

## "Comment on ``Encoding many channels on the same frequency through radio vorticity: first experimental test``"

Tamagone, Michele ; Craeye, Christophe ; Perruisseau-Carrier, Julein

### Abstract

We show that the public experiment held in Venice by Tamburini et al and reported in 2012 *New J. Phys.* 14 033001 can be regarded as a particular implementation of multiple-input-multiple-output (MIMO) communications and, therefore, has no advantages over established techniques. Moreover, we explain that the use of a 'vortex' mode (orbital angular momentum  $\ell = 1$ ) at one of the transmit antennas is not necessary to encode different channels since only different patterns—or similarly different pointing angles—of the transmit antennas are required. Finally, we identify why this MIMO transmission allowed the decoding of two signals, despite being line-of-sight. This is due to the large separation between the receiving antennas, which places the transmit antennas in the near-field Fresnel region of the receiving 'array'. This severely limits the application of this technique in practice, since, for a fixed separation between receiving antennas, the detectable signal power fro...

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## Comment on ‘Encoding many channels on the same frequency through radio vorticity: first experimental test’

Michele Tamagnone<sup>1</sup>, Christophe Craeye<sup>2,3</sup>  
and Julien Perruisseau-Carrier<sup>1,3</sup>

<sup>1</sup> Adaptive MicroNanoWave Systems Group, LEMA/Nanolab, Ecole Polytechnique Fédérale de Lausanne (EPFL), 1015 Lausanne, Switzerland

<sup>2</sup> Université Catholique de Louvain (UCL), ICTEAM Institute, Bâtiment Stévin-2, Place du Levant B-1348 Louvain-la-Neuve, Belgium

E-mail: [christophe.craeye@uclouvain.be](mailto:christophe.craeye@uclouvain.be) and [julien.perruisseau-carrier@epfl.ch](mailto:julien.perruisseau-carrier@epfl.ch)

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**Abstract.** We show that the public experiment held in Venice by Tamburini *et al* and reported in 2012 *New J. Phys.* **14** 033001 can be regarded as a particular implementation of multiple-input–multiple-output (MIMO) communications and, therefore, has no advantages over established techniques. Moreover, we explain that the use of a ‘vortex’ mode (orbital angular momentum  $\ell = 1$ ) at one of the transmit antennas is not necessary to encode different channels since only different patterns—or similarly different pointing angles—of the transmit antennas are required. Finally, we identify why this MIMO transmission allowed the decoding of two signals, despite being line-of-sight. This is due to the large separation between the receiving antennas, which places the transmit antennas in the near-field Fresnel region of the receiving ‘array’. This severely limits the application of this technique in practice, since, for a fixed separation between receiving antennas, the detectable signal power from any additional vortex mode decays at least as  $1/r^4$ .

<sup>3</sup> Authors to whom any correspondence should be addressed.



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### 1. Introduction: description of the experiment

The experiment performed in Venice on 24 June 2011 by Tamburini *et al* and described in [1] aimed to show how radio vorticity could be used to encode several communication channels on the same frequency band. With this aim, two transmitting (Tx) antennas were placed on the lighthouse of San Giorgio Island, and two receiving (Rx) antennas were placed on the balcony of the Palazzo Ducale in Venice. The distance  $r$  between the two ‘arrays’ was approximately 442 m. One of the two Tx antennas was a commercial Yagi–Uda antenna producing a classical directive radiation pattern interpreted as an  $\ell = 0$  orbital angular momentum (OAM) mode. The other Tx antenna was a modified reflector able to produce a pattern corresponding to an OAM mode with  $\ell = 1$ . Note that although the latter claim is not supported by antenna simulation or phase pattern measurements in [1], we will assume that this is correct. The two Rx antennas were also of the Yagi–Uda type, and were separated by a distance  $d$  of about 4.5 m. All antennas had horizontal polarization. By tuning the system and then *summing and subtracting* the signals received by the two Rx antennas, the team managed to reconstruct the two distinct signals transmitted by the two Tx antennas at the same time.

### 2. Analysis of the experiment

The Venice experimental setup can be considered as a point-to-point,  $2 \times 2$ , multiple-input–multiple output (MIMO) antenna system. In fact, a point-to-point  $M \times N$  MIMO system is characterized by a Tx node comprising  $M$  Tx antennas and an Rx node with  $N$  Rx antennas (in this definition a radiating structure having two input ports, for instance a dual-polarized antenna, can be seen as having *two* antennas). This is a general definition and is thus valid, independently of the type of antenna and so it also applies in the experiment in [1]. It is also worth mentioning that other authors have recently discussed OAM modes from the perspective of MIMO communications [2], thereby supporting the approach followed here, while providing different but complementary information. In particular, Edfords and Johansson [2] provided a general theoretical analysis of OAM modes at about the same time as [1], while this comment obviously focuses on analysing the experiment in [1]. Since Maxwell’s equations are linear, the signals received by the Rx antennas will be linear combinations of the signals transmitted by the Tx antennas:

$$y = Hs, \tag{1}$$

where  $y$  is the vector of the received signals,  $s$  is the vector of the transmitted signals and  $H$  is the matrix of coefficients (for simplicity, and without loss of generality, noise at the receiver is neglected here).

In analogue MIMO systems, it is, in general, possible to decode the original transmitted signals (if  $N \geq M$ ) by exploiting the fact that the linear combination coefficients are potentially different in each Rx antenna (assuming a deterministic knowledge of the coefficients). In general, these differences are due to significant scattering, but can also arise when one of the arrays is located in (or close enough to) the near-field of the other array, as in the case of the Venice demonstration [1] and of the alternative experiment that we propose in this paper.

The detection in such a MIMO system can then be achieved by multiplying the received signal  $y$  by the pseudo-inverse of  $H$ . This is exactly what is done by the ‘interferometer’ of [1], since from the experiment description provided, we have ( $Y$  and  $V$  being two system-dependent complex parameters)

$$H = \begin{pmatrix} Y & V \\ Y & -V \end{pmatrix} \rightarrow H^{-1} = \frac{1}{2YV} \begin{pmatrix} V & V \\ Y & -Y \end{pmatrix} \rightarrow \hat{s} = \frac{1}{2YV} \begin{pmatrix} V & V \\ Y & -Y \end{pmatrix} y. \quad (2)$$

In other words, in [1] the OAM  $\ell=0$  signal is reconstructed (the first component of  $\hat{s}$ ) by performing a sum (the first row of  $H^{-1}$ ) while the  $\ell=1$  signal (the second component of  $\hat{s}$ ) is recovered by performing a difference (the second row of  $H^{-1}$ ), and this is expressed as a particular case of standard MIMO detection (called linear detection, i.e., inversion of the channel matrix) in the previous equation.

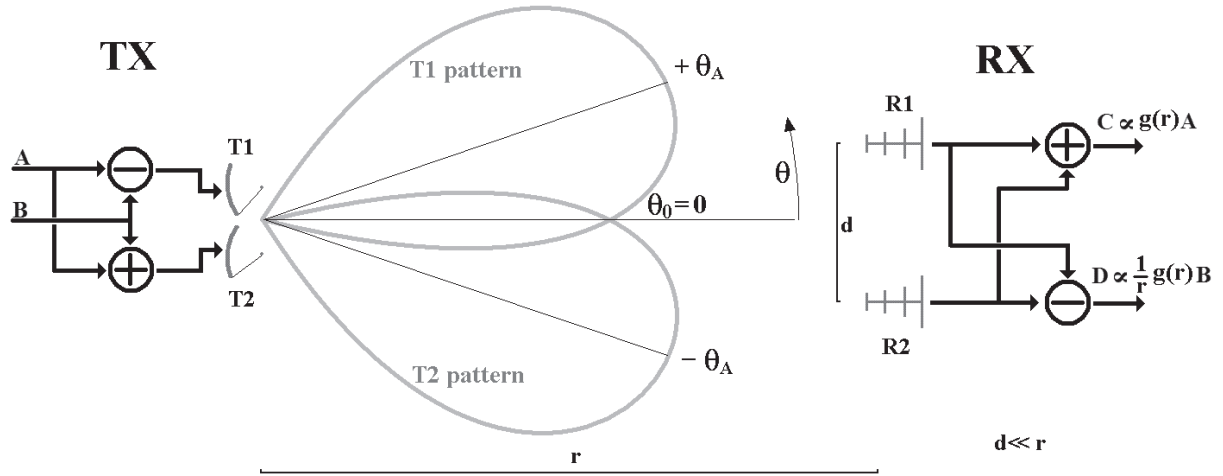
Having established that the experiment in [1] can rigorously be seen as a MIMO problem, from the discussion above, a second important conclusion can be drawn, namely, the vorticity of the modified reflector is not actually needed to achieve this result, since the same performance could be achieved with any pair of Tx antennas, provided that enough diversity in the linear combination coefficients is available at the two Rx antennas.

### 3. An alternative experiment

To better and intuitively illustrate the above claim, let us consider the alternative experiment depicted symbolically in figure 1. We will show that this experiment is similar in essence to that in [1], further demonstrating that the use of the OAM vortex mode is unnecessary here, and also drawing important conclusions with regard to the applicability of the concept.

In order to allow a more compact form of the equations provided next, we make a number of simple assumptions for the system of figure 1, *all without loss of generality*. First, the two Tx directional antennas are of the same type, are placed close to each other and have approximately the same phase centre. They point in two slightly different directions, and we assume that a single polarization is used and that the system is symmetrical with respect to the horizontal axis.

Unlike the Venice experiment, here the two input signals (called  $A$  and  $B$ ) are not fed directly to the Tx antennas, but are treated as a common and a differential mode (left-hand side of figure 1). In this way, we create a differential mode that will be shown to be similar to the ‘vortex’ mode in [1] as far as detection is concerned, but using standard antennas. Note also that the two Tx patterns are pointing slightly outwards from the line-of-sight between the Tx and Rx centres ( $\theta_0 = 0$  in figure 1). In this region, the patterns  $e_{Ti}(\theta)$  vary rapidly with  $\theta$ , and with



**Figure 1.** Schematic of an alternative experiment leading to equivalent performance without using OAM modes.

opposite slopes for the two patterns, which simply allows better detection sensitivity. The Rx architecture is unchanged: performing the sum of the signals received by the two Rx antennas, we can retrieve signal  $A$  (that works as a common mode signal) and, provided that the distance  $d$  between the two Rx antennas is sufficient, the difference will be proportional to signal  $B$ .

In fact, the electric field (written as a scalar as we consider it a single polarization) generated by the two antennas can be approximated by a first order Taylor expansion in the area around the Rx node (assuming  $d \ll r$  and that it is a radiation pattern without abrupt angular changes, as is always the case with finite radiating structures):

$$E_{T1} = g(r)e_{T1}(\theta)(A + B) = g(r) \left[ e_{T1}(\theta_0) + \Delta\theta \frac{\partial e_{T1}}{\partial \theta} \right] (A + B), \quad (3)$$

$$E_{T2} = g(r)e_{T2}(\theta)(A - B) = g(r) \left[ e_{T2}(\theta_0) + \Delta\theta \frac{\partial e_{T2}}{\partial \theta} \right] (A - B), \quad (4)$$

where  $g(r) = (4\pi r)^{-1} \exp(-jkr)$ ,  $\theta_0 = 0$  is the angle with respect to the axis,  $k$  is the wave-number and  $A$  and  $B$  are the  $a$ -dimensional complex envelopes of the two input signals. Since the structure is symmetrical

$$e_{T1}(\theta_0) = e_{T2}(\theta_0) \equiv e_0, \quad \frac{\partial e_{T1}}{\partial \theta} = -\frac{\partial e_{T2}}{\partial \theta} \equiv \partial e. \quad (5)$$

Since  $d \ll r$ , at the two receivers, we can set  $\Delta\theta = \theta \cong \pm d/2r$ , and then evaluate the field

$$E_{R1} = E_{T1}(+d/2r) + E_{T2}(+d/2r) = g(r) \left[ 2Ae_0 + 2B \frac{d}{2r} \partial e \right], \quad (6)$$

$$E_{R2} = E_{T1}(-d/2r) + E_{T2}(-d/2r) = g(r) \left[ 2Ae_0 - 2B \frac{d}{2r} \partial e \right]. \quad (7)$$

And hence (keeping  $d$  constant)

$$C \propto E_{R1} + E_{R2} = g(r)4Ae_0 \propto g(r)A, \quad (8)$$

$$D \propto E_{R1} - E_{R2} = g(r)4B \frac{d}{2r} \partial e \propto \frac{g(r)}{r} B. \quad (9)$$

Note that the common signal  $A$  is attenuated as  $r^{-1}$ , while the differential one is attenuated as  $r^{-2}$ . As can be intuitively inferred from figure 1, if  $r$  increases, the exploitable ‘difference’ between the two patterns decreases like  $r^{-1}$ , assuming that  $d$  is kept constant. Having more antennas, both at the Tx and Rx nodes, the number of multiplexed signals can be incremented by using more complex interferometers to implement the (pseudo)inverse of  $H$ , but only one mode can be common (in the single polarization case); the others are differential and rely on the Rx antennas’ mutual distance  $d_{ij}$  and thus also experience at least the same loss factor. This would be the case for any higher OAM mode added to the experiment in [1].

#### 4. Discussion

The Rx technique used for separating the two signals is the same in both experiments. The only difference is the transmitting section, where the differential mode is created by the feed section (figure 1) or by the antenna itself in [1]. In fact, in both experiments one mode is received as even (such as the  $\ell = 0$  mode) and the other as odd (such as the  $\ell = 1$  mode). When receiving the even mode, the two antennas are working in phase as a ‘normal’ broadside array. In contrast, the odd mode is detected by exploiting a difference of the received field in two different positions, i.e., in two slightly different directions with respect to the Tx array. In both cases, an interferometer implements the (pseudo)inverse of  $H$ , decoding the original signals.

Receiving the odd mode is made possible by using two Tx patterns varying with space in different ways: in [1], one pattern has a large variation in the receiver area (the vortex antenna) while the other pattern is almost constant (the Yagi–Uda antenna), while in the alternative setup of figure 1 we create this variation by placing the receiver where both Tx antenna patterns vary rapidly.

Whichever is the method used to transmit the signals, the patterns are necessarily continuous angular functions since the radiating structures are finite. Therefore, applying the Taylor expansion and following the same derivation as in the alternative example, it is clear that the odd mode signal transmitted by the vortex antenna will also suffer from the additional  $r^{-1}$  factor (or  $r^{-2}$  in terms of signal power), for a fixed Rx antenna spacing,  $d$ . Importantly, this additional loss factor *cannot* be compensated by trying to modify the Tx antennas’ orientation or patterns, since the patterns will always be continuous versus  $\theta$ .

The discussion so far has been based on observations about fields and antenna patterns, but our conclusions are also in line with well-known MIMO system results (as explained earlier, any multiple antenna system can be rigorously seen as MIMO). In particular, if we consider a single-polarization, line-of-sight and a far-field MIMO system, it is well known [3–5] that the corresponding  $H$  matrix will tend to a rank-1 matrix, i.e., in practice, only one signal can be transmitted. Attempting to transmit two distinct signals would mean not being able, at the Rx node, to de-multiplex their superposition. This is due to the fact that the vector of the linear combination coefficients (i.e., a row of  $H$ ) is the same for all Rx antennas, except for a phase factor that, being common to all the vector components, still leads to a rank 1 linear application.



If we remove the constraint on the polarization, we can achieve a rank 2 limit  $H$  matrix, i.e., two signals can be transmitted together (as in TV broadcasting satellites), but not more. This means that in a single polarization, line-of-sight, far-field situation, only one of the OAM modes can be transmitted successfully. Since the  $\ell = 0$  is a non-twisted ‘standard’ mode, it obviously can be transmitted, and hence it follows that it should not be possible to transmit all the other modes with  $\ell \neq 0$  in far-field conditions.

Therefore there is an apparent contradiction between these well-known MIMO results and the capability of decoding the two signals in [1]. This is actually not the case, and the explanation lies in the far-field condition from which the above well-known MIMO properties are derived. In brief, the Venice experiment was not held in a ‘far-enough-field’ situation: the condition for considering a MIMO system as far-field is:  $r \gg 2D^2/\lambda$ , where  $D$  is the size of the larger antenna array (either the Rx or the Tx). The threshold  $r_0 = 2D^2/\lambda$  is usually considered as an indicative separation point (see [6]) between the Fresnel near-field and the Fraunhofer far-field, but near-field quantities can also still be measured (even if highly attenuating with  $r$ ) in the ‘inner’ Fraunhofer region. In [1],  $\lambda = 12.4$  cm, and taking  $D = d = 4.5$  m (the Rx antennas’ separation), we obtain  $r_0 = 327$  m. The distance  $r$  (442 m) is of the same order of magnitude, and hence the detection of the OAM modes is still possible, which reconciles our analysis with well-known MIMO results. Finally, it is notable that in [1] the scattering from nearby walls, polarization imperfections and the distance between Tx antennas could have aided the detection as well.

## 5. Conclusions

Despite the originality of the idea and the positive outcome of the Venice experiment, in our opinion the authors did not identify that the system they developed actually implements a specific type of MIMO system, and in turn that ‘vortex’ OAM modes are not needed to achieve such a result. In our view, this contradicts the introduction in [1], which suggests that the proposed concept is different from—and overcomes the limitations of—the usual spatial diversity techniques.

Moreover, our analysis reveals that this kind of technique leads to an additional important received power reduction for a fixed spacing between Rx antennas, which seriously questions the applicability of the concept. If instead  $d$  is scaled in order to keep  $r/d$  constant, the results are impractical: if the system used in the Venice experiment is scaled, for example, to satellite distances of the order of  $10^3$  km, then a hypothetical Rx array would have a size  $d$  of the order of 10 km. Alignment would also be very sensitive in the proposed setup, probably preventing its use in broadcast applications. The idea could be used in other fixed line-of-sight radio links, but alternative MIMO solutions provide similar or better results.

Importantly, it should be noted that the beneficial use of vortex modes in guided communication does not contradict our conclusions, since our comment—and the original paper—only relate to the use of OAM modes in wireless systems.

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