5»6G INNOVATION CENTRE
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Exploiting Electromagnetic Degrees of Freedom for Spectrum Efficiency Enhancements

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- Polarisation Modulation
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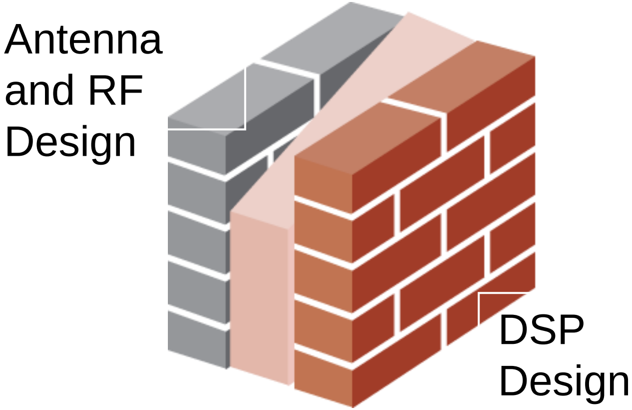
Electromagnetic Degrees of Freedom (DoFs)

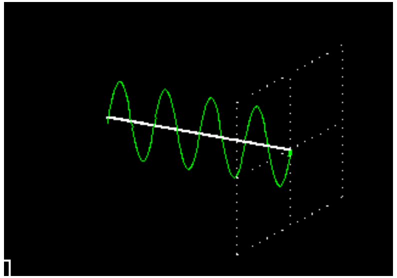
- Wireless communication system design aims to explore electromagnetic DoFs in
  - Time
  - Frequency
  - Space
  - Polarisation

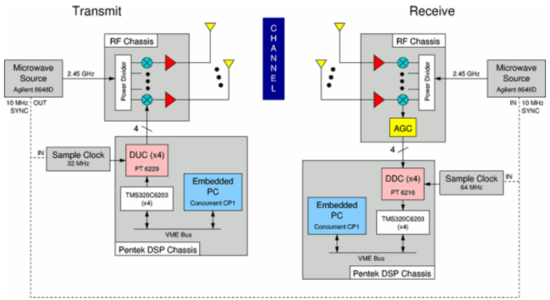
- Spectrum efficiency, energy efficiency and coverage can be improved by fully exploiting electromagnetic DoFs.

- We aim to fully exploit the DoF in the polarisation domain, which requires joint radio frequency (RF) and digital signal processing (DSP) design approach.

Current RF and DSP Design

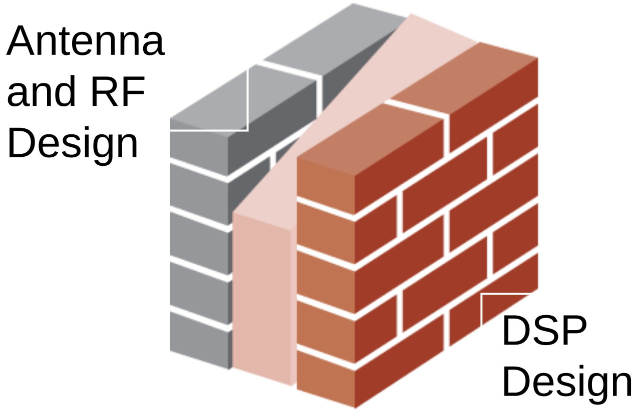






- Previous work has been focused either on the radio frequency (RF) or digital signal processing (DSP) aspect without major regard to the other.
    - In the former case, the conventional RF design fails to exploit the full potential that a co-designed system has to offer.
    - In the latter case, DSP algorithms are devised without considering the impairments caused by limitations and imperfect nature of the physical hardware, antenna, radio propagation and RF/microwave front-end electronics.
- The disjoint RF-DSP design approach represents a major obstacle for fully exploiting electromagnetic DoFs.

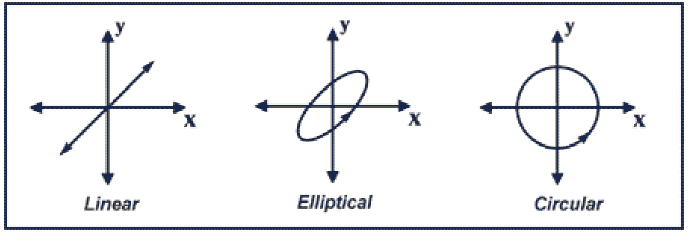
Joint RF-DSP Design Approach

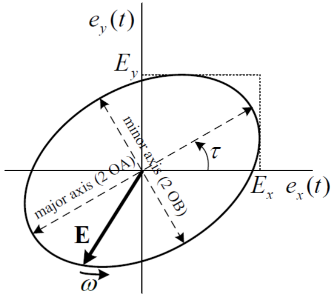


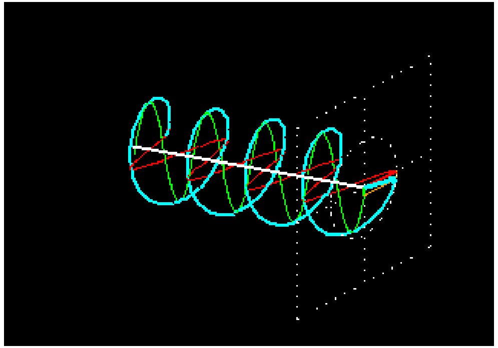
- We propose an integrated RF-DSP co-design to
    - Explore new dimensions of DoF, such as in polarisation.
    - Maximize the spectral efficiency of the existing available spectrum.
    - Fully utilize the new mm-wave, THz spectrum.

DoF in Polarisation Domain

- The polarisation of a radio wave can also be utilised to carry information bearing signals
- The distinction between the polarisation states of radio waves can be determined by the ***axial ratio (AR)*** and ***tilt angle*** of an elliptically polarised electric field.
- Channel effect can be compensated by DSP design





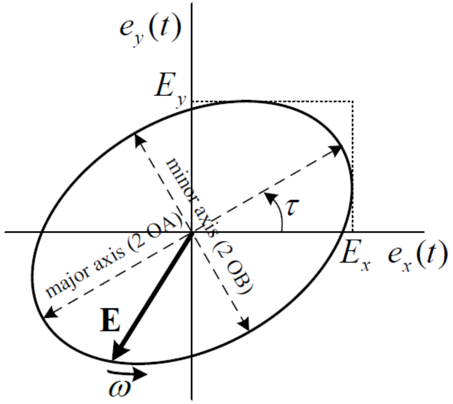


Polarisation Modulation ⟹ *Exploring the polarisation domain degrees of freedom*

Axial Ratio (AR) and Tilt Angle

The parameters of the polarization ellipse are given by

- Major axis (2xOA) $\mathrm{OA} = \sqrt{\frac{1}{2}\left[E_x^2 + E_y^2 + \sqrt{E_x^4 + E_y^4 + 2E_x^2E_y^2\cos(2\delta_L)}\right]}$
- Minor axis (2xOB) $\mathrm{OB} = \sqrt{\frac{1}{2}\left[E_x^2 + E_y^2 - \sqrt{E_x^4 + E_y^4 + 2E_x^2E_y^2\cos(2\delta_L)}\right]}$
- Tilt angle $\tau = \frac{1}{2}\arctan\left(\frac{2E_xE_y}{E_x^2 - E_y^2}\cos\delta_L\right) \pm \frac{\pi}{2}$
- Axial ratio $AR = \frac{\text{major axis}}{\text{minor axis}} = \frac{\mathrm{OA}}{\mathrm{OB}}$



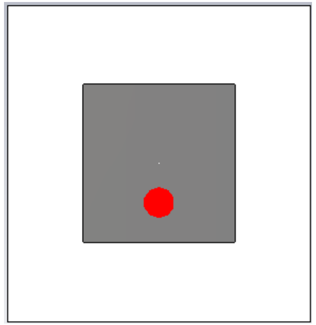
AR= 0 dB circular polarisation

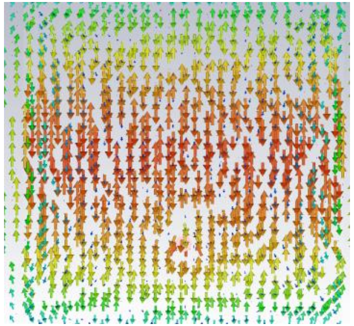
AR=40 dB Linear Polarisation

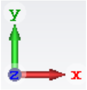
Reconfigurable Polarisation Antenna Design

- If the horizontal electric field (E_x) and vertical electric field (E_y) can be controlled by a mechanism, the AR and the tilt angle can be controlled.
- To verify this approach an example Patch antenna is chosen.
- By having slots on the radiating element it is possible to affect the current distribution.
- Different polarisation states can be produced by changing the length of the slot.

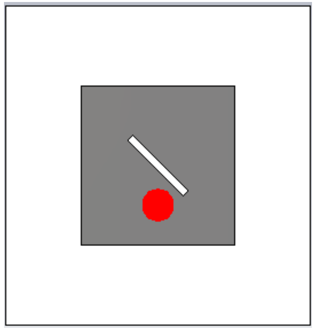
Current on conventional patch

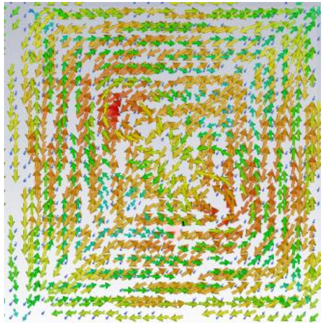






Current on slotted patch





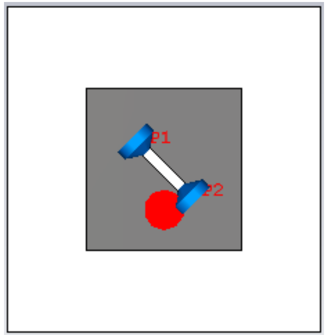
Polarisation reconfigurable antenna

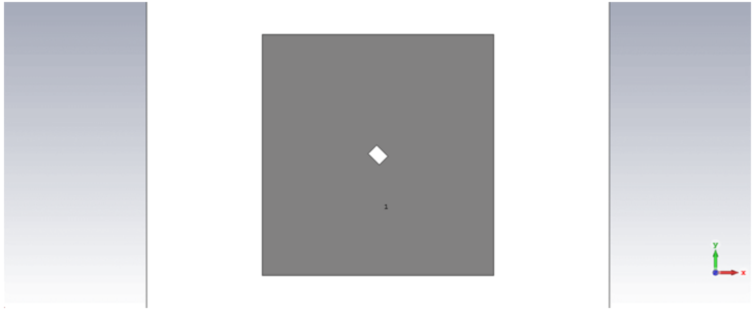
- The slot’s dimensions can change x and y component of the current on the radiating element (patch) and therefore E_x, E_y

- The dimensions of the slots can be electrically changed, to control the current, via varactor diode.

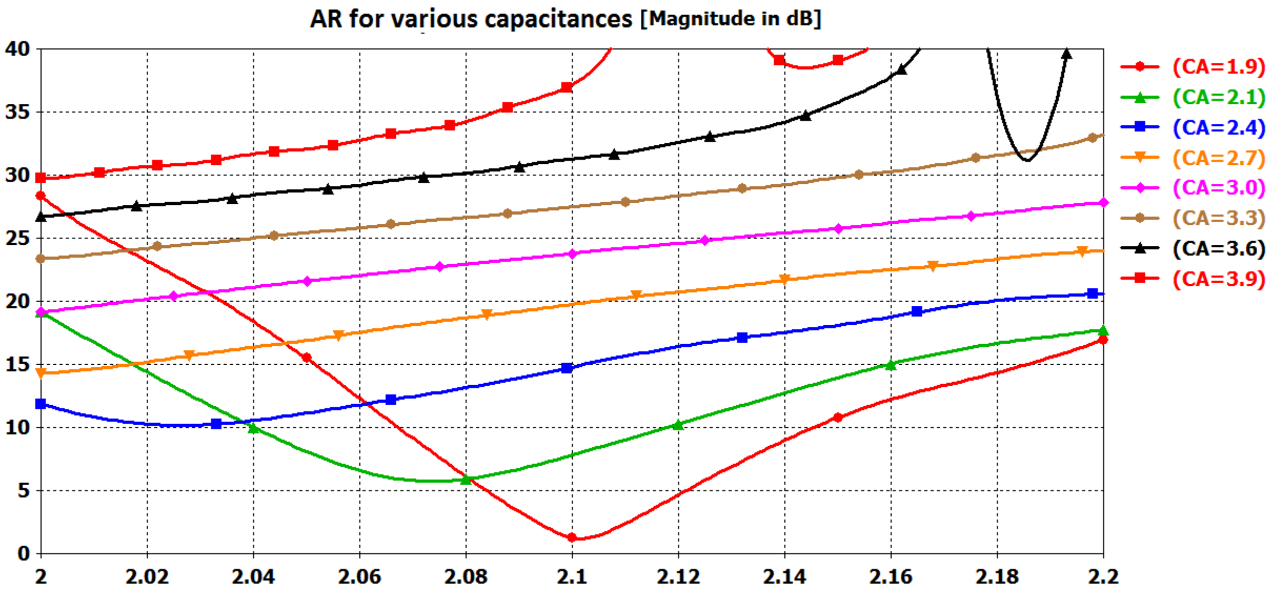
- Changing the bias voltage across the varactor diode will change the capacitance, thus the electric length, the required behaviour can be achieved.

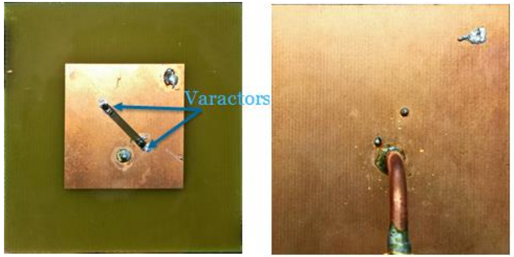
Changing voltage across the Varactor





Reconfiguration in Axial Ratio

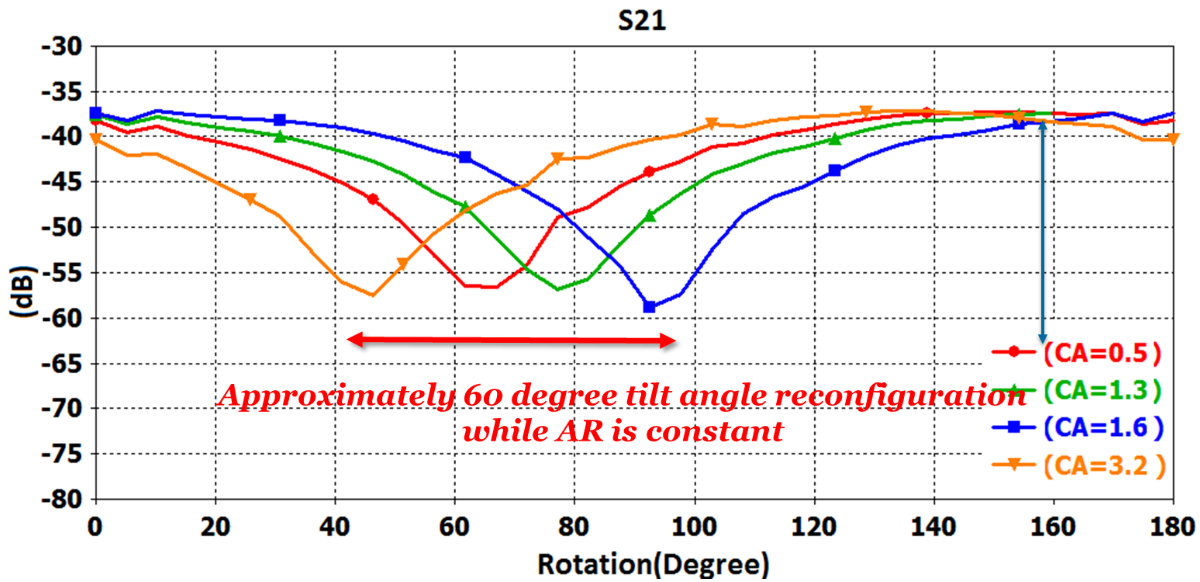




- CA represents the capacitance (in pF)
- The antenna can reconfigure its polarisation from circular to linear in a continuous manner

It can reconfigure the polarization from circular to linear continuously

Reconfiguration in Tilt Angle

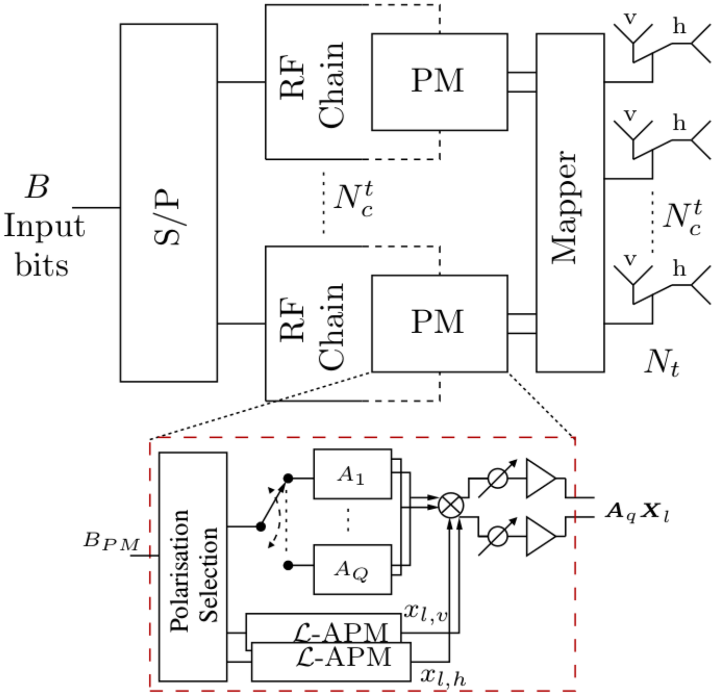


Comparison of Simulation and Measurement

	Simulation	Measurement
Tilt angle tuning from-to (degree)	40-100	40-100
AR tuning at (degree)	50	50
Max AR tuning range (dB)	40	35
Max tilt angle tuning range (degree)	60	60

Polarisation Modulation (PM) System Design

- N_c^t RF chain
  - Each connected to specific DP-AE
- Total of $N_t \;\; = 2N_c^t$ Aes
- At each DP-AE, we can transmit:
  - Two L-QAM/PSK symbols
  - One out of Q Polarisation configurations
- The system is referred to as
  - PM(AR/Tilt/TAR, N_c^t, N_c^r, Q, L-QAM/PSK)

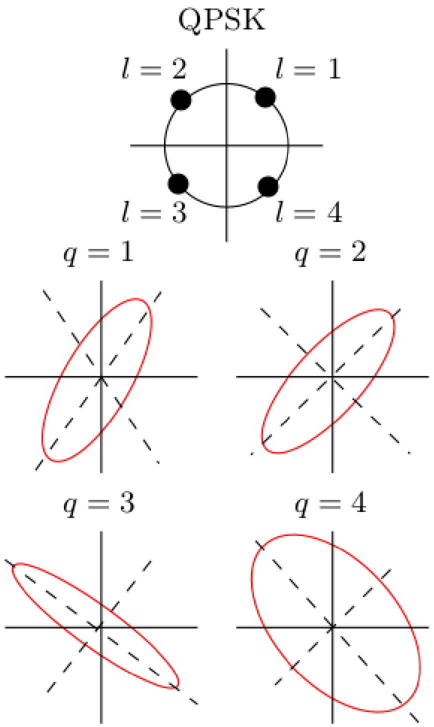


PM Example

For Example:

- Consider a PM (TAR, 2, 1, 4, QPSK)
- At each RF chain, the PM system conveys a total of $\log_2(QL^2) = 6$ bits

- While an ordinary system with a similar configuration can transmit only 4 bits



Assumptions

- Flat Rayleigh fading channels
- AR tuning range [0 40dB]
- Tilt angle tuning range [40° 100°]
- Cross-Polar Discrimination (XPD)

$XPD_v = XPD_H = 10dB$ (unless otherwise stated)

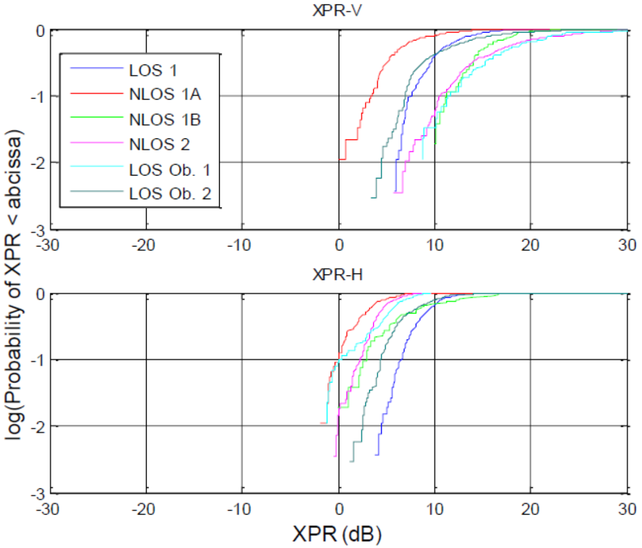
$$\text{Channel Matrix } \mathbf{H} = \begin{bmatrix} h_{VV} & h_{VH} \\ h_{HV} & h_{HH} \end{bmatrix}$$

XPD is defined as

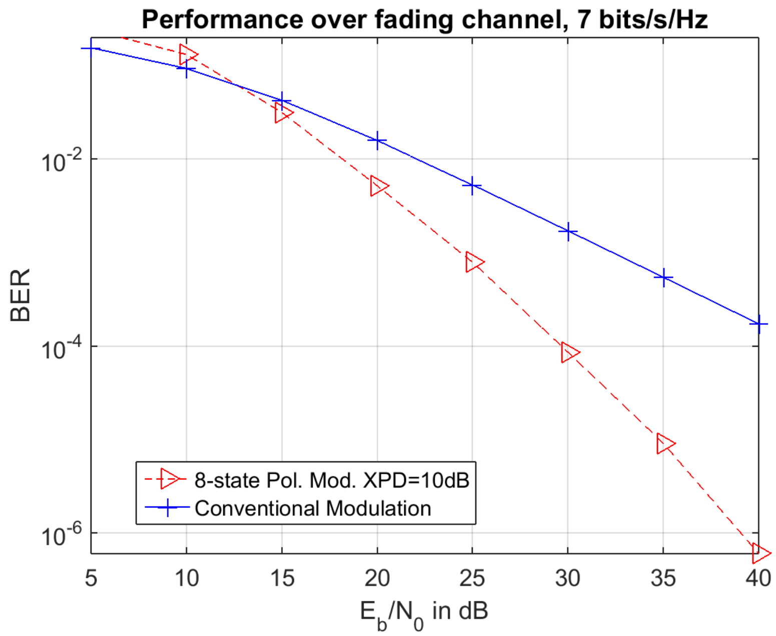
$$XPD_H = \frac{E[h_{HH}^2]}{E[h_{VH}^2]}; \qquad XPD_V = \frac{E[h_{VV}^2]}{E[h_{HV}^2]}$$

- Branch Polar Ratio (BPR)

$$BPR = \frac{E[h_{HH}^2]}{E[h_{VV}^2]} = 1$$



8-State Polarisation Modulation

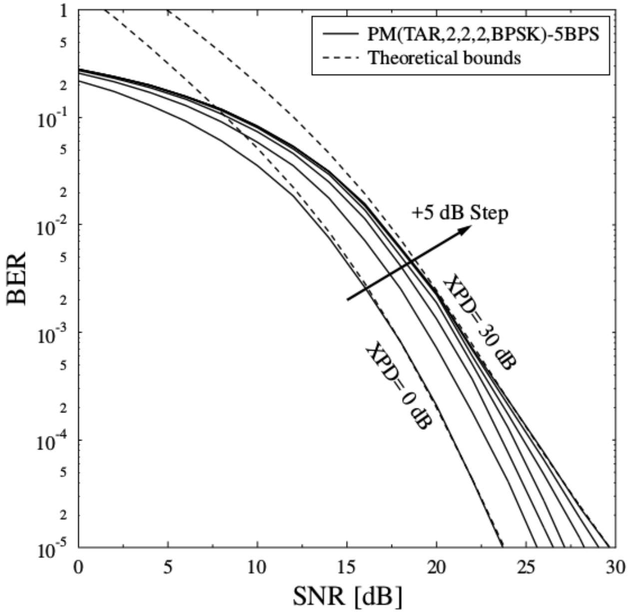


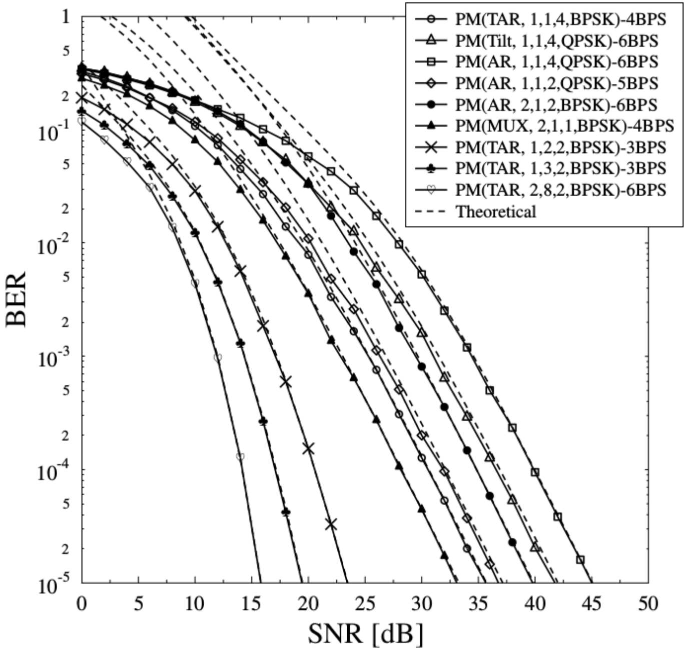
2-dimensional, 8-state Polarisation Modulation

Bits	E_h	E_v	δ_L	τ	AR_{lin}	AR_{dB}
[0 0 0]	1	1.09	1.2°	47°	96	39.6
[0 0 1]	1	1.09	25°	49°	4.5	13
[0 1 0]	1	1.09	46°	49°	2.4	7.5
[0 1 1]	1	1.8	5°	61°	27	28.6
[1 0 0]	1	1.8	45°	65°	3	5.5
[1 0 1]	1	2.6	12°	70.2°	14.3	23.1
[1 1 0]	1	2.6	30°	70°	5.8	15.3
[1 1 1]	1	2.6	56°	76°	3.3	10.4

- By exploiting the polarisation domain DoF, this 2D 8-state PM achieves 12dB gain compared to the conventional modulation with the same spectrum efficiency.

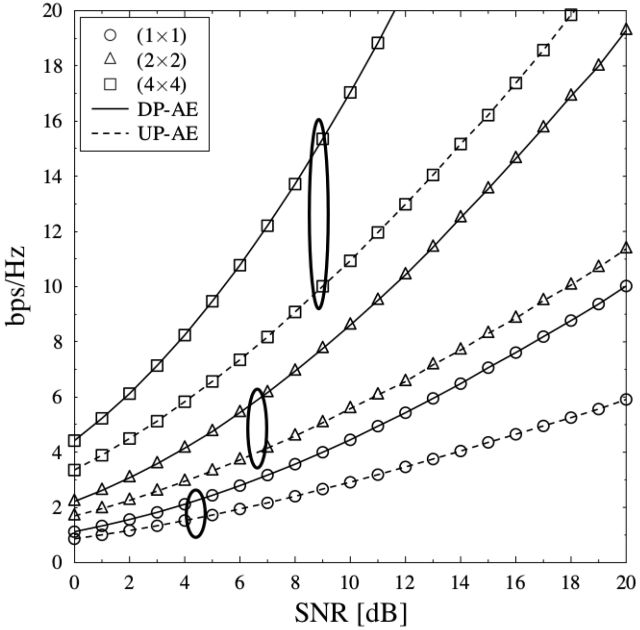
BER Performance with Different Configurations

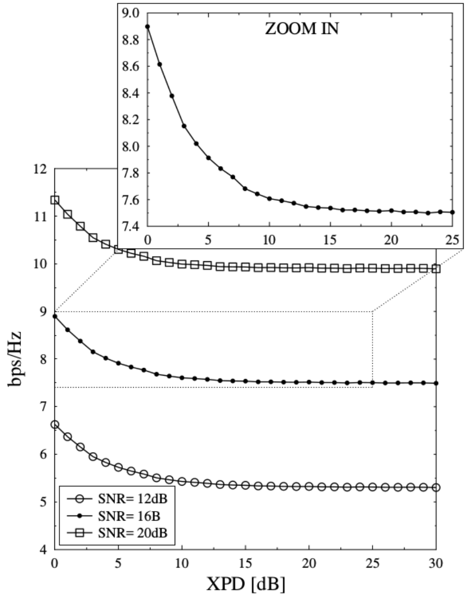




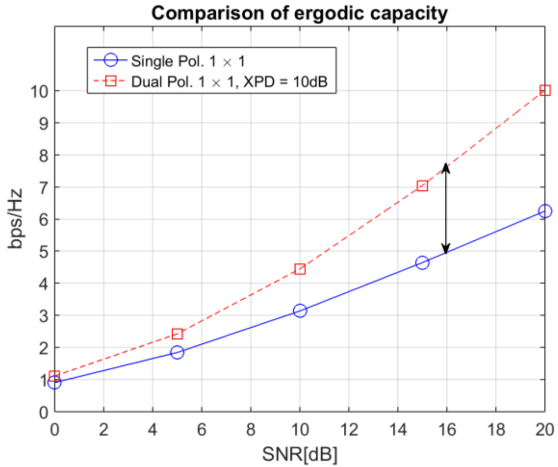
- The **BER performance** of the PM system is **improved** as the XPD decreases.
- The **BER** performance is **slightly affected** after **XPD=25 dB**

Ergodic Capacity Analysis





$$C_{CCMC} = \max_{p(\boldsymbol{S})} H(\boldsymbol{Y}) - I(\boldsymbol{Y}|\boldsymbol{S})$$
$$= E\left\{\log_2 \left| \boldsymbol{I}_{N_r} + \frac{\rho}{N_t}\left(\boldsymbol{H}\boldsymbol{H}^H\right)\right|\right\}$$



- **PM** can approach the capacity of dual polarisation channels, representing **50%** improvement in spectral efficiency compared to conventional modulation techniques.

Further Reading

- Y. Kabiri, P. Xiao, J. Kelly, T. Brown, R. Tafazolli. "Wireless Data Transmission using Polarised Electromagnetic Radiation". UK Patent filed. Patent Applicatin Number: GB1812108.7. Filing date: 25 July 2018.

- I. Hemadeh, P. Xiao, Y. Kabiri, L. Xiao, V. Fusco, R. Tafazolli. "Polarization Modulation Design for Reduced RF Chain Wireless." *IEEE Transactions on Communications,* vol. 68, no. *6,* pp. 3890-3907, June, 2020.

Conclusions

- **Impact on spectrum efficiency, energy efficiency and coverage**
  - An increase of 50% in spectrum efficiency can be achieved by using the proposed PM.
  - Given the same spectrum efficiency, the proposed PM can improve energy efficiency by more than 10dB.
  - PM can be integrated into MIMO and cell-free massive MIMO systems to extend the coverage.
  - PM is generally applicable to different frequency bands (sub-6GHz, mm-wave, THz).
- Spectrum efficiency, energy efficiency and coverage can be improved by fully exploiting electromagnetic DoFs, which requires joint RF-DSP design.

Thank You