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EuCAP 2015, WS4: In Memoriam of Perruisseau-Carrier

The orbital angular momentum (OAM) multiplexing controversy: OAM as a subset of MIMO

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Outline

- OAM modes and multiplexing
- OAM multiplexing as a subset of MIMO: the controversy
- The far field limit
- A simpler alternative to OAM multiplexing: LENS based MIMO
- Conclusions

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- **OAM modes and multiplexing**
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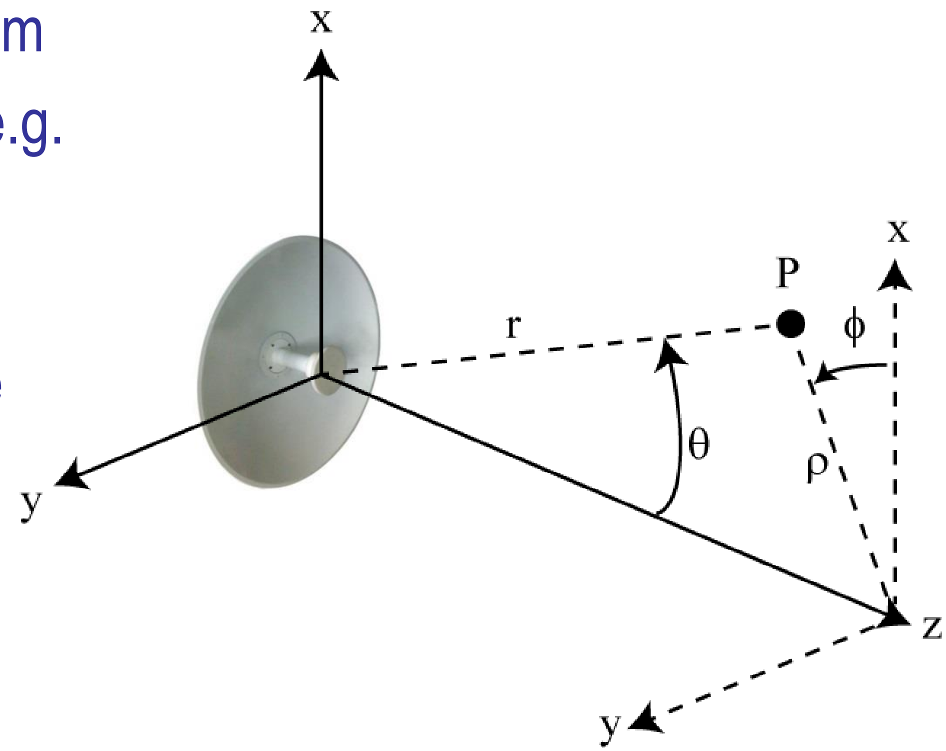
OAM modes and multiplexing

- OAM = Orbital Angular Momentum
- Same polarization everywhere (e.g. vertical)
- Null in the propagation axis
- Phase integer-proportional to the azimuthal angle φ



$$\angle E = \mathrm{m}\varphi$$
$$\mathrm{m} = 0, +1, -1, +2, -2, \ldots$$

- Orthogonality

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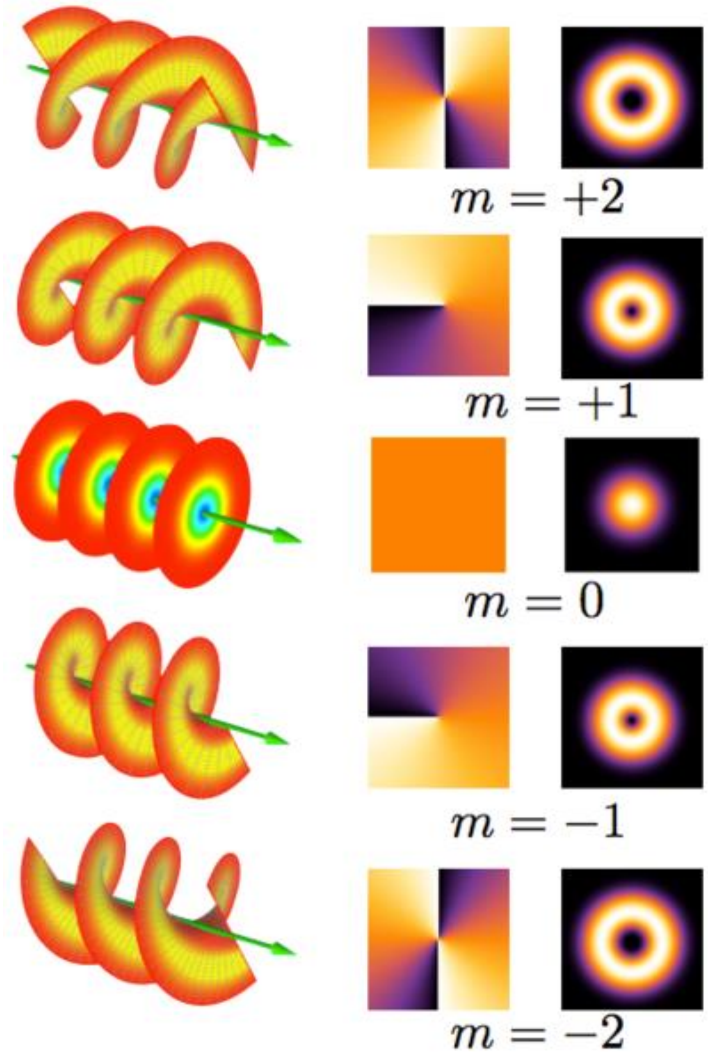

OAM multiplexing at various frequencies

- F. Tamburini, E. Mari, A. Sponselli, B. Thidé, A. Bianchini, and F. Romanato, "Encoding many channels on the same frequency through radio vorticity: first experimental test," **New Journal of Physics**, vol. 14, p. 033001, 2012
- J. Wang, J.-Y. Yang, I. M. Fazal, N. Ahmed, Y. Yan, H. Huang, Y. Ren, Y. Yue, S. Dolinar, M. Tur, and A. E. Willner, "Terabit free-space data transmission employing orbital angular momentum multiplexing," **Nat Photon**, vol. 6, pp. 488-496, 2012.
- A. E. Willner, J. Wang, and H. Huang, "A Different Angle on Light Communications," **Science**, vol. 337, pp. 655-656, August 10, 2012 2012.
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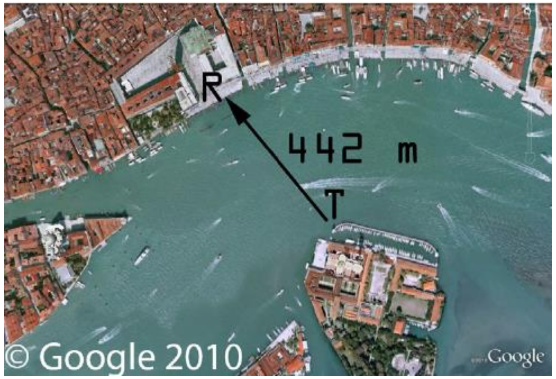

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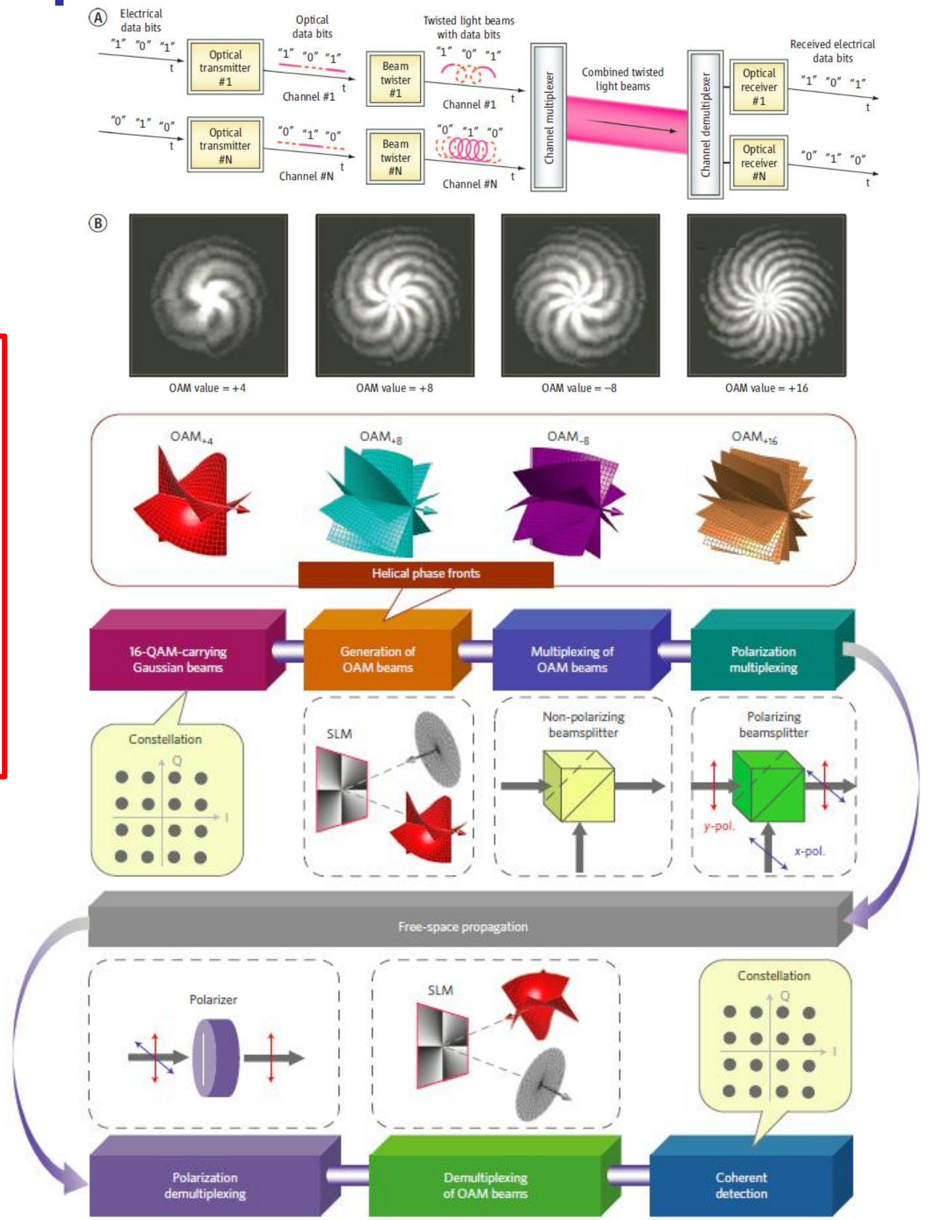

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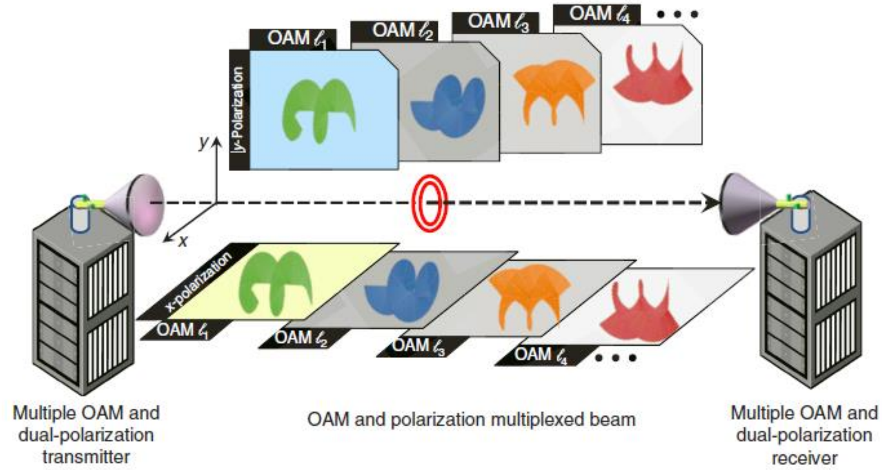

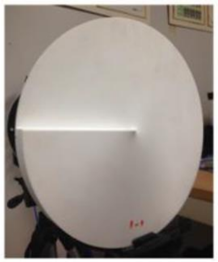

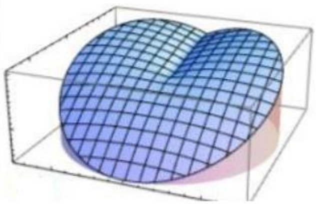

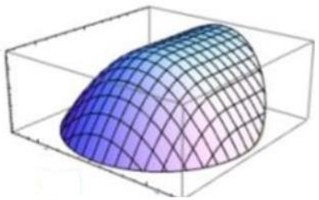

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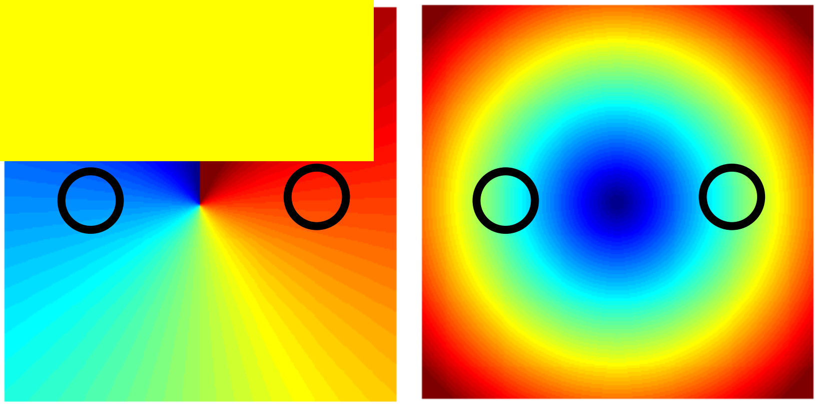
The "Venice experiment"



This is just a 2x2 line of sight MIMO system!

- Tamburini F, Mari E, Sponselli A, Thidé B, Bianchini A. and Romanato F, "Encoding many channels on the same frequency through radio vorticity: first experimental test" 2012 *New J. Phys.* **14** 033001

The controversy

The controversy is mainly about two points

- MIMO vs OAM multiplexing
  - Some groups claim that OAM multiplexing is a subset of spatial multiplexing (MIMO systems).
  - Other ones maintain that it is a new physical layer

- Far field
  - Some groups claim that the increased capacity is just a near field effect
  - Other ones claim that the OAM multiplexing can be exploited also in far field conditions.

If OAM multiplexing is a subset of MIMO then it cannot work in far field

The controversy: references

- F. Tamburini et al, “Experimental verification of photon angular momentum and vorticity with radio techniques”, APL
- O. Edfors and A. J. Johansson, "Is Orbital Angular Momentum (OAM) Based Radio Communication an Unexploited Area?,“ TAP
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Are all OAM systems MIMO systems?

TX

RX

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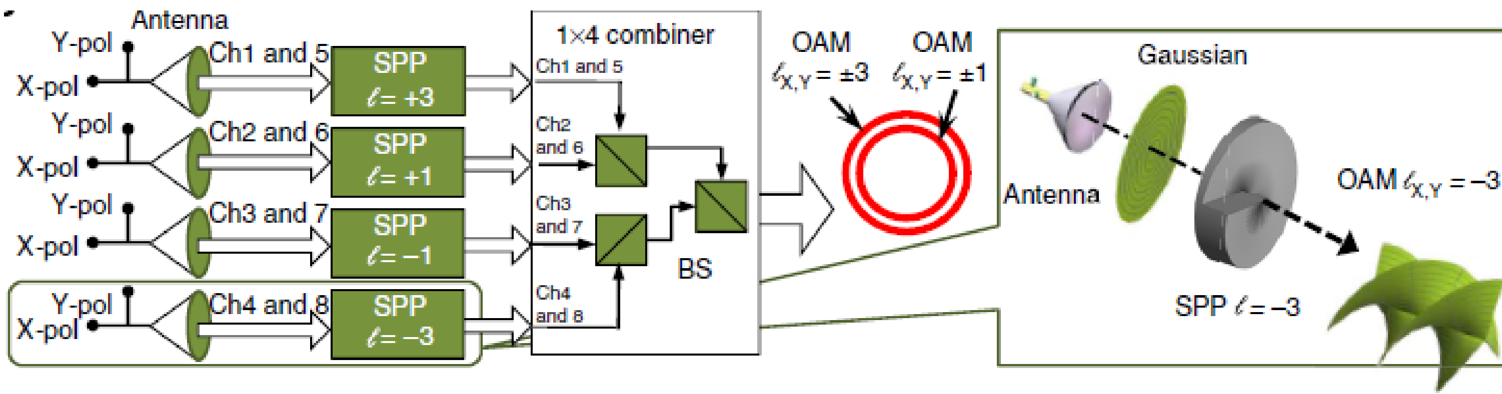

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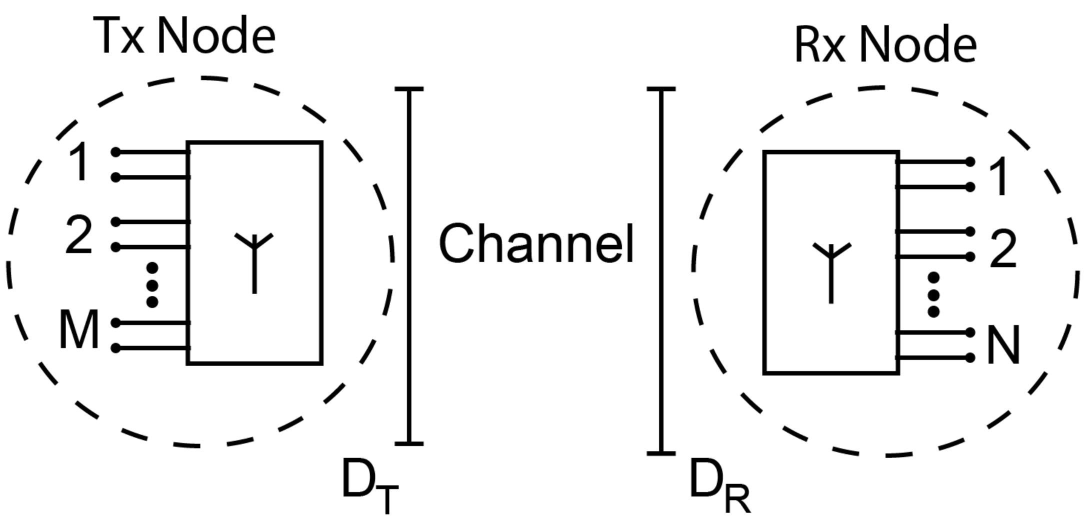
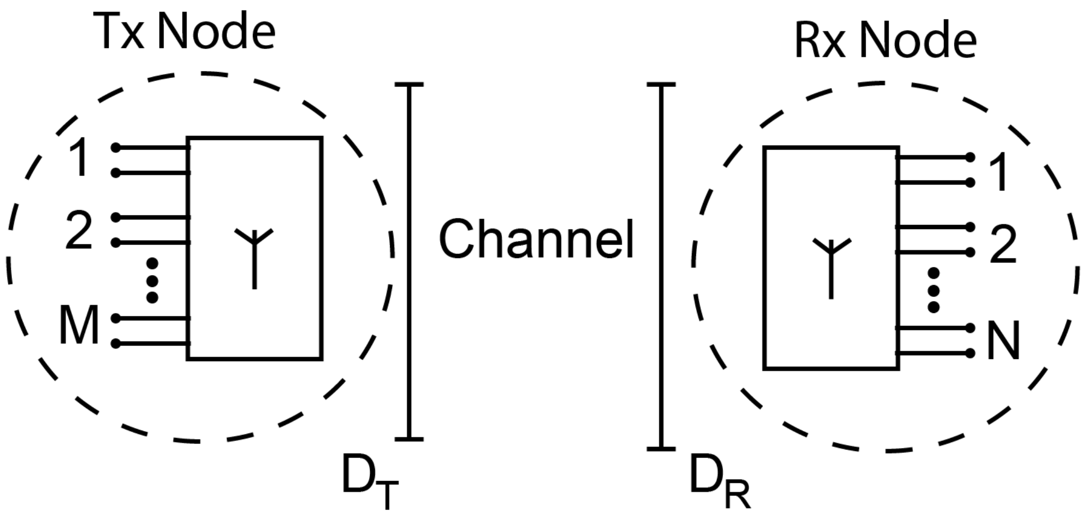
General definition of MIMO system

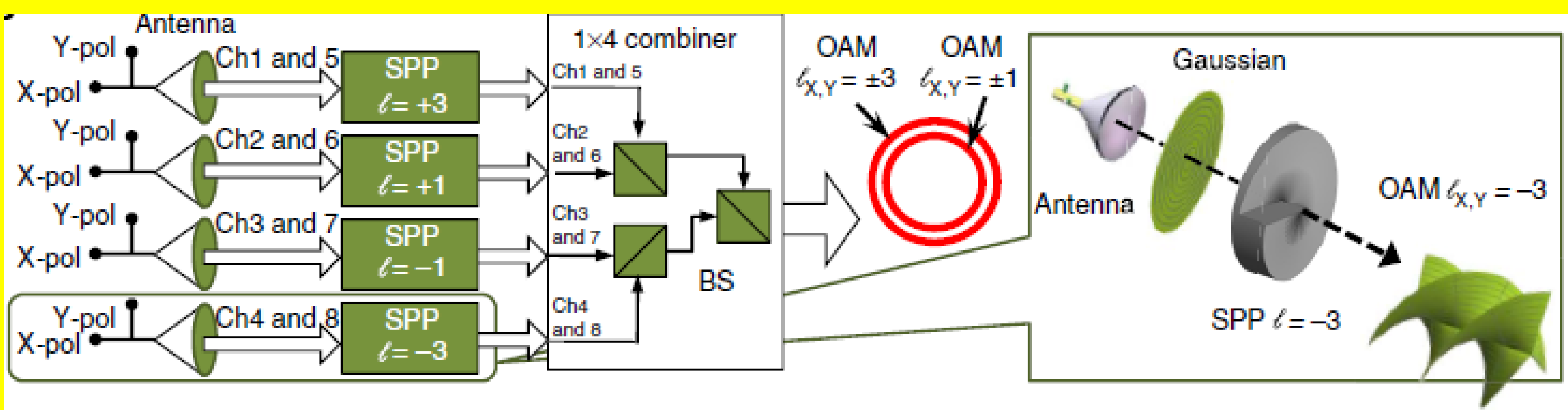


- Two nodes: Tx and Rx
- Nodes separated by "channel"
- The Tx node comprises:
  - M ports (or input signals)
  - an electromagnetic radiating structure
- The Rx node comprises:
  - N ports (or output signals)
  - an electromagnetic receiving structure
- Linearity
- Finite sizes and currents

General definition of MIMO system



This is a 8x8 line of sight MIMO system!



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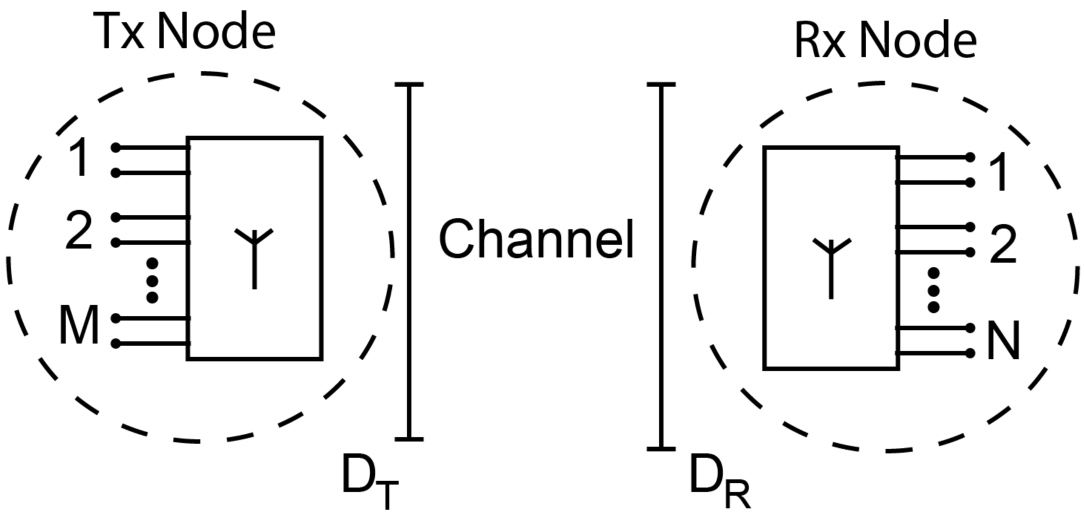
MIMO systems cannot work in far field



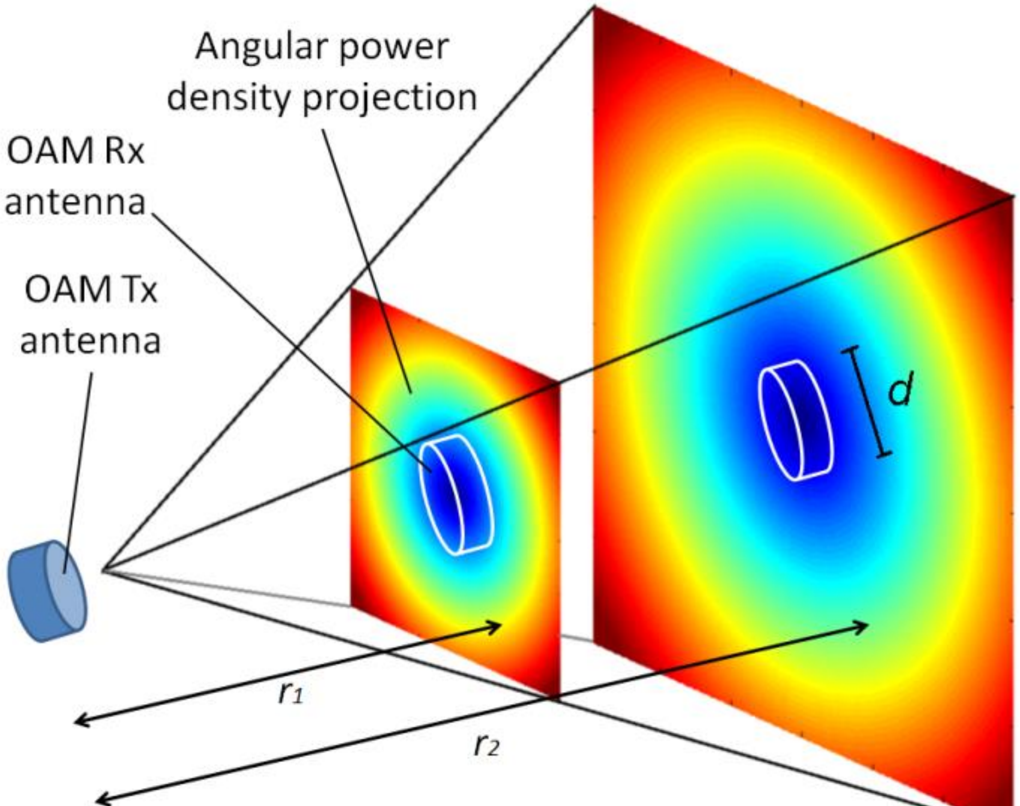
$$\boldsymbol{A}(\boldsymbol{r}) = \iiint_V \boldsymbol{J}(\boldsymbol{r}')\frac{e^{-jk|\boldsymbol{r}-\boldsymbol{r}'|}}{|\boldsymbol{r}-\boldsymbol{r}'|}d\boldsymbol{r}'$$

$$\boldsymbol{A}(\boldsymbol{r}) = G(r)\boldsymbol{I}(\hat{\boldsymbol{r}})$$

$$\boldsymbol{I}(\hat{\boldsymbol{r}}) = \iiint_V \boldsymbol{J}(\boldsymbol{r}')e^{-jk(\boldsymbol{r}'\cdot\hat{\boldsymbol{r}})}d\boldsymbol{r}'$$

$$\iint_{RxArea} \boldsymbol{I}_1(\hat{\boldsymbol{r}})\boldsymbol{I}_2{}^*(\hat{\boldsymbol{r}})d\hat{\boldsymbol{r}} = 0 \quad \rightarrow \quad RxArea \cdot \boldsymbol{I}_1(\boldsymbol{0}) \cdot \boldsymbol{I}_2(\boldsymbol{0}) \propto \frac{D_R}{r}$$

Why OAM multiplexing cannot work in far field



$$|E| \propto \frac{1}{r^{|m|+1}} \left(\frac{\sqrt{2}\pi d W_0}{\lambda} \right)^{|m|}$$

Far field or near field?

$$\xi \triangleq \frac{D_T D_R}{\lambda\, r}$$

	Frequency	Link range	ξ
Tamburini et al 2012	2.4 Ghz	442 m	0.16
Willner et al 2012	193 THz	1m	5.8
Willner et al 2014	28 GHz	2.5 m	3.36

All these systems work only because they are not in deep far field region

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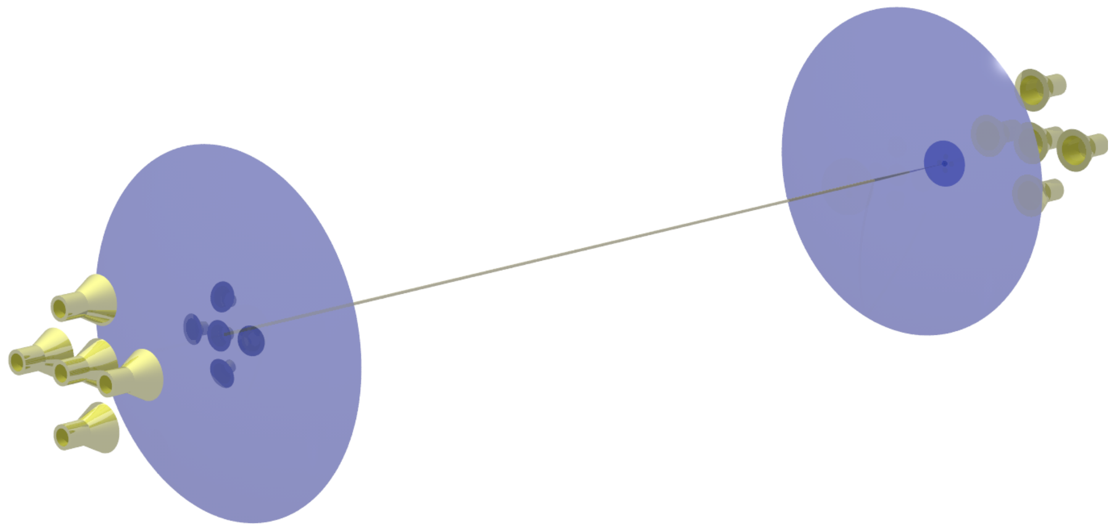
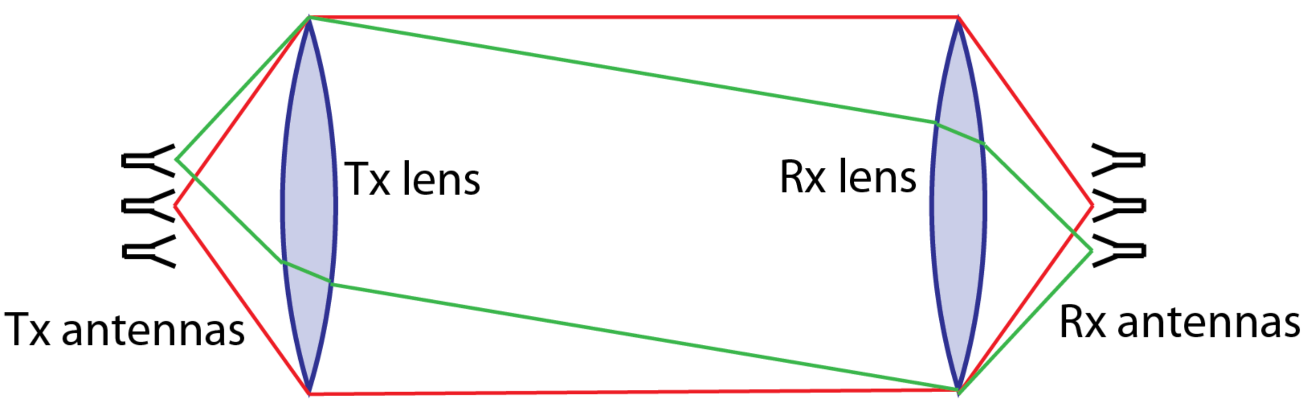
OAM in near field

- OAM multiplexing cannot be used in far field
- It is however working in near field.
- Advantages of OAM:
  - intrinsic orthogonality → no MIMO decoder needed.
  - Line of sight → no need for environment rich in scattering

Can a simpler MIMO system (not based on OAM) be designed with these properties?

Near field lens based MIMO





Same frequency and size of [1] but longer distance (3.27 m) instead of 2.5.

10 modes (instead of 8)

BROADBAND !

[1] Y. Yan, G. Xie, M. P. J. Lavery, H. Huang, N. Ahmed, C. Bao, Y. Ren, Y. Cao, L. Li, Z. Zhao, A. F. Molisch, M. Tur, M. J. Padgett, and A. E. Willner, "High-capacity millimetre-wave communications with orbital angular momentum multiplexing," Nat Commun, vol. 5, 2014.

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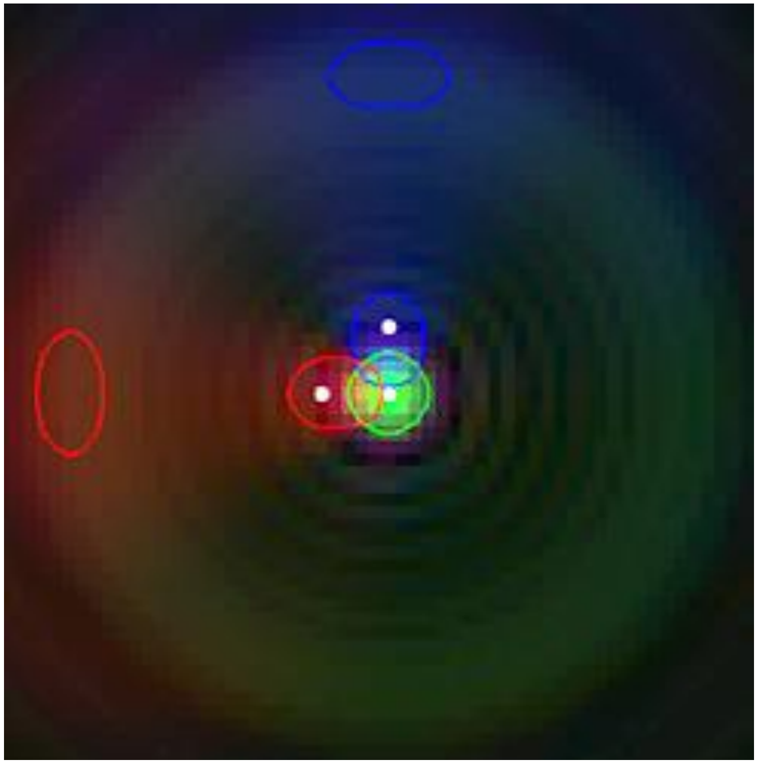

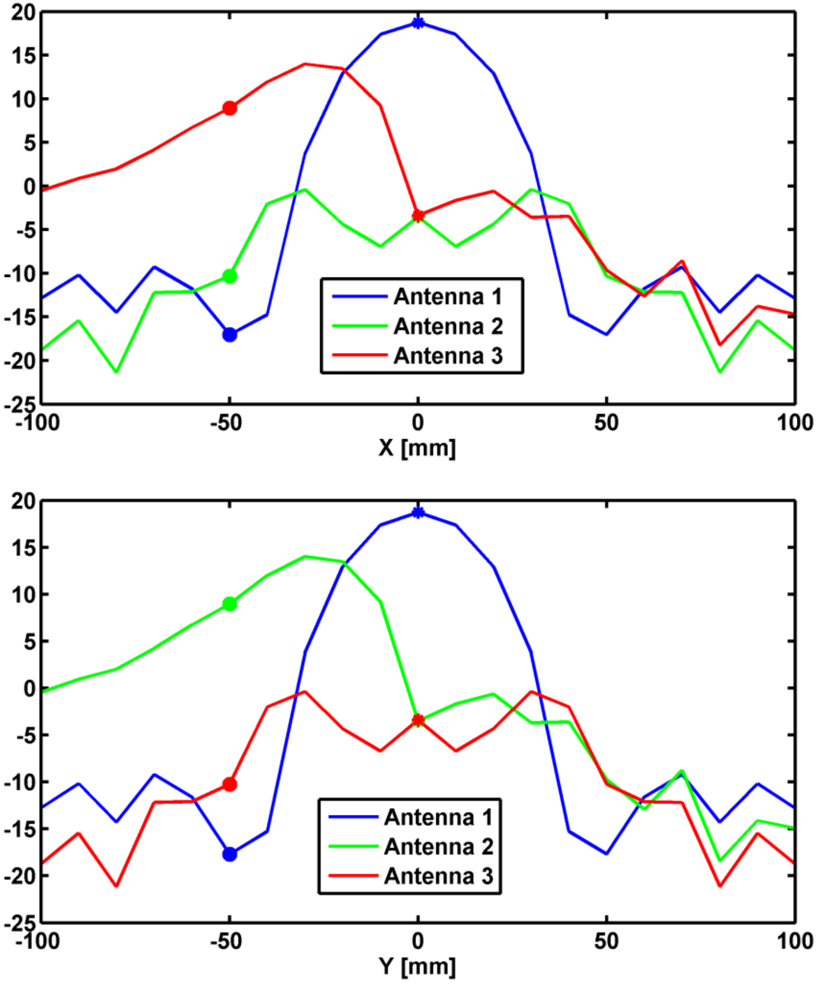

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Conclusions

- OAM multiplexing is a subset of MIMO systems
- Line of sight MIMO systems fail in far field
  $\longrightarrow$ OAM multiplexing also cannot work in far field conditions
- In near field much simpler MIMO systems can be designed showing:
  - The same or better performance of OAM counterparts
  - Broadband behavior

- OAM multiplexing seems to have very little apllicability/utility

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- Julian Richard Trinder
- Ivan Maio (Politecnico di Torino)
- Lazlo Kish and Robert Nevels (Texas A&M University)
- Andrea Alu (University of Texas at Austin)

For the very useful discussions

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In Memoriam
of Prof. Julien Perruisseau-Carrier
(1979-2014)

Thank you very much for attending.
Any questions?

APPENDIX

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