polarized antennas in practical cases can achieve an axial ratio of less than 3dB [25][26] but will never reach 0dB for perfect circular polarization, which again limits the co to cross polar ratio to within 20-30 dB. This paper therefore sets a new novel paradigm hypothesized by the authors in [27] that exploits the fact that no practical antenna is either perfectly linearly or circularly polarized but elliptically polarized due to its imperfections. Therefore in this work, two linear polarized

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antennas, as a reference with 20-30 dB co to cross polar ratio, are compared with two antennas deliberately having elliptical polarization. Results show these two antennas inherently with low polarization cross coupling substantially improve the polarization multiplexing to reach the capacity limits in a line of sight with minimal multipath scattering. Measurements representing static links were carried out in free space and real indoor environments from 2.2 to 2.4 GHz. Where multipath is present, the antennas use angular and polarization diversity.

Section II begins with the relevant background theory behind linear and elliptical dual polar orthogonal static links including the derivation and purpose of the cross polar ratio. Section III shows the design of an elliptically polarized star shaped crossed dipole antenna used as an example antenna in this work. Sections IV and V show measurement results in both free space and indoor environments while section VI finishes with a conclusion.

II. ORTHOGONAL ELLIPTICAL POLARIZATIONS

The multiplexing capability of a line of sight static dual polar MIMO link must include a high cross polar power ratio (XPR), which is derived for linear and elliptical polarization in this section. XPR depends on both the antenna and the propagation channel as a measure of cross polarization coupling where a high (ideally infinite) XPR corresponds to low cross polarization coupling. Heavy multipath fading or a non line of sight would reduce the XPR to a low value through scattering depolarization, forming a diversity rich channel.

For a 2x2 dual linear polarized (DLP) static MIMO link, the channel matrix, $\mathbf{H}_{DLP}$ can be defined for vertical (V) and horizontal (H) transmit to receive polarizations as follows:

$$\mathbf{H}_{DLP} = \begin{pmatrix} h_{VV} & h_{HV} \\ h_{VH} & h_{HH} \end{pmatrix} \quad (1)$$

where XPR_V and XPR_H , for vertical and horizontal transmit polarization cases are defined in this work as follows [28]:

$$XPR_V = \left| \frac{h_{VV}}{h_{VH}} \right|^2 \quad XPR_H = \left| \frac{h_{HH}}{h_{HV}} \right|^2 \quad (2a) \quad (2b)$$

It is well known from antenna theory that a perfect circular polarized antenna transmits orthogonal vertical and horizontal polarizations of the same magnitude and the phase difference between the two is $\pm 90^\circ$ depending on whether the rotation of polarization is left or right hand [29]. An elliptical polarization does not meet these two criteria causing the polarization to have an axial ratio (AR) that is greater than 1, which would be infinite for perfect linear polarization. Additionally, as illustrated in Fig. 1, two orthogonal ellipses have a difference in tilt angle of 90° [31][31]. To reach the capacity limit, the ARs of the two ellipses must be equal and have opposite rotations. Two further XPRs are required, defined as XPR_{E1} and XPR_{E2} for ellipses 1 and 2 respectively in this work, which can undergo different de-polarization as they could be subjected to different multipath.

Fig. 1. Illustration of two orthogonally polarized ellipses.

Fig. 2. Illustration of the antenna and propagation channel architecture for dual elliptical polarization.

Fig. 2 shows a 2x2 MIMO link with four fixed channel coefficients, h_{ij} , which are determined by antenna polarization in the case of free space or they also have random values within Rayleigh or Rice distribution if multipath is present. It is possible that two separate antennas such as patches in [24] could be used to transmit two separate ellipses and a further two used to receive them. In this paper, two co-located linear antenna elements are used each at the transmitter and receiver and as such the phase weights $e^{j\phi_{T1}}$ and $e^{j\phi_{T2}}$ can be set to transmit two orthogonal ellipses while the two weights $e^{j\phi_{R1}}$ and $e^{j\phi_{R2}}$ can be set to receive them. By inspection of the input powers, P_{in1} and P_{in2} and output powers, P_{out1} and P_{out2} in Fig. 2, XPR_{E1} and XPR_{E2} are defined and derived as:

$$XPR_{E1} = \left. \frac{P_{out1}}{P_{out2}} \right|_{P_{in2}=0} = \frac{|h_{11} + h_{12}e^{j\phi_{R1}} + h_{22}e^{j(\phi_{T1}+\phi_{R1})} + h_{21}e^{j\phi_{T1}}|^2}{|h_{11} + h_{12}e^{j\phi_{R2}} + h_{22}e^{j(\phi_{T1}+\phi_{R2})} + h_{21}e^{j\phi_{T1}}|^2} \quad (3a)$$

$$XPR_{E2} = \left. \frac{P_{out1}}{P_{out2}} \right|_{P_{in1}=0} = \frac{|h_{11} + h_{12}e^{j\phi_{R2}} + h_{22}e^{j(\phi_{T2}+\phi_{R2})} + h_{21}e^{j\phi_{T2}}|^2}{|h_{11} + h_{12}e^{j\phi_{R1}} + h_{22}e^{j(\phi_{T2}+\phi_{R1})} + h_{21}e^{j\phi_{T2}}|^2} \quad (3b)$$

where the phase weights $e^{j\phi_{T1}}$, $e^{j\phi_{T2}}$, $e^{j\phi_{R1}}$ and $e^{j\phi_{R2}}$ are resolved to form maximum XPRs by means of a search algorithm. For perfect elliptical polarization multiplexing in total free space $h_{11} = h_{22} = h_C$ and $h_{21} = h_{12} = h_X$, while $h_C = \pm j h_X$. This corresponds to a case of infinite XPR, but also the eigenvalue decomposition (EVD) returns two equal eigenvalues setting two criteria for perfect elliptical polarization multiplexing. If multipath is present in the channel, the channel coefficients' magnitudes will have imbalance so XPR_{E1} or XPR_{E2} will not be infinite. While high XPR identifies low polarization cross coupling, EVD determines if the two elliptical polarizations (or eigenvalues) have equal magnitude, which will reach the capacity limit. Unequal eigenvalues correspond to one ellipse having different magnitude from the other.

III. DESIGN OF AN EXAMPLE ELLIPTICALLY POLARIZED ANTENNA

For this study, a simple semi directional elliptically polarized antenna is designed to operate in two modes, narrowband centered at 2.25 GHz and wideband operating from approximately 2.2-2.4 GHz. A diagram of the antenna design is shown in Fig. 3 (a). The antenna is based on a modification of a crossed dipole with a ground plane reflector. One of the ground arms is effectively removed from the crossed dipole and made into a common ground arm, which is connected to both coaxial ground braids.

Fig. 3. Diagram of a simple elliptically polarized semi directional antenna setup for a static link showing (a) the setup, key dimensions and (b) the two mirrored antennas designed for a static link measurement.

All three antenna arms in Fig. 3 (a) have equal length of 24 mm. Arms 1 and 2, connected to the inner core of the left and right coaxial cable, are parallel with the horizontal and vertical axis respectively. The ground arm on the other hand is slanted at 45°. The other two dimensions crucial to this design are the width of the square copper ground plane of 160 mm and the height of the semi rigid coaxial cable feeding the three antenna arms above the ground plane, which has a height of 29 mm. The length of extra coaxial cables from underneath the ground plane to the 180° hybrid coupler is arbitrary so long as they

have low loss and are equal in length. The purpose of the hybrid coupler is known to improve the isolation between two coupled antennas, while providing a modest impedance match over a wide bandwidth [32]. The two open circuit stubs, shown in green in Fig. 3(a) are used to achieve a good narrowband impedance match at 2.25 GHz and hence are added when the antenna is in narrowband mode.

To carry out measurements with elliptical polarization multiplexing, two versions of the antenna had to be built but they had to be a mirror image of each other when facing in a line of sight as shown in Fig. 3 (b). The antennas have been named “STAR” antennas by their shape so that STAR1 is the transmit antenna and STAR2 is the receive. Arm 1 is connected to port 1 of STAR1 at the transmit end and port 1 of STAR 2 at the receive end. Likewise arm 2 is connected to port 2 at the transmit end of STAR1 and port 2 at the receive end of STAR2. A photograph of the fabricated antennas is shown in Fig. 4.

Fig. 4. Photograph of the two elliptically polarized antenna prototypes. The antenna arms are highlighted in white for clarity

Measured results of the S-parameters of the antennas are shown in Fig. 5 for comparison between narrowband and wideband modes. To begin with, the reflection coefficients of ports 1-2, s_{11} and s_{22} , of both STAR1 and STAR2 in wideband mode are shown in Fig. 5 (a) while Fig. 5 (c) plots their cross coupling, s_{21} , in both wideband and narrowband mode, i.e. without and with the stubs. The antenna is considered to be operational in wideband mode as the reflection coefficients are close to or lower than -10 dB while the mutual coupling is less than -15 dB. It is difficult to get good impedance match when a hybrid coupler is used and so stubs were applied to the narrowband mode where a good return loss better than 15 dB for all four ports was shown at 2.25 GHz in Fig. 5 (b). This response is cyclic at 2.15 GHz and 2.25 GHz where low mutual coupling is maintained as shown in Fig. 5 (c).

Finally, two pairs of vertical and horizontal half wavelength dipoles each on 320x160 mm ground planes spaced 125 mm apart to have negligible mutual coupling and 29 mm above the ground plane as with the STAR antennas were used for comparison in this study. Diagrams are not included due to their simple design. It is important to compare the measured peak gains of the STAR antennas with these dipole antennas so as to ensure the test is fair in comparing orthogonality.

STAR1	STAR1	STAR2	STAR2	V	H	V	H
1	2	1	2	1	1	2	2
6.2	6.2	6.9	6.3	6.3	5.8	6.6	6.3

Table I – Peak gain values of both polarizations combined in dBi for the two STAR antennas and the spaced vertical and horizontal dipoles.

Table I compares the absolute peak gains of the combined co-polar and cross-polar components of the STAR antennas as well as the two linear polarized antennas 1 and 2, each with a vertical (V) and horizontal (H) dipole. Clearly it can be seen that there is sufficiently low variation within 1.1 dB.

Fig. 5. Measured reflection Coefficients of the two elliptically polarized antennas (a) without stub matching in wideband mode, (b) with stub matching in narrowband mode and (c) antenna element coupling in both modes.

IV. FREE SPACE ORTHOGONALITY MEASUREMENTS

Using the two STAR antennas, MIMO channels were measured in free space both in narrowband and wideband mode and compared with the linear polarized antennas. Fig. 6 (a) compares the eigenvalues, λ_1 and λ_2 , between the linear case and the narrowband STAR antennas, which are normalized such that the sum of the eigenvalues at each frequency is equal to 4 as is required for a 2x2 channel [33].

Fig. 6. Comparison of eigenvalues for linear (LP) and elliptical polarization (EP) from free space measurements in the (a) narrowband and (b) wideband cases.

It is observed in Fig. 6 (a) at approximately 2.17 GHz, 2.24 GHz and 2.33 GHz the eigenvalues come close, which are the three regions where the impedance match is resonating as seen in Fig. 5 (b) thus giving the opportunity to form polarization multiplexing. The best case occurs at 2.17 GHz when the eigenvalues are almost equal, approximately 0.2 dB apart, while the linear antennas have greater than 1 dB separation over the whole frequency band, and thus achieve weaker multiplexing. Fig. 6 (b) compares the eigenvalues using the STAR antennas in wideband mode with the linear case. Between 2.2 and 2.3 GHz it can be seen that elliptical polarization forms closer eigenvalues than linear, except at approximately 2.26 GHz and also from 2.3-2.4 GHz. Before

analyzing these results further, the corresponding capacity, C , can be calculated and plotted based on the eigenvalues, and an assumed signal to noise ratio, ρ , in the channel [33]:

$$C = \log_2 \left(1 + \frac{\rho}{2} \lambda_1^2 \right) + \log_2 \left(1 + \frac{\rho}{2} \lambda_2^2 \right) \quad (4)$$

Fig. 7. Comparison of capacity for linear (LP) and elliptical polarization (EP) from free space measurements in the (a) narrowband and (b) wideband cases. Signal to Noise ratio is fixed to 10dB.

The corresponding capacity to the eigenvalues in Fig. 6 is plotted in Fig. 7 (a) and (b) respectively for a 10 dB signal to noise ratio. Where there is less than 0.5 dB difference between the two eigenvalues, the capacity limits can practically be reached, which linear polarization does not achieve. The XPR_{E1} and XPR_{E2} values for both are compared with XPR_V and XPR_H in Fig. 8 (a) in wideband mode. The high values of XPR_{E1} and XPR_{E2} , which are no different in the narrowband mode not shown, purely indicate that the free space has no multipath, while the antennas can form orthogonal ellipses across the band. Where the eigenvalues are not equal such as 2.2 and 2.3 GHz in the narrowband case, one of the ellipses is substantially weaker than the other and hence there is no

strong polarization multiplexing. In Fig. 8 (b), the channel coefficients for the narrowband case show that the criteria noted in section II for polarization multiplexing are not met as there over 1 dB magnitude difference at these frequencies. In Fig. 8 (c) for the wideband case, the channel coefficients' magnitude are within 1 dB for polarization multiplexing, but the phase criteria is not met at every frequency where eigenvalues separate more than 0.5 dB. These results show the antennas can achieve good polarization multiplexing, where the next section will analyze the impact of multipath.

Fig. 8. Graphs showing (a) wideband XPR_{E1} and XPR_{E2} values vs frequency compared against XPR_V and XPR_H ; (b) magnitude of channel coefficients for the narrowband and (c) wideband elliptical free space measurements.

V. MEASUREMENT CAMPAIGN

An indoor measurement campaign representing static links was performed to determine the impact of multipath scattering on elliptical polarization multiplexing using eigenvalue and XPR metrics. Two measurement routes are documented in this paper, namely elliptical multiplexing (EM) and round door (RD) whereby the measurements took place in a lower ground meeting room. Photographs of the environment, antennas and also a plan view of the routes depicted in Figs. 9 (a)-(d). At both the transmitter (TX) and receiver (RX) end, was one STAR antenna in wideband mode, a vertical and horizontal linear antenna spaced 150 mm apart as shown in Fig. 9 (c) to conduct comparative simultaneous measurements.

Fig. 9. Photograph of the (a) propagation environment in the lower ground meeting room (b) the STAR, vertical and horizontal dipole at the receive end (antenna wires highlighted in white for clarity) and (c) plan view including the line of sight EM and non line of sight RD route.

The EM route, representing several iterations of a line of sight static link that could be implemented by a wall at a high height was conducted to see how effective the elliptical multiplexing is in a low scattering environment. The TX was moved along the EM route from the middle of the room to the opposite end of the RX as seen in Figs. 9 (a) and (d). In the RD measurement, the TX was positioned outside the meeting room and moved along the diagonal line in the atrium as seen in Figs. 9 (b) and (d). This provided several non line of sight static link measurement points to analyze the antenna diversity performance when not used for multiplexing.

Measurements were recorded with an Elektrob Propound channel sounder was used with a center frequency of 2.3 GHz and total bandwidth of 200 MHz to measure the two channels. The sounder generated a pseudo noise code with a corresponding chip rate of 100 MHz with two samples per chip in a code length of 512 samples to capture all the necessary multipath components. A sampling rate of 30.9 Hz

was used to exceed three times the maximum Doppler shift and meet Nyquist sampling criteria.

Fig. 10. Analysis of the average (a) eigenvalues (b) capacity and (c) comparison of cross polar ratios for the EM route with elliptical (EP) and linear (LP) polarization.

The results from the EM route are plotted in Fig. 10 (a)-(c). First, in Fig. 10 (a), the eigenvalues averaged over time for each frequency bin are compared and are found to be closer for elliptical polarization and experienced less fluctuation as compared to the linear eigenvalues. This is because the co-

location of the elliptical antennas are less vulnerable to difference in received multipath than the linear antennas, which had to be spaced to be sufficiently polarization pure. The closer eigenvalues on the EM route correspond to improvement and consistency in capacity as plotted in Fig. 10 (b) assuming 10 dB signal to noise ratio.

Fig. 11. Analysis of the average (a) eigenvalues (b) capacity and (c) comparison of cross polar ratios for the RD route with elliptical (EP) and linear (LP) polarization.

In Fig. 10 (c), the XPRs are averaged over time for each frequency bin where they begin to fluctuate compared with free space in Fig. 8 (a). In the elliptical case, with the exception of narrowband points near to 2.3 GHz, 2.35 GHz and the band edges, which had deep channel fluctuations, high XPR_{E1} and XPR_{E2} over 40 dB is maintained. However, the vertical and horizontal linear antennas were more vulnerable to spatial multipath, leading to low and heavily fluctuating XPR_V and XPR_H . This does show a great advantage in using elliptical polarized antennas, which can be easily co-located, where inherent polarization impurities in antenna elements can be exploited. Linear polarization is otherwise limited by polarization impurities that worsen further when co-located.

The corresponding RD route measurement results are presented in the same manner in Fig. 11 (a)-(c). The point of these measurements are to show that the angular diversity of the STAR antennas, compared with the angular and spatial diversity of the linear polarized antennas in a non line of sight environment have no measureable difference. This is evidenced by comparable eigenvalues and capacity in Fig. 11 (a) and (b). Therefore the STAR antenna has agility to operate in multiplexing mode in a line of sight environment while also it has diversity richness in a non line of sight environment. Inevitably, there is more substantial depolarization as evidenced by the more significant fluctuations in XPR shown in Fig. 11 (c), thus polarization multiplexing is weak.

VI. CONCLUSION

The case for exploiting the fact that any antenna is elliptically polarized, hence deliberately constructing an antenna in such a way to achieve improved polarization multiplexing has been demonstrated in this paper. A simple prototype elliptically polarized wire antenna with ground reflector was constructed and compared through measurement with an equivalent linear polarized antenna. Results show that antennas with suitable directivity could be more effective in static line of sight links and have higher resilience to multipath compared to linear polarization. Such antennas can perform equally effectively using angular diversity when in a non line of sight. This work sets a precedent for a new antenna design paradigm for polarization multiplexing capability by exploiting their elliptical nature.

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