\textit{N}-tupling the capacity of each polarization state in radio links by using electromagnetic vorticity

Fabrizio Tamburini$^1$, Bo Thidé$^3$, Elettra Mari$^2$, Giuseppe Parisi$^1$, Fabio Spinello$^4$, Matteo Oldoni$^5$, Roberto A. Ravanelli$^5$, Piero Coassini$^5$, Carlo G. Someda$^1$ and Filippo Romanato$^2$

$^1$Twistoff s.r.l., via della Croce Rossa 112, I-35129 Padova, Italy
$^2$Department of Physics and Astronomy, University of Padova, via Marzolo 8, I-35100 Padova, Italy
$^3$Swedish Institute of Space Physics, Physics in Space, Ångström Laboratory, P.O. Box 537, SE-751 21, Sweden
$^4$Department of Information Engineering, University of Padova, via Gradenigo 5B I-35131 Padova, Italy
$^5$SIAE Microelettronica, 21, via Michelangelo Buonarroti, I-20093 Cologno Monzese, Milan, Italy

Abstract. The congestion of the radio frequency bands imposes serious limitations on the capacity and capability of modern wireless information infrastructures. One approach to enable frequency re-use is to exploit other physical conserved quantities of the electromagnetic fields, such as the angular momentum in addition to linear momentum, exploited in present-day telecommunications. Whereas in the optical regime the increase of channel capacity by using orbital angular momentum (OAM) states was demonstrated recently, the receiving antennas in commercial radio links have a much smaller extent than the transmitted beam, making the signal reception and characterization of the OAM state demanding. Moreover, radio data transmission with $N$ channels per polarization state at the same frequency for radio links when $N>2$ is known to be notoriously difficult to realize even with multiport techniques, long antenna baselines and digital post-processing. Here we report results from an outdoor experiment where the physical properties of OAM states were used to transfer information, using far-field multiplexing/demultiplexing of $N=3$ coexisting, collinear, vertically polarized and mutually independent OAM radio beams, opening new perspectives in wireless telecommunications.

Keywords: Applied classical electromagnetism, Electromagnetic wave propagation, Antennas: theory, components and accessories, Telecommunications: signal transmission and processing, Electromagnetic vorticity.

PACS numbers: 41.20.-q, 41.20.Jb, 84.40.Ba, 84.40.Ua

‡ Corresponding author: tamburini@twistoff.it, fabrizio.tamburini@unipd.it
1. Introduction

In 1895, Guglielmo Marconi invented the wireless telegraph and from that the communication world spread in all directions [1]. In order to allow different stations to communicate simultaneously without interfering with each other, Marconi later proposed the rasterization of the available radio frequency spectrum of into different sub-bands. All long-distance wireless systems presently in use exploit the linear momentum degree of freedom of the electromagnetic (EM) radiation, and make use of various forms of phase, frequency and/or amplitude modulation of it. However, the ever-growing use of wireless communication with radio unavoidably leads to the saturation of all available frequency bands, even with the adoption of clever engineering techniques to increase the information-carrying capacity within a given bandwidth. The focus on the saturation problem is by no means new, and an intense research effort is underway along well-known avenues (e.g., multiport technique protocols such as multiple-input-multiple-output, MIMO). The experimental results that we report in this paper were obtained following a different approach where the physical properties of electromagnetic vorticity [2] were utilized. To the best of our knowledge, the results presented here are unprecedented at radio frequencies.

In addition to energy and linear momentum, the EM field can carry also angular momentum. The total angular momentum, \( \mathbf{J} = \mathbf{S} + \mathbf{L} \), is the sum of two contributions. The quantity \( \mathbf{S} \) represents the spin angular momentum, which is related to photon helicity and thus to wave polarization. As is well known, \( \mathbf{S} \) is already being exploited in radio communications and can yield, at most, a two-fold increase in capacity. The other quantity, \( \mathbf{L} \), describing the electromagnetic vorticity of the beam, is the orbital angular momentum (OAM) associated with the structured orbital helicoidal phase profile that a suitable beam can exhibit, can yield an \( N \)-fold increase in capacity \((N = 1, 2, 3, \ldots)\) for each polarization state \( \mathbf{S} \). The OAM degree of freedom [3, 4, 5, 6] can be described in terms of classical theory based on Maxwell’s equations [7, 8]. Paraxial beams carrying OAM can be readily described by Laguerre-Gaussian (LG) modes that are identified by two integers \( \ell \) and \( p \). The parameter \( \ell \) describes the number of twists of the helical wavefront in a wavelength, whereas \( p \) gives the number of radial nodes of the mode, characterized by a phase profile azimuthally spanning \( 2\pi\ell \) radians in the plane orthogonal to the beam propagation. When OAM beams propagate, they have a characteristic intensity (linear momentum density /Poynting vector) profile with a ‘doughnut’ shape with a null on the propagation axis. This fundamental physical property of EM waves has already found practical applications in several fields: nanotechnology [9, 10], optical [11, 12] and radio [2, 8] communications and in astronomy [13, 14, 15, 16] to improve the resolving power of diffraction-limited optical instruments [17], to image extrasolar planets [18, 19, 20] and to detect Kerr black holes [21].

In our experiment we achieved a stable link with three beams over a distance of 100 meters (5700 wavelengths \( \lambda \) at 17.1–17.3 GHz) by using only simple analog post-processing to enhance the signal-to-noise ratio (SNR). These three independent beams were modulated by means of 4-Quadrature Amplitude Modulation (4-QAM) and carried each about 11 Mbit s\(^{-1}\). Our results clearly prove that \( N > 2 \) OAM radio beams per polarization state can be
Table 1. End-to-end measurements with a radome (Tx is the transmitted beam, IL the insertion loss, RL the return loss, OP the open field, SH with a metal plane covering the whole aperture.

| $\ell$ | Rx / status | Parameter | Measurement (dB) |
|--------|-------------|-----------|-----------------|
| $0$    | OP          | RL        | 13.7            |
| $0$    | SH          | RL        | 2.3             |
| $0$    | $0$         | IL        | 3.3             |
| $+1$   | OP          | RL        | 14.2            |
| $+1$   | SH          | RL        | 16.2            |
| $+1$   | $+1$        | IL        | 3.2             |
| $+1$   | $0$         | IL        | 18.6            |
| $+1$   | $-1$        | IL        | 26.2            |

used for simultaneous data transmission for a given link. We also set up a bidirectional data exchange between two OAM radio stations, each carrying a 436 Mbit s$^{-1}$ 1024-QAM signal, and two simultaneous OAM transmissions with digital modulation up to $2 \times 171$ Mbit s$^{-1}$, opening new perspectives in wireless telecommunications.

1.1. Schematics of the experiment

With present technologies, the detection and characterization of EM waves carrying OAM can, in experiments where a given OAM state is being used, be made with simple interferometric methods, such as those used in radio astronomy [2, 22]. For telecommunication purposes, however, the practical needs of construction and installation require that both antennas, in case of bidirectional links, have similar characteristics. To this end, in order to transmit and receive electromagnetic waves carrying OAM, we used pairs of identical twisted parabolic antennas [2], each couple generating and receiving either $\ell = +1$ or $\ell = -1$ LG-OAM modes with $p = 0$. A twisted parabolic antenna is a reflection phase mask that converts a spherical phase front into a helical one with a specific OAM value. The reception of OAM beams is also made through an identical twisted parabolic reflector placed in front of the transmitter. Because of parity change (recall that angular momentum is a pseudovector), this latter antenna acts as an inverse phase mask and transforms the received OAM beam into a planar beam that is injected into the feeder/coupler and propagates to the receiver via the fundamental mode of the waveguide. If the impinging beam has instead a different OAM $\ell$ value than the receiving parabola, their mutual orthogonality suppresses the former, preventing it from reaching the receiver.

Initial tests of the newly designed and constructed twisted antennas were made at distances up to 7 meters, in the (linear momentum) near field zone. They showed an excellent modal insulation even when two opposite antennas were coaxially placed face-to-face at a short distance (a few centimetres). On the other hand, we observed good transmission between two equal twisted antennas facing each other (see Table 1).

In order to investigate the data transport capabilities of OAM radio beams, we designed
and ran three experiments in the 17.1–17.3 GHz unlicensed band at a distance of 100 metres with the antennas mounted on the rooftops of two buildings of the SIAE Microelettronica industrial compound near Milan, Italy: (1) a single bidirectional link without additional analog interference suppression, (2) a double unidirectional link without and with additional analog interference suppression, and (3) a triple unidirectional link with additional analog interference suppression. The radio equipment used in these experiments was a commercially available outdoor transmitting/receiving unit manufactured by SIAE Microelettronica. These units are completely configurable in their radio properties of interest (transmitted power, modulation scheme, carrier frequency and modulated bandwidth). A block diagram of the various experiments is shown in Figure 1 with all the antennas mounted for operation in vertical polarization.

The measured phase and intensity profiles of the OAM beams are presented in Figure 2, the received-power matrix of the setup is reported in Table 2.

The 3 dB ring of these OAM beams were about 6 and 9 metres in diameter, respectively, implying that the dark region hosting the singularity was much larger than the receiving antenna cross section. Because of the doughnut geometry, one can obtain good signal and phase information by placing the receivers in an off-centre region of higher intensity (linear

---

**Figure 1.** Schematics of the radio experiments. 1: single link; 2: double link without (a) and with (b) additional mode cancelling; 3: triple link. The letter T denotes 10 dB attenuators, whereas PT represents phase shifter and rotary attenuator blocks. Tx is the transmission unit, Rx the receiver. Dashed lines represent the directions where the antennas are pointed (angles and distances are not in scale). The bifurcation of each signal line represents a -3dB directional coupler.
Figure 2. Intensity (magnitude of the linear momentum density) a) and phase map b) of the $\ell = -1$ radio beam vortex measured in free space at a distance of 100 m. The corresponding OAM spectrum, peaking at the $\ell = -1$ value, as expected, is shown in the inset c). The dip at the center of the intensity distribution corresponds to the phase singularity and the notch depth is 30 dB below the peak. Instead, d) shows the simulation of the phase distribution obtained through numerical simulations that confirm the good quality of the experimental data.

|               | Tx1 $\ell = +1$ | Tx2 $\ell = 0$ | Tx3 $\ell = -1$ | SNR (dB) |
|---------------|-----------------|----------------|-----------------|----------|
| Pow (dBm)     | 22              | 8              | 22              |          |
| Rx1 $\ell = +1$ | -55.500        | -65.625        | -72.625         | 9.5      |
| Rx2 $\ell = 0$   | -73.000        | -55.375        | -65.375         | 9.3      |
| Rx3 $\ell = -1$  | -70.125        | -52.875        | -40.875         | 11.3     |

Table 2. Matrix of received powers and estimated signal-to-noise ratio (SNR) for the triple link setup. Pow indicates the output power from each radio transmitter.
momentum density/Poynting vector), although this decreases the orthogonality among the received OAM modes. Additional modal isolation can be obtained by exploiting the topology of OAM beams. What is crucial is that this situation is different from the experiments in the optical domain where most of the beam is collected; in radio links, only a small fraction of the beam can normally be gathered by the receiving antenna.

The single link experiment (Figure 1, inset 1) proved that the beam generated by the twisted $\ell = +1$ antenna can support a complex modulation scheme (1024-QAM) over a wide bandwidth (56 MHz), resulting in an error-free throughput of 436 Mbit/s per direction with a transmitted power of 17 dBm, such as for a standard radio beam.

The double link experiment was conceived to test unidirectional data transfer via two 20 dBm OAM beams generated by the twisted parabolas $\ell = \pm 1$ on the same carrier frequency (17.128 GHz) and polarization; see Figure 1 insets 2a and 2b. To this end we exploited the peculiar linear momentum radiation pattern of the antennas so that the interfering signals reaching the $\ell = \pm 1$ receivers were minimum, due to the doughnut-shaped linear momentum radiation pattern and to the mutual orthogonality of the coaxial OAM beams. The error-free throughput achieved was $2 \times 171$ Mbit/s, with 16-QAM modulation over a 56 MHz bandwidth. We further improved the isolation between channels by introducing a pair of attenuator-phase shifter blocks, implementing a basic static cancelling scheme. This however required a reduction of the bandwidth to 7 MHz only due to the narrow-band response of the phase shifters. The modulation was however increased to 256-QAM, with an errorless throughput of $2 \times 42$ Mbit/s with transmitted power of 18 dBm.

The triple link at 17.128 GHz was set up by adding an $\ell = 0$ (standard antenna) channel to the double link experiment. To minimize the interference of the transmitted signals on the relative opposite receivers, we exploited the aiming of the twisted parabolas as shown in Figure 1 inset 3, so to use their inherent ‘natural’ mode insulation of about 23 dB. A pair of static mode-cancellers removed the interference of the transmitted signals in the $\ell = 0$ channel, due to the loss of orthogonality experienced by the standard antenna when receiving a portion of the radiated OAM beam far off its axis. With such a scheme we achieved an error-free throughput of $3 \times 11$ Mbit/s with 4-QAM over a 7 MHz bandwidth, with standard forward error correction based on low-density parity-check codes (LDPC) algorithm [23]. A screenshot of the received constellations is shown in Figure 3 whereas the received powers and the signal-to-noise ratio (SNR) values for the triple link setup are reported in Table 1.

To minimize the mutual interference on the $\ell = 0$ receiver we then aimed the beam axes of the twisted receiving parabolas toward the untwisted transmitting antenna and increased the capacity of the $\ell = 0$ beam to 16 QAM. We also changed the modulation bandwidths to 56 MHz for the twisted channels and to 7 MHz for the untwisted one, respectively.

2. Twisted parabolic antennas, design and realization

To optimize the antenna design for both transmission and reception, we performed a numerical study with MOM (method of moments) simulations to couple, in the best way, the geometry of the modified parabolic phase mask with the hyperbolic feeder from the original standard
Received digital 4-QAM constellations of three independent digital channels sent through as many different and superimposed OAM beams on the same carrier frequency, bandwidth and polarization. By using the topological properties of OAM beams, each receiver detects its specific OAM state/channel. From left to right: channels RX1 ($\ell = -1$), RX2 ($\ell = 0$) and RX3 ($\ell = +1$).

Cassegrain antenna. The original parabolic reflector was a standard 36 cm parabola with approximately 30–35 dB gain at 17.2 GHz. A conventional parabolic reflector described in a cylindrical coordinate system $(r, z, \phi)$ ideally produces plane wavefronts at very long distances from a spherical source at the focus thanks to its profile $z$ as a function of distance, $r$, from its axis. For a focal length $F$ the profile is

$$z(r) = \frac{r^2}{4F}$$

(1)

To imprint vorticity onto the beam emitted by the Cassegrain feeder, one can deform the shape of the standard parabolic reflector and azimuthally gradually elevate its surface along the symmetry axis as a function of the azimuthal angle $\phi$ so as to obtain a final step of half the wavelength after having encircled the symmetry axis an angle of $\phi = 2\pi$. The modified parabolic reflector designed to generate a vortex with order $\ell = m$ is defined by the formula

$$z(r, \phi) = \frac{m(\phi - \pi)\lambda}{4\pi} + \frac{\pi r^2}{4\pi F - m(\phi - \pi)\lambda}.$$  

(2)

Equation (2) ensures that the focus $F$ of the twisted reflector is independent of $\phi$ and that the focus of the twisted parabolic antenna coincides with the focus $F$ of the original parabolic reflector. Our twisted antennas have a gap of $\lambda/2$ at 17.2 GHz ($\lambda = 1.74$ cm).

Figure 4 shows the Cassegrain configuration of the twisted parabolic antenna. The feeder is mounted in the same position as for a conventional parabolic Cassegrain antenna. Both the left-handed ($\ell = +1$) and the right-handed ($\ell = -1$) OAM mode antennas as well as the untwisted one ($\ell = 0$) have the same focus.

Numerical simulations show that the feeder emits a wave resembling the (transversal electric) TE11 waveguide mode. The MOM simulations of the complete structure (feeder
plus twisted parabolic reflector) were carried out by setting the TE11 waveguide mode as port excitation.

Figure 5 shows the radiated electric field as obtained in the MOM simulations in the far zone of a twisted antenna. The electric field magnitude and phase exhibit the expected doughnut shape together with the phase variation and the singularity located at the centre. The phase of the polarized electric field is obtained by estimating the argument of the complex function describing the electric field on its polarization axis, $\arg(E_x)$, and the numerical simulations confirm that the vortex emitted by the antenna has the typical $0$–$2\pi$ phase variation of the $\ell = 1$ mode. The peculiar ‘fish-mouth’ shape exhibited by the radiated vortex, as shown in the right panel b) of Figure 5, is caused by the two local minima present in the TE11 mode coming from the circular feeder propagating in the far field region.

2.1. Realization and test of the modified parabolic antennas

The twisted parabolic antennas were manufactured by using the stereolithography printing technique (U.S. Patent 4,575,330) directly from 3D CAD plots used in our MOM simulations. The polymer-derived ceramic support was 3 mm thick with a surface roughness of 0.1 mm thick and the inner part of the antenna was coated with a 0.1 mm-thick copper layer deposited with a galvanic method with a 0.25% surface-error tolerance.

The electrical parameters of these antennas were measured by evaluating the short-circuit
Figure 5. a) The magnitude of the electric field in the far field zone calculated in the plane perpendicular to the propagation direction. The scale is in arbitrary units. b) Three dimensional plot of the radiation lobe emitted by the twisted parabolic reflector. Here, the color palette represents the phase of the x-component of electric field, calculated as arg($E_x$).

return loss (RL) in open field (OP) and with a metal plane covering the whole aperture (SH). We measured the ratio between the reflected wave coming from the antenna port and the signal injected into it when the antenna was located in front of a metallic surface. The OAM and transient modes, present in the near field, because of the change of parity due to the reflection on the metallic surface, actually make the twisted antenna exhibit a rather different behavior compared to a standard parabolic antenna, as depicted in Figure 6.

We also evaluated the transmission characteristics (insertion loss, IL) for various combinations of transmitting and receiving antennas when facing each other at a short distance (< 1 cm between the planes of the apertures) and with and without a protective radome cover. Tables 1 and 3 report the measured values at 17.2 GHz. To analyze the results, we used the standard parabolic reflector ($\ell = 0$) as reference (first three rows in Table 1). The RL is acceptable (13 dB) when the antenna is free to radiate, whereas it drops dramatically to 2.3 dB when the aperture is closed by a brass plate. This is a clear indication of an almost complete rejection of the radiated power, being reflected back into the feeder and on to the generator. We also evaluated the transmission between homologue antennas at a distance of 2 m (see Table 4).

The same measurements for a twisted parabola $\ell = +1$ show a good RL (14.2 dB) for unimpaired radiation, thus suggesting that the antenna is indeed radiating power. Interestingly, a similar value (16.2 dB) is also exhibited as RL when the aperture is closed onto the brass plate. We explain this phenomenon by the behavior of OAM beams reflected from perfect
Figure 6. Return loss (RL) of a standard parabolic antenna ($\ell = 0$) with respect to a twisted one ($\ell = 1$) when both were placed in front of a metallic surface. The standard antenna is sensitive to its reflected wave and therefore exhibits a poor RL; by contrast, the OAM antenna, thanks to the parity change, is not sensitive to its reflected wave.

| Tx   | Rx / status | Parameter | Measurement (dB) |
|------|-------------|-----------|------------------|
| $\ell = +1$ | OP         | RL        | 13.4             |
| $\ell = +1$ | SH         | RL        | 15.5             |
| $\ell = +1$ | $\ell = +1$ | IL        | 3.1              |
| $\ell = -1$ | $\ell = +1$ | IL        | 16.8             |

Table 3. End-to-end measurements without radome (IL = insertion loss, RL = return loss, OP = open field, SH = with a metal plane covering the whole aperture.

| Tx | Rx / status | Parameter | Measurement (dB) |
|----|-------------|-----------|------------------|
| $\ell = 0$ | $\ell = 0$ | IL        | 7.74             |
| $\ell = +1$ | $\ell = +1$ | IL        | 12.24            |

Table 4. Transmission at 2 m, with radome (IL = insertion loss).

electric conductors: the wave changes its topological charge due to a reversed propagation direction. Therefore, it impinges as an $\ell = -1$ beam onto the $\ell = +1$ antenna that produced it and thus, due to the opposite curvature of the reflector, does not reach the generator. As a consequence, the wave remains trapped within the cavity and is dissipated by the conduction losses of the metal surfaces.

This behaviour is virtually unaffected by the presence of the radome cover, as can be seen by comparison with Table [I]. Concerning the transmission characteristics, we observe that a pair of $\ell = 0$ antennas exhibit an IL value of about 3 dB, which, for this experiment, is thus considered, to be a good power transfer. A pair of $\ell = +1$ antennas show similar
behavior, suggesting that the same power flow is sustained between them. This may however raise doubts concerning the validity of such measurements, as we are located well into the near-field region. If the antennas are generating a residual $\ell = 0$ beam, this might transfer power between them. But a further IL measurement between $\ell = +1$ and $\ell = 0$ shows that the transmission is severely impaired, and similarly between $\ell = +1$ and $\ell = -1$. We deem this to be compatible with the hypothesis of the receiving antenna being sensitive to a perpendicular beam, as happens with two antennas with orthogonal polarizations. Transmission among homologue antennas at a distance of 2 m ($\sim 110$ wavelengths) shows that the magnitude of the received signal in the $\ell = +1$ pair is about 4.5 dB smaller than the corresponding $\ell = 0$ pair. This can be ascribed to the larger spread of the $\ell = +1$ beam, which is thus captured to a lesser degree by the finite area of the receiving antenna than the $\ell = 0$ beam.

3. OAM radio links—experimental results

In this Section we present a more detailed account of the experimental results of transmission/reception for each link pictured in Figure 1.

1. Single OAM link: Two twisted $\ell = +1$ antennas, manufactured and characterized as described in the previous section, were deployed at the two sites (namely A and B), respectively, and connected to a pair of commercially available radio Full Outdoor Units provided by SIAE Microelettronica. They function as full duplex transceivers in the chosen frequency band and implement standard forward error correction based on the LDPC algorithm. The frequency for the A $\rightarrow$ B link is 17.128 GHz whereas for the B $\rightarrow$ A direction it is 17.272 GHz. The $\ell = +1$ at site A (B) was aimed towards its counterpart at site B (A) which caused, as a side effect, the received power to lie in a relative minimum due to the doughnut-shaped radiation pattern. We set up the transceiver units to operate with a modulation bandwidth of 56 MHz and increased the constellation levels up to 512-QAM, which carries 9 bits/symbol. By tilting the antennas slightly upward (< 1 degree), we were moreover able to increase the received power and safely switch to a 1024-QAM, which carries 10 bits/symbol. This tilt is not strictly necessary to operate the link, but may be used as a way to overcome the minimum of received signal with direct aiming. This is consistent with the measured radiation pattern of these twisted parabolas, whose intensity doughnut at the selected distance exhibits a radiation maximum at an angle between 2 and 3 degrees from the axis. The number of errors detected at both sides remained zero for the whole duration of the experiment (one day), and in fact the evaluated signal-to-noise ratios were both well above the equipments error-free safety thresholds. The total throughput for this duplex link was about $2 \times 436$ Mbit/s.

2. Double OAM link: A setup similar to the one described for the single link was used here, except that in this case we mounted an $\ell = +1$ and an $\ell = -1$ antenna on the masts at both sites of the link, in order to set up a double unidirectional link from site A toward site B on a single frequency (17.128 GHz) and with the same polarization (vertical for both antennas).
The antennas on the mast were spaced by about 1 m between their apertures. We first aimed the two transmitting antennas (at site A), so that their axes pointed approximately towards their opposite counterpart. In other words, \( \ell = \pm 1 \) at site A were aimed toward \( \ell = \mp 1 \) at site B, in a sort of cross-aiming manner to minimize the received interference power at the receivers. Then, the aiming of the four antennas was slightly adjusted to provide the minimum received power at \( \ell = \mp 1 \) due to the transmitting \( \ell = \pm 1 \), switched on one at a time. Once a proper aiming was obtained, we switched both transmitters on and increased the bandwidth and modulation up to 56 MHz with a 16-QAM, carrying 4 bits/symbol and achieving an error-free throughput of \( 2 \times 171 \text{ Mbit/s} \). In order to improve the signal-to-noise ratio at the receivers, we then introduced an elementary static analog cancellation scheme, based on a pair of rotary attenuator-phase shifter blocks. These were wired at the receiver end via 3 additional directional couplers so that the residual \( \ell = \mp 1 \) signal received spuriously by \( \ell = \pm 1 \) could be suppressed. We manually adjusted the attenuation levels and phase delays to reduce this interference and achieved an error-free 256-QAM modulation (carrying 8 bits/symbol). The total throughput was \( 2 \times 42 \text{ Mbit/s} \), as in fact we used a smaller bandwidth (7 MHz) to match the inherently narrow-band response of the phase shifters.

3. **Triple link:** To further investigate the capabilities of multiple OAM beams on the same frequency and with the same polarization, we installed an additional standard (\( \ell = 0 \)) parabolic antenna at each site of the double link in order to establish a triple link A \( \rightarrow \) B at 17.128 GHz with vertical polarization. The standard antennas had a diameter of 36 cm, equal to the maximum diameter of the twisted parabolas and had same focal ratio. The three antennas at each site were vertically stacked with a distance of about 30 cm between their apertures. The \( \ell = 0 \) antennas were equipped with an additional 10 dB attenuator so that the power levels at the three receivers due to their respective transmitters were comparable. For the same purpose we also calibrated the transmitters to output different power levels, as reported in Table 2. The two \( \ell = 0 \) antennas were directly aimed toward each other. The first tests were made by aiming the transmitting twisted antennas to those with opposite OAM sign, obtaining a 3 channel 4-QAM link. To optimize the link, the receiving \( \ell = \pm 1 \) at site B were then aimed so that the power received by them due to the transmitting \( \ell = 0 \) at site A was minimum.

Next we cross-aimed the remaining antennas in a manner similar to that described for the double link (without the additional mode suppression): the \( \ell = \pm 1 \) antennas at site A were rotated so that their opposite counterparts (\( \ell = \mp 1 \) at site B) received the minimum interfering signal. Such an aiming procedure relies on two of the main properties of OAM beams:

- In order to have minimum interference on \( \ell = \pm 1 \) at site B due to the \( \ell = 0 \) beam, we aimed the receiving OAM antennas toward the source of \( \ell = 0 \) so that they intercepted a portion of a standard Gaussian beam, which can also be assumed locally and at large distance to be a plane wave. Thanks to the intrinsic orthogonality of OAM beams with plane waves, the \( \ell = \pm 1 \) at site B will theoretically transfer no \( \ell = 0 \) power to their receivers. In this way we increased the capacity of the \( \ell = 0 \) beam to 16 QAM, and widened the modulation bandwidths to 56 MHz for the twisted channels and 7 MHz for the untwisted one, respectively.
In order to have minimum interference on $\ell = \pm 1$ at site B due to the $\ell = \mp 1$ at site A, we exploited in this case mainly the radiation zero, i.e. the doughnut centre exhibited by the transmitting antennas. In fact, in the double link experiment, we reciprocally cross-aimed the antennas at both sides and were thus able to place the receiver antenna at the same spot but we also experienced the intrinsic orthogonality of coaxial OAM beams. In the triple link experiment, however, the receiving antenna was not pointing exactly toward the opposite OAM source and therefore it cannot, analytically, rely on a complete modal orthogonality. The radiation zero, however, manifests itself as a notch with extremely weak fields and, the receiving antenna being small with respect to the size of this dip, it is sufficient to provide an acceptable isolation.

Once a proper aiming had been obtained, we introduced a basic static cancelling scheme similar to the one described for the double link case, although here wired to cancel the residual $\ell = \pm 1$ interference onto the $\ell = 0$ branch. This is necessary since the $\ell = 0$ antenna is sampling only a portion of the OAM beam and thus cannot fully utilize the modal orthogonality. Hence, at its port, the $\ell = 0$ is affected by heavy interference that must be reduced in order to achieve an acceptable signal-to-noise ratio.

4. Conclusions

This experiment verifies the basic properties of radio OAM beams and provides a practical proof of the data transport characteristics of OAM beams. It also constitutes an example of radio OAM multiplexing/demultiplexing. The OAM therefore can be used as a physical layer to use for increasing the capacity of radio links and communication systems, also when only a small fraction of the EM beam is received, a rather common situation in real-world radio communication scenarios. Further theoretical and experimental investigations are called for.

Acknowledgments

The authors acknowledge the logistic and financial support of SIAE Microelectronics in the designing, building, and testing of the setup. B.T. also gratefully acknowledges the financial support from the Swedish National Space Board and the Swedish Research Council under the contract number 2012-3297.

References

[1] Dunlap O. E., Jr, Marconi: The Man and His Wireless (Macmillan, New York, 1937).
[2] F. Tamburini et al., Encoding many channels on the same frequency through radio vorticity: first experimental test New J. Phys. 14, 033001 (2012).
[3] Berestetskii, V. B., Lifshitz, E. M., Pitaevskii, L. P., Quantum Electrodynamics. (Butterworth-Heinemann (UK) Vol. 4, 2nd ed. 1982).
[4] Mair, A. Vaziri, A., Weihs, G. and Zeilinger A., Entanglement of the orbital angular momentum states of photons, Nature 412, 313 316 (2001).
[5] Leach, J., Padgett, M. J., Barnett, S. M., Franke-Arnold, S. and Courtial, J., Measuring the Orbital Angular Momentum of a Single Photon *Phys. Rev. Lett.* **88**, 257901(4) (2002).

[6] Tamburini, F. and Vicino, D., Photon wave function: A covariant formulation and equivalence with QED *Phys. Rev. A* **78**, 052116(5) (2008).

[7] Thidé, B. *Electromagnetic Field Theory* (Dover Publications, Inc., Mineola, NY, USA, 2nd edn., in press), URL [http://www.plasma.uu.se/CELO/CED/Book](http://www.plasma.uu.se/CELO/CED/Book) ISBN: 978-0-486-4773-2.

[8] Tamburini, F. et al., Reply to Comment on Encoding many channels on the same frequency through radio vorticity: first experimental test, *New J. Phys.* **14**, 118002 (2012).

[9] Grier, D. G., A revolution in optical manipulation, *Nature* **424**, 810–816 (2003).

[10] Zilio, P., Mari E, Parisi, G., Tamburini, F. & Romanato, F., Angular momentum properties of electromagnetic field transmitted through holey plasmonic vortex lenses *Opt. Lett.* **37**, 3234-3236 (2012).

[11] Wang, j., et al., Terabit free-space data transmission employing orbital angular momentum multiplexing *Nat. Phot.* **6**, 488496 (2012).

[12] Bozinovic, N. et al., Terabit-Scale Orbital Angular Momentum Mode Division Multiplexing in Fibers *Science* **340**, 1545-1548 (2013).

[13] Thidé, B. et al., Utilization of Photon orbital angular Momentum in the Low-Frequency Radio Domain *Phys. Rev. Lett.* **99**, 087701(4) (2007).

[14] Elias, N. M. II, , Photon orbital angular momentum in astronomy *Astron. Astrophys.* **492**, 883–922 (2008).

[15] Harwit, M., Photon Orbital Angular Momentum in Astrophysics *Astrophys. J.* **597**, 1266–1270 (2003).

[16] Berkhout, G. & Beijersbergen, M., Method for Probing the Orbital Angular Momentum of Optical Vortices in Electromagnetic waves from Astronomical Objects *Phys. Rev. Lett.* **101**, 100801(4) (2008).

[17] Tamburini, F., Anzolin, G., Bianchini, A. and Barbieri, C., Overcoming the Rayleigh Criterion Limit with Optical Vortices *Phys. Rev. Lett.* **97**, 163903(4) (2006).

[18] Lee, J. H., Foo, G., Johnson E. G. and Swartzlander, G. A. Jr., Experimental Verification of an Optical Vortex Coronagraph *Phys. Rev. Lett.* **97**, 053901(4) (2006).

[19] Mari, E. et al., Sub-Rayleigh optical vortex coronagraphy *Optics Express* **20**, 24452451 (2012).

[20] Serabyn, E., Mawet, D. & Burruss, R., An image of an exoplanet separated by two diffraction beamwidths from a star *Nature* **464**, 1018-1020 (2010).

[21] Tamburini, F., Thidé, B., Molina-Terriza, G. & Anzolin, Twisting of light around rotating black holes *Nature Physics* **7**, 195197 (2011).

[22] Kraus, J. D., *Radio Astronomy* (McGraw-Hill, NY, USA, 1966).

[23] Gallager, R. G., *Low-Density Parity-Check Codes* (Cambridge, MA: MIT Press, 1963).