Multi-Modal Active Antennas for Accurate Polarimetric Measurements Over an Ultra-Wide Field-of-View

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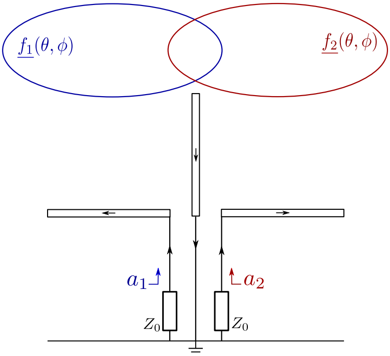
Outline

Motivation

- Sparse and dense antenna arrays for the Square Kilometre Array (SKA) are required to have high sensitivity and polarisation purity over a large Field-of-View (FoV) coverage [1]
- In an attempt to reduce the system noise temperature active differential antennas are being considered [2]
  - Array antenna elements excited by balanced transmission lines
  - Common-Mode (CM) signals are suppressed by differential Low-Noise Amplifiers (LNAs) or within the antenna feed
- Investigate the feasibility of utilizing both Differential-Mode (DM) and CM propagation to increase the FoV coverage of the antenna elements
- Determine if the utilization of multiple modes within an antenna feed can improve sensitivity and polarimetric performance of conventional purely differential antenna elements

[1] A. van Ardenne, J.D. Bregman, W.A. van Cappellen, G.W. Kant, and J.G. Bij de Vaate, "Extending the field of view with phased array techniques: results of european SKA research," Proceedings of the IEEE , vol.97, no.8, pp.1531-1542, Aug. 2009.
[2] E. de Lera Acedo, *et al.*, "Study and design of a differentially fed tapered slot antenna array," *IEEE Trans. Antennas Propag.*, vol. 58, no. 1, pp. 68-78, Jan. 2010.

Operating Principle

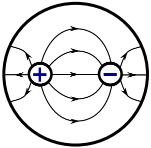


- Dipole antenna with integrated monopole
- Balanced transmission line feed
  - Antenna excited through two Single-Ended (SE) excitations
  - Resulting in two respective SE radiation patterns

Balanced Transmission Line Modes

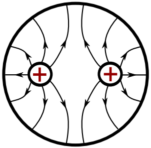
- Balanced transmission line supports Differential- and Common-mode (Mixed-Mode) propagation
- Mixed-mode incident and reflected waves can be defined in terms of single ended values

Differential-mode



$$a_{\mathrm{d}} = \frac{1}{\sqrt{2}}\left[a_1 - a_2\right]$$

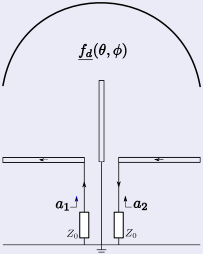
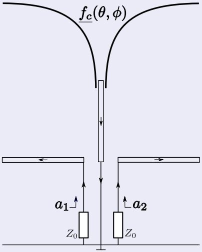
Common-mode



$$a_{\mathrm{c}} = \frac{1}{\sqrt{2}}\left[a_1 + a_2\right]$$

- Mixed differential- and common-mode scattering matrix can be defined in terms of the mixed-mode incident and reflected waves

Mixed-mode Operation [3] $(\Omega) = (\theta, \phi)$

Radiation Pattern	$f_{\mathrm{d}}^{p}(\Omega) = \frac{1}{\sqrt{2}}\left[f_1^p(\Omega) - f_2^p(\Omega)\right]$	$f_{\mathrm{c}}^{p}(\Omega) = \frac{1}{\sqrt{2}}\left[f_1^p(\Omega) + f_2^p(\Omega)\right]$
Schematic Illustration		
$\underline{a} = \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}$	$\underline{a} = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 \\ -1 \end{bmatrix}$	$\underline{a} = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 \\ 1 \end{bmatrix}$

[3] D.S. Prinsloo, P. Meyer, R. Maaskant, and M. Ivashina, "Design of an active dual-mode antenna with near hemispherical Field of View coverage," *Electromagnetics in Advanced Applications (ICEAA), 2013 International Conference on*, pp.1064-1067, 9-13 Sept. 2013.

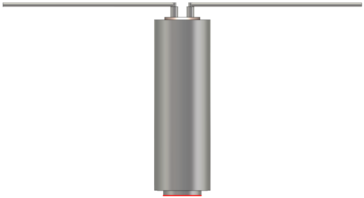
Single-Ended to Mixed-Mode Transformation

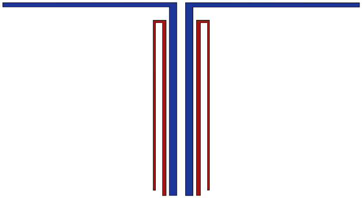
- For each component p of the SE radiated far-field patterns

Single-Ended	$\mathbf{S}_{\text{SE}}^{\text{ant}} = \begin{bmatrix} S_{11}^{\text{ant}} & S_{12}^{\text{ant}} \\ S_{21}^{\text{ant}} & S_{22}^{\text{ant}} \end{bmatrix}$	$\mathbf{F}_{\text{SE}}^{p} = \begin{bmatrix} f_1^p(\theta,\phi) \\ f_2^p(\theta,\phi) \end{bmatrix}$
Transformation $\mathbf{M}_{\text{S}}^{\text{ant}} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & -1 \\ 1 & 1 \end{bmatrix}$	$\mathbf{S}_{\text{MM}}^{\text{ant}} = \mathbf{M}_{\text{S}}^{\text{ant}} \mathbf{S}_{\text{SE}}^{\text{ant}} \left(\mathbf{M}_{\text{S}}^{\text{ant}}\right)^{-1}$	$\mathbf{F}_{\text{MM}}^{p} = \mathbf{M}_{\text{S}}^{\text{ant}} \mathbf{F}_{\text{SE}}^{p}$
Mixed-Mode	$\mathbf{S}_{\text{MM}}^{\text{ant}} = \begin{bmatrix} S_{\text{dd}}^{\text{ant}} & S_{\text{dc}}^{\text{ant}} \\ S_{\text{cd}}^{\text{ant}} & S_{\text{cc}}^{\text{ant}} \end{bmatrix}$	$\mathbf{F}_{\text{MM}}^{p} = \begin{bmatrix} f_{\text{d}}^p(\theta,\phi) \\ f_{\text{c}}^p(\theta,\phi) \end{bmatrix}$

Dual-Mode Antenna Design

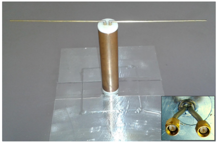
- Cylindrical dual-mode antenna design excited through a twinaxial transmission line
  - Centre conductors of twinaxial line connected to each dipole arm
  - Ground shield of twinaxial line folded back toward ground plane realising a monopole sleeve

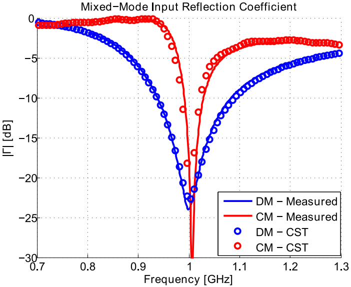




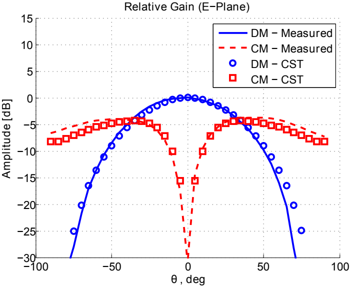
Dual-Mode Antenna Design

- Dual-mode antenna manufactured and measured with finite ground plane
- Single-ended S-parameters and far-field patterns measured
- Mixed differential- and common-mode response obtained through SE to MM transformations



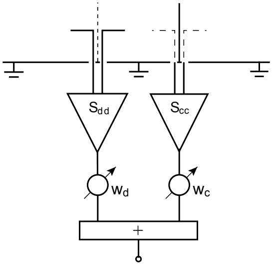


$$\mathbf{S}_{\mathrm{MM}}^{\mathrm{ant}} = \mathbf{M}_{\mathrm{S}}^{\mathrm{ant}} \mathbf{S}_{\mathrm{SE}}^{\mathrm{ant}} \left(\mathbf{M}_{\mathrm{S}}^{\mathrm{ant}}\right)^{-1}$$



$$\mathbf{F}_{\mathrm{MM}}^{p} = \mathbf{M}_{\mathrm{S}}^{\mathrm{ant}} \mathbf{F}_{\mathrm{SE}}^{p}$$

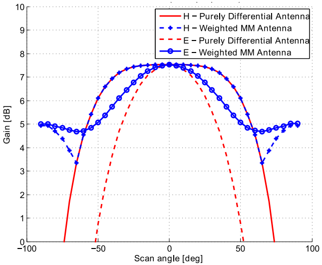
Mixed-Mode Receiver Model



- Dual-mode antenna element modelled as coupled two element array
  - Respective antenna elements representing differential- and common-mode propagation
- Complex beamforming weights can be solved for each mode to maximize the antenna gain and sensitivity at each scan angle

Maximized Gain

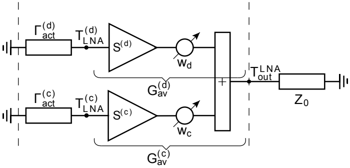
$$G(\Omega) = 4\pi \frac{P_{\text{rad}}(\Omega)}{P_{\text{in}}} = \frac{2\pi}{\eta} \left[\frac{|w_{\text{d}} f_{\text{d}}(\Omega) + w_{\text{c}} f_{\text{c}}(\Omega)|^2}{\mathbf{w}^H \left[\mathbf{I} - \mathbf{S}_{\text{MM}}^{\text{ant}} (\mathbf{S}_{\text{MM}}^{\text{ant}})^H \right] \mathbf{w}} \right]$$



- Differential- and common-mode weights solved at each scan angle to maximize antenna gain
- Dual-mode antenna can provide increased FoV coverage by utilizing common-mode propagation
- Maximum gain variation over hemispherical FoV below 3 dB in E-plane and approximately 4 dB in H-plane

Sensitivity Analysis

- Noise-decouple the receiver using the active reflection coefficient for each mode (d, c) [4]
- Active reflection coefficients computed using weights solved for maximum gain



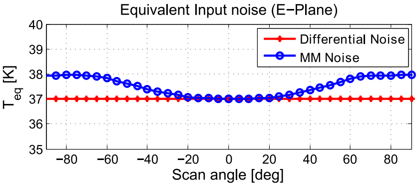
- Noise contributed by LNAs in each mode can be solved using the equivalent mixed-mode noise parameters
- Mixed-mode noise parameters for two identical LNAs with two-port noise parameters $\{F_{\text{min}}, R_{\text{n}}, Y_{\text{opt}}\}$ [5]

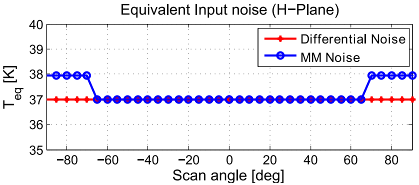
$$\begin{aligned} F_{\text{min}}^{\text{d}} &= F_{\text{min}} & F_{\text{min}}^{\text{c}} &= F_{\text{min}} \\ R_{\text{n}}^{\text{d}} &= 2R_{\text{n}} & R_{\text{n}}^{\text{c}} &= \tfrac{1}{2}R_{\text{n}} \\ Y_{\text{opt}}^{\text{d}} &= \tfrac{1}{2}Y_{\text{opt}} & Y_{\text{opt}}^{\text{c}} &= 2Y_{\text{opt}} \end{aligned}$$

[4] M.V. Ivashina, R. Maaskant, and B. Woestenburg, "Equivalent representation to model the beam sensitivity of receiving antenna arrays," *IEEE Antennas Wireless Propag. Lett.*, vol. 7, no. 1, pp. 733-737, Jan. 2008.
[5] D.S. Prinsloo, R. Maaskant, M.V. Ivashina, and P. Meyer, "Mixed-mode sensitivity analysis of a combined differential and common mode active receiving antenna providing near-hemispherical field-of-view coverage," *Antennas and Propagation, IEEE Transactions on*, submitted Dec. 2013.

Equivalent Receiver Noise Temperature

- Only consider noise due to LNAs
- LNAs noise matched to passive differential input impedance of the dual-mode antenna

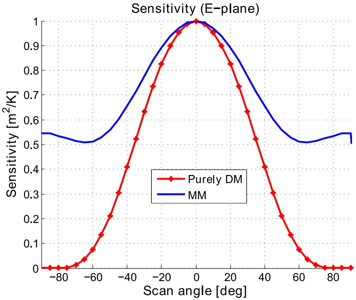


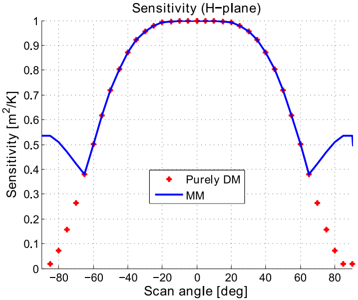


- Standard two-port noise parameters: $T_{\text{min}} = 37$ K, $R_{\text{n}} = 3\,\Omega$, $Y_{\text{opt}} = Y_{\text{dd}}^{\text{ant}}$

Sensitivity

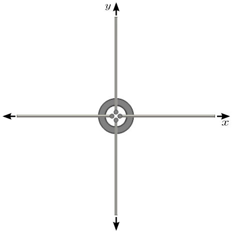
$$\frac{A_{\mathrm{eff}}(\Omega)}{T_{\mathrm{sys}}} = \frac{\lambda^2}{2\eta T_{\mathrm{eq}}} \frac{|w_{\mathrm{d}} f_{\mathrm{d}}(\Omega) + w_{\mathrm{c}} f_{\mathrm{c}}(\Omega)|^2}{\mathbf{w}^H \left[\mathbf{I} - \mathbf{S}_{\mathrm{MM}}^{\mathrm{ant}} (\mathbf{S}_{\mathrm{MM}}^{\mathrm{ant}})^H\right] \mathbf{w}}$$



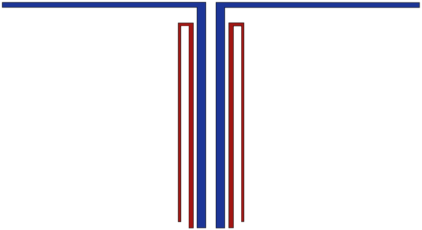


- Variation in sensitivity in the E-plane less than 50 percent over a hemispherical FoV coverage

Quad-Mode Antenna Design



- Quad-mode antenna realised by integrating a pair of perpendicularly oriented dipole antennas with a monopole
- Monopole realised as a sleeve around the ground shield of the antenna feed
- Antenna excited by four orthogonal Transverse Electromagnetic (TEM) excitation modes through a quadraxial transmission line feed [6]

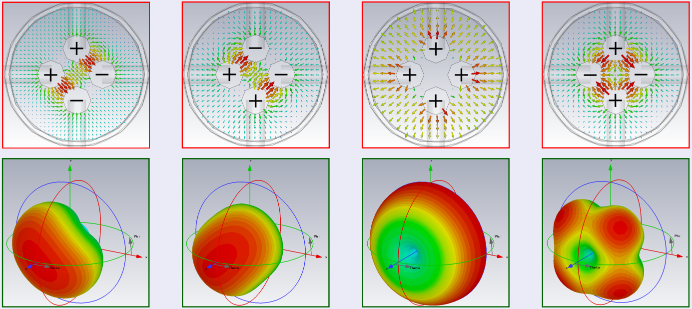


[6] D.S. Prinsloo, P. Meyer, M.V. Ivashina, and R. Maaskant, "A quad-mode antenna for accurate polarimetric measurements over an ultra-wide field-of-view," *in Proc. Eur. Conf. Antennas Propag. (EuCAP)*, The Hague, The Netherlands, Apr. 2014, submitted for publication.

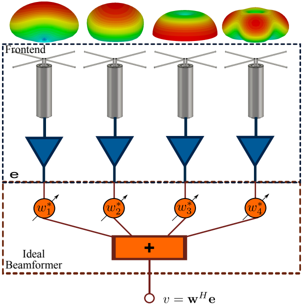
TEM Excitation Modes

- Field distribution and respective radiated far-field patterns of the four TEM excitation modes
- Design simulated in CST with infinite ground plane at 1 GHz

TEM_1	TEM_2	TEM_3	TEM_4



Quad-Mode Receiver Model



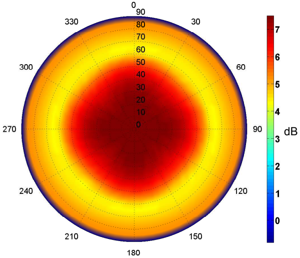
- Quad-mode antenna modelled as a four element array
- Each excitation mode represented by an array element
- Solve complex beamforming weights for each mode to maximize the gain or sensitivity at each scan angle (Ω)

Maximized Gain

- Effective utilization of the excitation modes results in near-hemispherical FoV coverage

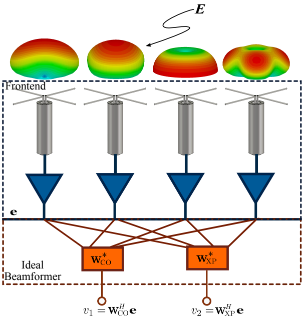
$$G(\Omega) = \frac{2\pi}{\eta}\left[\frac{|\sum_{m=1}^{4} w_{\mathrm{m}} f_{\mathrm{m}}(\Omega)|^2}{\mathbf{w}^H\left[\mathbf{I} - \mathbf{S}_{\mathrm{MM}}^{\mathrm{ant}}(\mathbf{S}_{\mathrm{MM}}^{\mathrm{ant}})^H\right]\mathbf{w}}\right]$$

- Variation in maximum gain approximately 3 dB over hemispherical FoV coverage



Polarimetric Performance

- Quad-mode antenna modelled as a four element polarimeter - each element representing one of the excitation modes
- Voltages at the output ports of the polarimeter are related to the incident field components by the Jones matrix (**J**)



- For an incident electric field $E(r) = E_{\text{co}}\hat{co} + E_{\text{xp}}\hat{xp}$

$$\begin{bmatrix} v_1 \\ v_2 \end{bmatrix} = \mathbf{J} \begin{bmatrix} E_{\text{co}} \\ E_{\text{xp}} \end{bmatrix}$$

- Jones matrix solved in terms of weights $\mathbf{w}_{\text{co}}$ and $\mathbf{w}_{\text{xp}}$ solved to optimally receive the co- and cross-polar field components

$$\mathbf{J} = \begin{bmatrix} \mathbf{w}_{\text{co}}{}^H \mathbf{e}_{\text{co}} & \mathbf{w}_{\text{co}}{}^H \mathbf{e}_{\text{xp}} \\ \mathbf{w}_{\text{xp}}{}^H \mathbf{e}_{\text{co}} & \mathbf{w}_{\text{xp}}{}^H \mathbf{e}_{\text{xp}} \end{bmatrix}$$

Polarimetric Performance

- Polarimetric performance assessed using the Intrinsic Cross-polarization Ratio (IXR) [5]
- The IXR allows the polarimetric performance of the polarimeter to be assessed independent of reference coordinate system
- By applying two orthonormal transformations to the Jones matrix

$$\mathbf{J}' = c \begin{bmatrix} 1 & d \\ d & 1 \end{bmatrix}$$

- For this polarimeter alignment the cross-polarization ratios converge to the IXR

$$\text{XPRs} = \text{IXR} = \frac{1}{d^2}$$

- with d defined in terms of the singular values of the Jones matrix ($g_{\text{max}}, g_{\text{min}}$)

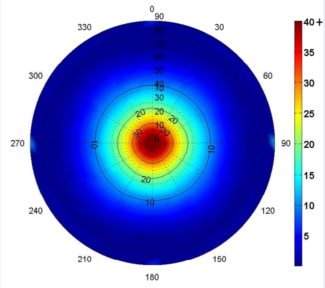
$$d = \frac{g_{\text{max}} - g_{\text{min}}}{g_{\text{max}} + g_{\text{min}}}$$

[5] T.D. Carozzi, G. Woan, "A fundamental figure of merit for radio polarimeters," *Antennas and Propagation, IEEE Transactions on*, vol.59, no.6, pp.2058-2065, June 2011.

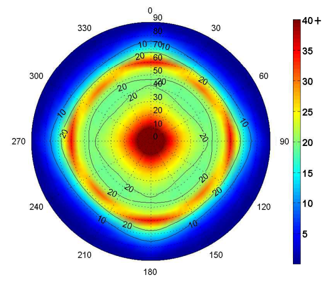
Intrinsic Cross-polarization Ratio

- IXR of quad-mode antenna compared to conventional pair of crossed dipoles excited through a balun

Crossed Dipoles with Balun



Quad-Mode Antenna



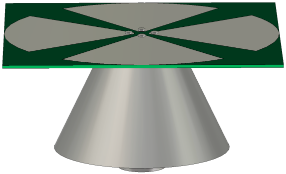
- Integrated monopole element improves the polarimetric capabilities of a pair of crossed dipole antennas
- Effective utilization of the fundamental excitation modes in the quadraxial feed extends the 20 dB IXR scan range from 30° to 60° from zenith

Conclusion

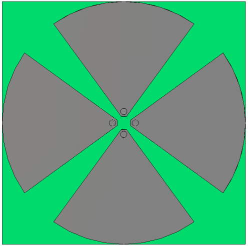
- Introduced a Quad-mode antenna element
  - Realized by integrating a pair of perpendicular dipoles and a monopole
  - Allows for four orthogonal excitation modes through a quadraxial transmission line

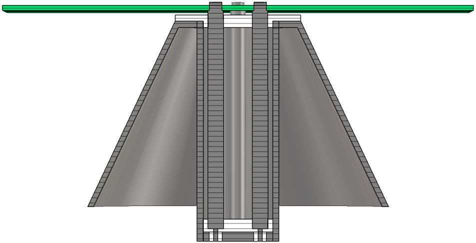
- Illustrated that the utilization of the fundamental modes in multi-conductor antenna feeds can provide improved FoV coverage with respect to both gain and polarimetric performance

Continued Work

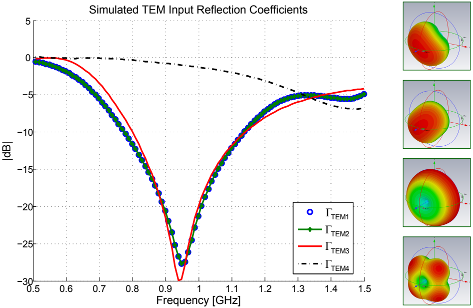


- Quad-mode antenna design with improved operating bandwidth
- Integrates a conical monopole sleeve with two perpendicularly oriented bow-tie dipole antennas printed on a substrate





Continued Work



- Modes TEM_1–TEM_3 -10 dB bandwidth approximately 35 percent
- Investigate the effect mismatched mode TEM_4 has on the polarimetric performance and sensitivity
- Compare beamforming strategies to achieve optimal gain, sensitivity and polarimetric performance over an extended FoV coverage

Acknowledgements

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