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(71) Applicant (for all designated States except US): **UNIVERSITÀ DEGLI STUDI DI PADOVA** [IT/IT]; Via 8 febbraio 2, I-35122 Padova (PD) (IT).

(72) Inventors; and

(75) Inventors/Applicants (for US only): **TAMBURINI, Fabrizio** [IT/IT]; Via Ciardi 27/7, I-30174 Mestre (VE) (IT). **THIDE', Bo Y** [SE/SE]; Swedish Institute of Space Physics, Box 537, S-751,21 Uppsala (SE). **ROMANATO, Filippo** [IT/IT]; via Bellavista 42/2, I-34151 Trieste (IT). **BARBIERI, Cesare** [IT/IT]; Università di Padova, Dipartimento di Fisica ed Astronomia, Vicolo Osservatorio 3, I-35122 Padova (IT).

(74) Agents: **DE BORTOLI, Eros** et al.; Via Melchiorre Gioia, 64, I-20125 Milano (IT).

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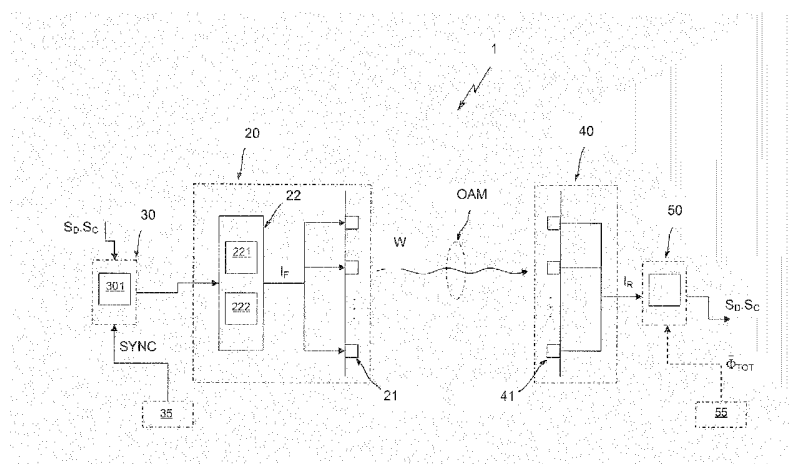


FIG. 1

(57) Abstract: The invention relates to a telecommunication method and apparatus for the transmission and/or reception of EM waves. EM waves are structured with a plurality of OAM modes, said EM waves having a same carrier frequency and one or two orthogonal polarization states. One or more control signals and data signals associated to said EM waves are encoded, so that a channel for transmitting and receiving information is associated to each of said OAM modes. Each of said control signals is associated to a corresponding OAM mode of said EM waves while each of said data signals is one-to-one associated to a corresponding OAM mode of said EM waves. Said control signals and said data signals are simultaneously transmitted through the transmission of said EM waves and are simultaneously received through the reception of said EM waves. Said control signals and data signals are then decoded.

A TELECOMMUNICATION METHOD AND APPARATUS EXPLOITING THE TRANSMISSION AND RECEPTION OF ELECTROMAGNETIC WAVES

DESCRIPTION

FIELD OF THE INVENTION

The invention relates to a telecommunication method and apparatus exploiting the transmission and reception of electromagnetic (EM) waves.

STATE OF THE ART

As is well known, if common techniques of channel multiplexing are not considered, TV and radio broadcasting is limited by the fact that only two independent signals, one for each polarization state of the EM field, can be transmitted for each carrier frequency.

With current technology and international standards, the available frequencies for the transmission of radio signals, each identified by their carrier frequency and bandwidth, are confined to a relatively narrow spectrum, which accordingly limits the number of signals that can be transmitted independently within a given geographical region.

Telecommunication methods and systems that exploit a further characteristic quantity of the EM waves, the orbital angular momentum, for increasing the capacity of transmitting information, have been recently proposed.

The orbital angular momentum (OAM) is a fundamental physical property of the EM field. The simplest example of an EM field in a pure OAM eigenstate, independent of frequency, is a paraxial beam of light propagating in vacuum along a z axis. In this case, the complex amplitude of the EM field, measured in the plane orthogonal to z , $U_{\ell,p}^{LG}$, can be described, in terms of a Laguerre-Gaussian mode in a cylindrical reference frame r, ϑ, z , by:

$$U_{\ell,p}^{L-G}(r, \vartheta) \propto \left(\frac{r\sqrt{2}}{w} \right)^{|\ell|} L_p^\ell \left(-\frac{r^2}{w^2} \right) \exp \left(-\frac{r^2}{w^2} \right) \exp(-i\ell\vartheta)$$

where ℓ describes the number of twists of the helical wavefront (OAM mode, topological charge), p the number of radial nodes of the mode, w the beam waist, $L_p^\ell(x)$ is an associated Laguerre polynomial.

More in general, the amplitude of a field carrying OAM state can be described in an apparatus of spherical coordinates as the factorization of two parts: the first, $A_\ell(r, \vartheta, \varphi)$, depends on the spatial coordinates and the OAM mode while the second, $\exp(-i\ell\vartheta)$, gives the phase dependence, according to the following relation:

$$U_{\ell,p}^{L-G}(r, \vartheta, \varphi) = A_\ell(r, \vartheta, \varphi) \exp(-i\ell\vartheta)$$

A superimposition of different OAM states can generate non-integer OAM states, i.e. a beam endowed with a phase dependence $\exp(i\alpha\vartheta)$ corresponding to a non-integer OAM value α . A non-integer OAM state can be represented as a series superimposition of integer OAM modes, according to the following relation:

$$\exp(i\alpha\vartheta) = \frac{\exp(i\pi\alpha)\sin(\pi\alpha)}{\pi} \sum_{\ell=-\infty}^{\infty} \frac{\exp(i\ell\vartheta)}{\alpha - \ell}$$

An EM wave is therefore characterised by a set of OAM modes, which are naturally quantized and can ideally be infinite.

OAM eigenstates, each identified by a unique integer, are quantised by nature and can therefore be superimposed into various bit patterns that can be resolved at the receiving end. Each OAM mode may be tagged with an integer number (known as “quantum number”) ℓ that identifies the corresponding state of vorticity of the propagating EM wave. The quantum number ℓ of an OAM mode may be positive or negative depending on the vorticity type (left-handed or right-handed) with respect to the propagation direction of the EM wave.

OAM modes are independent of the polarization state of the EM field, i.e. they may exist for any type of polarization of the EM wave.

A beam of EM waves on a given carrier frequency can be encoded with an OAM spectrum in term of pure, integer OAM eigenstates.

OAM eigenmodes with different quantum numbers are orthogonal in a Hilbert sense and therefore correspond to mutually and reciprocally independent quantum states for the radio beam. For this reason, the different OAM eigenmodes in a radio beam that carries OAM of any kind, do not interact during the propagation of the radio beam in a homogeneous unbounded medium, in particular in free space.

The exploiting of OAM modes for wireless communication offers a number of relevant advantages, since several orthogonal and independent communication channels become available for any given carrier frequency.

In a propagating EM wave having a given carrier frequency, the phase of OAM modes having a state of vorticity $\ell \neq 0$ is not constant along a plane but it has a well-defined spatial periodic structure, which may be properly exploited for the transmission of information.

The idea of exploiting the superimposition of OAM modes for performing a multi-modal transmission of information is already used in optics, mostly in the visible region.

However, this concept of physics is basically valid for any wavelength, since Maxwell's equations are linearly scalable in wavelength.

Telecommunication apparatuses exploiting OAM modes are at present very crude and apparently addressed towards only a point-to-point transmission/reception of EM waves that is mainly designed for optical applications. Apparently, the extension of the proposed solution to radio telecommunication is inherently not suitable for radio signal broadcasting.

At present no radio telecommunication systems exploiting OAM modes are commercially available.

However some papers have envisaged to use antennas having a particular kind of geometry shape for OAM transmission and reception. Radiation lobes of the transmitting antennas, which are designed for point-to-point transmission/reception, may be directed only towards predefined directions, basically towards a single receiving antenna and are not suitable for broadcasting. Also the receiving antennas are designed for preferable direction reception.

Further, such telecommunication systems are apparently difficult and expensive to realize at industrial level, at radio frequencies.

Finally, they do not allow properly identifying/ recognizing the transmitted/received OAM states.

DISCLOSURE OF THE INVENTION

The main aim of the invention is to provide a telecommunication method and apparatus, which are capable of overcoming the drawbacks of the prior art cited above.

A further object of the invention is to provide a telecommunication method and apparatus, which are suitable for a broadcasting transmission and for independent reception of radio signals.

A further object of the invention is to provide a telecommunication method and apparatus, which are suitable also for a point-to-point transmission/reception of radio signals.

A further object of the invention is to provide a telecommunication method and apparatus, which are particular easy to implement at industrial level, at competitive costs.

In order to fulfil the above-mentioned aims and objects, the invention provides a telecommunication method, according to the claims proposed in the following.

In a first aspect, the present invention relates to a telecommunication method that comprises the following steps:

- generating EM waves structured with a plurality of OAM modes, said EM waves having a same carrier frequency and one or two orthogonal polarization states,
- encoding one or more control signals and one or more data signals associated to said EM waves, so that a channel for transmitting and receiving information is associated to each of said OAM modes, each of said control signals being associated to a corresponding

OAM mode of said EM waves, each of said data signals being one-to-one associated to a corresponding OAM mode of said EM waves;

- transmitting said EM waves, said control signals and said data signals being simultaneously transmitted through the transmission of said EM waves.

Preferably, said telecommunication method comprises also the steps:

- receiving said EM waves, said control signals and said data signals being simultaneously received through the reception of said EM waves;
- decoding the control signals and the data signals received through the reception of said EM waves.

In a further aspect, the present invention relates also to a telecommunication method that comprises the steps:

- receiving EM waves (W) structured with a plurality of OAM modes, said EM waves having a same carrier frequency and one or two orthogonal polarization states;
- simultaneously receiving, through the reception of said EM waves, one or more encoded control signals and one or more encoded data signals, said control signals and said data signals being associated to said EM waves, so that a channel for transmitting and receiving information is associated to each of said OAM modes, each of said control signals being associated to a corresponding OAM mode of said EM waves, each of said data signals being one-to-one associated to a corresponding OAM mode of said EM waves, said control signals and said data signals being simultaneously transmitted through the transmission of said EM waves.

In yet a further aspect, the present invention relates also to a telecommunication method that comprises the steps:

- generating EM waves structured with a plurality of OAM modes, said EM waves having a same carrier frequency and one or two orthogonal polarization states;
- encoding one or more control signals and one or more data signals associated to said EM waves, so that a channel for transmitting and receiving information is associated to each of said OAM modes, each of said control signals being associated to a corresponding OAM mode of said EM waves, each of said data signals being one-to-one associated to a corresponding OAM mode of said EM waves;
- transmitting said EM waves, said control signals and said data signals being simultaneously transmitted through the transmission of said EM waves;
- receiving said EM waves, said control signals and said data signals being simultaneously received through the reception of said EM waves;

- decoding the control signals and the data signals received through the reception of said EM waves.

The present invention provides also a telecommunication apparatus, according to the claims proposed in the following.

In a first aspect, the telecommunication apparatus, according to the invention, comprises:

- transmitting means for generating and transmitting EM waves structured with a plurality of OAM modes, said EM waves having a same carrier frequency and one or two orthogonal polarization states, said transmitting means comprising one or more transmitting devices;
- encoding means for encoding one or more control signals and one or more data signals associated to said EM waves, so that a channel for transmitting and receiving information is associated to each of said OAM modes, each of said control signals being associated to a corresponding OAM mode of said EM waves, each of said data signals being one-to-one associated to a corresponding OAM mode of said EM waves, said transmitting means transmitting simultaneously said control signals and said data signals through the transmission of said EM waves.

Preferably, said telecommunication apparatus comprises also:

- receiving means for receiving said EM waves, said receiving means receiving simultaneously said control signals and said data signals through the reception of said EM waves, said receiving means comprising one or more receiving devices;
- decoding means for decoding the control signals and the data signals received by said receiving means, said decoding means being operatively associated to said receiving means.

In further aspect, the present invention relates to a telecommunication apparatus that comprises:

- receiving means for receiving EM waves structured with a plurality of OAM modes, said EM waves having a same carrier frequency and one or two orthogonal polarization states, said receiving means simultaneously receiving one or more control signals and one or more data signals associated to said EM waves, through the reception of said EM waves, said control signals and said data signals being encoded so that a channel for transmitting and receiving information is associated to each of said OAM modes, each of said control signals being associated to a corresponding OAM mode of said EM waves, each of said data signals being one-to-one associated to a corresponding OAM mode of said EM waves, said control signals and said data signals being simultaneously transmitted through

the transmission of said EM waves, said receiving means comprising one or more receiving devices;

- decoding means for decoding said control signals and said data signals.

In yet a further aspect, the present invention relates to a telecommunication apparatus that comprises:

- transmitting means for generating and transmitting EM waves structured with a plurality of OAM modes, said EM waves having a same carrier frequency and one or two orthogonal polarization states, said transmitting means comprising one or more transmitting devices;
- encoding means for encoding one or more control signals and one or more data signals associated to said EM waves, so that a channel for transmitting and receiving information is associated to each of said OAM modes, each of said control signals being associated to a corresponding OAM mode of said EM waves, each of said data signals being one-to-one associated to a corresponding OAM mode of said EM waves, said transmitting means transmitting simultaneously said control signals and said data signals through the transmission of said EM waves;
- receiving means for receiving said EM waves, said receiving means receiving simultaneously said control signals and said data signals through the reception of said EM waves, said receiving means comprising one or more receiving devices;
- decoding means for decoding the control signals and the data signals received by said receiving means, said decoding means being operatively associated to said receiving means.

Preferably, said EM waves have carrying frequencies between 30 MHz and 30 THz.

Preferably, said EM waves have carrying frequencies comprised in the field of radio frequencies, e.g. from 300MHz to 300GHz.

In general, said transmitting devices and/or said receiving devices may be of the fixed or mobile type.

The telecommunication apparatus, according to the invention, may comprise one or more groups of transmitting devices (e.g. groups of transmitting antennas), each group illuminating the surrounding space with EM waves structured with OAM modes.

One or more groups of receiving devices (e.g. groups of receiving antennas) may be advantageously arranged to receive the EM waves structured with OAM modes that are transmitted by said groups of transmitting devices.

The telecommunication apparatus, according to the invention, is thus particularly suitable for

the broadcasting transmission and reception of radio signals endowed with orbital angular momentum.

However, the telecommunication apparatus, according to the invention, may be easily configured to implement a point-to-point transmission and reception of radio signals.

BRIEF DESCRIPTION OF THE DRAWINGS

Further advantages of the invention will appear more evident in the following detailed description, with reference to the accompanying drawings, in which:

- figure 1 schematically shows an embodiment of the telecommunication apparatus, according to the invention;
- figure 2, 3, 4A, 4B schematically show possible embodiments of the transmitting devices of the telecommunication apparatus of figure 1;
- figure 5 schematically shows a portion of a further embodiment of the telecommunication apparatus, according to the invention.

DETAILED DESCRIPTION

With reference to the cited figures, the invention relates to a method and an apparatus exploiting the transmission and reception of EM waves.

According to some aspects of the present invention, the method of telecommunication comprises the step of generating EM waves W that are structured with a plurality of OAM modes, said EM waves having a same carrier frequency and one or two orthogonal polarization states.

In order to implement such a step, transmitting means 20 may be preferably adopted, which are configured so as to be capable of illuminating the surrounding space with radiation lobes that are controllable along the azimuthal and zenithal coordinates.

Advantageously, the typical form of the electromagnetic waves W is described by an analytical form that preserves the OAM modes.

In the simplest case of a set of 3D antennas positioned in a circular pattern and equally spaced, the isophase surface (the wavefront) of the field, in the far field region, has a spiral pattern, the number of arms of which depends on the topological charge ℓ .

In the simplest case, such a phase pattern can be represented in the plane, where the antennas are positioned, by a multi-arm linear spiral pattern.

This constant-phase locus of points can be described in terms of a generalized Archimedean spiral phase pattern, whose field amplitude is given by:

$$u(r, t, \theta) = A_0(r) + A(r)[kr + \ell\vartheta - \omega_\ell t]$$

where k is the wave number of the spiral waves, $A(r)$ is the amplitude, ϑ is the azimuthal angle, and r is the radial distance from the spiral tip (i.e. centre of symmetry). The term $A_0(r)$ is an arbitrary function of the radius, ℓ the OAM quantum number, and $\omega_\ell = \frac{2\pi\lambda}{c}\ell$ is the angular rotation frequency of the ℓ -armed spiral pattern.

A more convenient form for this equation that defines the location of all ℓ arms of such a spiral is given by:

$$\ell\vartheta + f(r, t) = \text{constant} \pmod{2\pi}$$

where $f(r, t) = \ell g(r, t)$ is the so-called shape function.

When said spiral has identical arms, the pattern results invariant with respect to any rotation of $\frac{2\pi}{\ell}$ around the centre and a simplified equation for the p^{th} arm is given by:

$$\vartheta + \frac{2\pi(p-1)}{\ell} + g(r, t) = \text{constant}$$

The time difference between the p^{th} arm and the $(p+1)^{\text{th}}$ arm (or the $(p-1)^{\text{th}}$ arm) may be sampled by an interferometer. The parameter p spans in the range $p=1, 2, \dots, \ell$.

Advantageously, logarithmic or more general spiral shapes are considered here as a possible generalization of propagation through certain media. The convolution with the topology of the antenna intensity diagrams of the present invention is the natural extension.

For an OAM state having a quantum number equal to $|\ell|$, the quantity $\frac{\omega_\ell}{2\pi}$ represents the number of times in which the EM field is equal to zero in a generic point of the space, per-unit-time.

By observing the behaviour of the EM field in a plurality of points of the space, it is then possible to discriminate $2\ell+1$ OAM states that have been simultaneously transmitted.

The EM waves W may be broadcasted over an azimuthal angle between 0 and 360°, even according to predefined angular ranges or sectors.

The broadcasting of the EM waves W can also be controlled over a zenithal angle between -90° and 90° so as to homogeneously cover the region around the transmitting means. Preferably, the interest for the transmitting apparatus in the zenith control is limited to a range between -75° and +30° in order to cover the broadcasting area.

In this way, the transmitted EM waves may be easily received by multiple groups of receiving devices.

The method, according to the invention, thus allows an easy broadcasting of radio signals

through the transmission and reception of EM waves W having a same carrier frequency and a given polarization.

The space propagation of the EM waves W may occur according to manners known in the radio-engineering field.

Advantageously, the propagation of the EM waves W may be used to acquire information about the propagation medium positioned between transmitting and receiving means of such waves.

The method, according to the invention, advantageously provides for the characterization of control signals S_C and data signals S_D that have to be transmitted through the transmission of the OAM modes.

Within the framework of the invention, the term “data signal” relates to any generic set of information (analog or digital) that needs to be transmitted through the transmission of the OAM modes, while the term “control signal” relates to information that is aimed at coordinating the implementation/operation of the method/apparatus of the invention.

The method, according to the invention, comprises the step of encoding one or more control signals S_C and one or more data signals S_D , associated to the EM waves W .

In this manner, a channel for transmitting and receiving information is associated to each of the OAM modes.

Each of the control signals S_C is associated to a corresponding OAM mode while each of the data signals S_D is one-to-one associated to a corresponding OAM mode.

For each carrier frequency, a number of data signals S_D equal to the number of the OAM modes of the EM wave W , can thus be transmitted.

Preferably, the method, according to the invention, comprises the step of associating one or more synchronization sequences SYNC to each of the OAM modes.

Each of said synchronization sequences SYNC is indicative of the OAM mode that is generated and transmitted and is configured to allow the identification of said OAM mode at the reception of this latter.

The synchronization sequences SYNC are in practice control signals that are transmitted with the EM waves W to ensure that each OAM mode is correctly discriminated when it is received by suitable receiving means 40.

Preferably, the synchronization sequences SYNC convey information on characteristic quantities with which transmitting means 20 are operated for generating and transmitting the OAM modes.

Preferably, the SYNC sequences convey information about the angular frequency $\omega_\ell = \frac{2\pi\lambda}{c}\ell$

for each OAM mode.

Preferably, the above step of associating said synchronization sequences SYNC is advantageously repeated at predefined time intervals. This solution is quite useful particularly in case mobile transmitting/receiving devices are adopted for transmitting/receiving the OAM modes.

The method, according to the invention, comprises the step of transmitting the EM waves W, so that the control and data signals S_C , S_D are simultaneously transmitted through the transmission of the OAM modes to which they are associated.

In this way, the method, according to the invention, allows transmitting the control and data signals S_C , S_D with said EM waves while implementing a coding of said signals during the transmission process.

According to some aspects of the present invention, the method, according to the invention, comprises the step of receiving the EM waves W that are structured with OAM modes.

The data and control signals S_D , S_C associated to the EM waves W are simultaneously received through the reception of said EM waves, i.e. of the OAM modes to which they are associated.

The method, according to the invention, advantageously provides for the identification of the data and control signals S_D , S_C received through the reception of the OAM modes.

The method, according to the invention, thus comprises also the step of decoding the control and data signals S_C , S_D received through the reception of the EM waves W.

In order to allow a correct decoding of the received signals S_C , S_D , the method, according to the invention, preferably comprises the step of discriminating the received OAM modes, on the base of the synchronization sequences SYNC associated to each of said OAM modes.

As a particular case of broadcasting transmission, an implementation of antennas arrays can be considered, which is dedicated to a point-to point transmission and reception of radio signals. In such a case, the transmission, propagation and reception are preferably directed along one specific direction with confined lobes. Of course the transmission/reception of control and data signals S_C , S_D , and synchronization SYNC will occur in the same way as described above.

Referring now to figures 1-5, the invention relates also to a telecommunication apparatus 1.

According to some aspects of the present invention, the telecommunication apparatus 1 comprises transmitting means 20 for generating the EM waves W that are structured with

OAM modes.

The transmitting means 20 comprise one or more transmitting devices 21 that may be of various types.

According to some embodiments of the present invention, the transmitting devices 21 may comprise reflector antennas shaped to generate the OAM modes thanks to their shape.

According to an embodiment of the invention, the transmitting means 20 comprise an array of transmitting antennas 21.

Preferably, the transmitting means 20 comprise N transmitting antennas 21, with $N \geq 2L_t + 1$, where L_t is the maximum quantum number ℓ of the OAM modes that have to be generated and transmitted.

The number N of transmitting antennas 21 limits the maximum quantum number L_t of the OAM modes that can be transmitted, including right-handed and left-handed OAM modes. Only OAM modes having a quantum number sweeping, according to a discrete spectrum, the range from $-L_t$ to L_t , can be transmitted.

Therefore, at least $N = 2L_t + 1$ transmitting antennas 21 are needed to transmit a spectrum of OAM modes varying between $-L_t$ to L_t .

The known case of EM waves W with null vorticity, i.e. with OAM modes having the sole quantum number $\ell = 0$, is the one obtained with a single ($N=1$) transmitting antenna 21.

It has to be evidenced that the transmission means 20 preferably comprise an odd number of transmitting antennas 21, differently from the solutions of the state of art.

The transmitting means 20 preferably comprises feeding means 22 for providing the transmitting antennas 21 with feeding current signals I_F .

The feeding means 22 may comprise electronic means, which are operatively associated with the transmitting antennas 21 for properly feeding these latter. Said electronic means may be of the analog or digital type, according to the needs.

Preferably, the feeding means 22 comprise phase controlling means 221 for controlling the phase of the feedings signals I_F for the different transmitting antennas 21 and amplitude controlling means 222 for controlling the amplitude of the feedings signals I_F for the different transmitting antennas 21.

Preferably, the feeding means 22 feed the transmitting antennas 21 so that these latter are phase shifted one from another and are fed by feeding signals I_F , which have a phase shift Φ that is determined for obtaining a spatial distribution of the phase that is proper of the OAM modes to be transmitted.

In certain cases, said phase shift Φ can be described by Laguerre-Gauss modes.

The transmitting antennas 21 (for an arbitrary distribution) can be suitably fed with varying currents I_F in time to generate a far EM field through a superposition of radiating modes that have angular frequency ω and that are endowed with a specific OAM value ℓ .

The amplitude of the generated far EM field is given by the following relation:

$$U_\ell(\vec{r}, \omega) = A_\ell(\vec{r}, \omega) \exp(-i\ell\vartheta)$$

where ℓ describes the number of twists of the helical wavefront (OAM mode).

Each of the transmitting antennas 21, according to Stratton, Panofsky-Phillips and Jefimenko equations generate OAM states in the far zone with the same intensity decay as the linear momentum.

The generated EM field can be decomposed into a general discrete superposition that, at a given ω , is given by the relation:

$$U_\ell(\vec{r}, \omega) = A_\ell(\vec{r}, \omega) \exp(-i\ell\vartheta) = \sum_{k=0}^{N-1} u_k(r_i, \omega, \vartheta)$$

where the terms $u_k(r_i, \omega, \vartheta)$ represent the OAM modes and the parameters r_i represent the positions of each transmitting device 21.

From the above, it is apparent that the feeding means 22 may determine the phase for operating the transmitting antennas 21 by means of suitable calculating procedures.

Each OAM state ℓ of the EM waves W can be identified by the phase shifts through which the transmitting antennas 21 are operated.

It is evidenced that this aspect of the invention constitutes an important difference from commonly available MIMO (Multiple Input Multiple Output) transmission systems, which normally exploit the linear angular momentum of electromagnetic waves, all having an OAM state $\ell = 0$ for the multimodal transmission of information.

It is evidenced that the above relations/considerations are valid also for different kinds of transmitting devices 21.

In principle, the transmitting antennas 21 may be arranged to any spatial distribution, according to the needs.

In an embodiment of the invention (figure 3), the transmitting antennas 21 are arranged along a curve C_Q of planar type, such as a quadratic curve, e.g. a parabola, a hyperbola, an ellipse or a circle.

In order to generate OAM modes with quantum number $\ell \geq 0$, each of the transmitting antennas 21 may preferably comprise three transmitting dipoles that are orthogonally arranged one respect to the others.

Preferably, a first and a second transmitting dipole 21A, 21B are arranged respectively according to a tangential and a radial direction with respect to the curve C_Q and a third transmitting dipole 21C is arranged perpendicularly with respect to the plane comprising the curve C_Q .

In general, such configurations allow to control the lobe shape through a suitable control of the I_F currents.

Preferably, the transmitting antennas 21 are arranged along a circle C and are equally spaced one from another.

Also in this case, each transmitting antenna 21 has preferably three dipoles oriented according to mutually perpendicular directions.

For the sake of simplicity, it is assumed that the antennas 21 are fed with feeding signals I_F having a single carrier frequency.

As mentioned above, the feeding means 22 provide each transmitting antenna 21 with feeding signals I_F that are phase shifted one another.

If the transmitting antennas 21 are azimuthally spaced, the phase delay Φ can be suitably calculated and implemented by the phase controlling means 221.

Each transmitting antenna 21 generates an EM field that is phase shifted with respect to the EM fields generated by the other transmitting antennas 21.

The convolution of the superimposed EM fields generates an EM wave W having an OAM mode with a helically shaped wavefront, which is propagated along the plane orthogonal to the antennas.

The EM wave W is radially spread with a phase shift that depends on the azimuthal angle, so as to create a phase oscillation of the spatial type on a generic plane (thus not only over time).

The overall phase oscillation over an azimuthal angle of 360° must be a positive or negative integer multiple of 360° .

These are basically the features that allow the transmission of the data and control signals S_D , S_C by performing a suitable modulation of the generated OAM modes.

Advantageously, the amplitude controlling means 222 may regulate the amplitude of the feeding signals I_F (i.e. the feeding currents) to the mutually orthogonal dipoles 21A, 21B, 21C, so that the overall EM field that is generated by the dipoles may have a constant intensity on a surface that is topologically equivalent to a toroid. Such a radiation diagram can be oriented with the toroid axis in the direction orthogonal to the plane on which the dipoles are arranged.

For broadcasting purposes, the lobes of the radiation diagrams are preferentially distributed over the full azimuthal angle, with zenithal angles mainly between $+30^\circ$ and -70° .

For point- to point transmission, the lobes of the radiation diagrams are preferentially elongated in paraxial directions.

The phase of said EM field for each OAM mode varies linearly along the azimuth and the overall variation of the phase is equal to $2\pi|\ell|$, where $|\ell|$ is the absolute value of the quantum number of the generated OAM mode.

EM fields with a given phase form a concentric vortex with the circle C. The number of arms of the phase distribution of said vortex is equal to the absolute value of the quantum number $|\ell|$ of the generated OAM mode. The arms of said vortex are left-handed or right-handed, depending on the sign of the vorticity state ℓ .

The EM field is thus radially transmitted with equal intensity but with phase that depends on the azimuthal angle.

The phase variation Φ for each azimuth angle ϑ is given by the quantum number ℓ of the single OAM mode, according to the following relation:

$$\Phi = \vartheta \cdot \ell$$

A circular array of $N = 2L_t + 1$ transmitting antennas 21 may thus simultaneously transmit a number OAM modes, the quantum number ℓ of which spans the range $[-L_t, L_t]$.

Each OAM mode is identified by the phase shift Φ between a transmitting antenna and the following one. Preferentially, such quantity can be transmitted by means of the control signals SYNC in order to provide information about the OAM modes.

According to an alternative embodiment, the transmitting antennas 21 may be arranged along a straight line.

In this case, the transmitting antennas 21 may form a linear array. In order to generate a non-vanishing OAM, such an array must not be a uniform one.

The feeding means 22 provide the transmitting antennas 21 with feeding signals I_F having a phase shift and amplitude that are not constant but depend on the position of the antennas 21 along the straight line.

In this configuration of the transmitting antennas 21, the radiation diagram, which results on a suitable plane from the superimposition of EM fields generated by the transmitting antennas 21, will substantially have, in the far field, the shape of a half-circle. The phase of the transmitted electromagnetic waves W spatially varies along the perimeter of said half-circle.

According to a further embodiment of the invention, each of the transmitting devices 21 comprises a first phase mask 216 operatively associated to a corresponding transmitting element 217.

The transmitting element 217, which works as a transmitting antenna, radiates an EM field E towards the phase mask 217. The phase mask 217 is helically shaped to suitably propagate an OAM mode M1.

The propagation of the OAM mode M1 may occur by reflection or transmission of the EM field E, according to the configuration of the surface of the phase mask 217, which receives the EM field E.

If the phase mask 217 is of the reflective type (figure 4A), it is helically shaped according to a helical step that is given by the following relation:

$$s = \frac{\lambda \cdot \ell}{2}$$

where λ is the carrying wavelength of the transmitted OAM mode M1.

If the phase mask 217 is of the transmission type (figure 4B), it is helically shaped according to a helical step that is given by the following relation:

$$s = \frac{\lambda \cdot \ell}{\Delta N}$$

where λ is the carrying wavelength and ΔN is the variation of the refraction index in the phase mask 217.

The generated OAM mode M1 may have left-handed or right-handed vorticity depending on the direction of the helical shape of the phase mask 217.

According to this embodiment of the present invention, each transmitting device 21 is arranged to provide a specific OAM mode. The transmitted EM wave W results from the superimposition of the OAM modes generated by one or more transmitting devices 21.

Also in this case, each transmitting device 21 is properly fed by the feeding means 22 that supply the feeding signals I_F to the transmitting elements 217.

The phase controlling means 221 and the amplitude controlling means 222 respectively regulate the phase and the amplitude of the feedings signals I_F for the different transmitting devices 21.

According to a further embodiment of the invention (figure 5), the transmitting devices 21 are operatively associated to an anamorphic reflector 219.

The transmitting devices 21 generate the EM waves W structured with one or more OAM modes according to a first direction that is substantially perpendicular to the plane P on which said transmitting devices are arranged.

The reflector 219 reflects the EM waves W, which come from the transmitting devices 21, according to a desired second direction, which is preferably substantially perpendicular to said first direction and parallel to the plane P.

The profile of the external surface of the reflector 21 may not have an axial symmetry, as shown in figure 5, and it may be advantageously shaped according to the possibility of generating directional lobes in specific azimuthal direction, for example for point-to point purposes or to better cover areas in the case of broadcasting.

The reflector 219 is thus capable of deflecting the radiation lobes of the transmitting devices 21 by reflecting the EM waves W received from these latter.

In particular, the reflector 219 is advantageously capable of directing the EM waves W along a horizontal plane parallel to the plane P, with remarkable advantages in broadcasting the OAM modes in a region around the transmitting devices 21.

It is highlighted that the embodiments described above may be generalized to the cases in which the transmitting devices 21 are fed with feeding signals I_F having several carrying frequencies.

As a result, the transmission means 20 can be characterised by a very broad band.

In order to prevent that this remarkable feature is spoiled by bandwidth limitations introduced by the feeding means 22 (e.g. comprising properly arranged phase shifters), the electronic circuitry of these latter may be replaced by a fibre-optic network, which can be designed according to known microwave photonics technologies.

According to the invention, the transmission apparatus 1 comprises encoding means 30 for encoding one or more control signals S_C and data signals S_D associated to the EM waves W. In this manner, a channel for transmitting and receiving information is associated to each of the OAM modes of the EM waves W.

The encoding means 30 advantageously associate each of the control signals S_C to a corresponding OAM mode.

Further, the encoding means 30 advantageously associate one-to-one each of the data signals S_D to a corresponding OAM mode.

The encoding means 30 are operatively associated to the transmitting means 20, so that the control signals S_C and the data signals S_D are simultaneously transmitted through the transmission of the EM waves W.

Preferably, the encoding means 30 comprise modulating means 301 that are operatively associated to the feeding means 20 to modulate the feeding signals I_F for feeding the transmitting antennas 21.

In general, the modulating means 301 may comprise any electronic device capable of modulating the feeding signals I_F , according to the needs, e.g. by performing a phase and/or amplitude and/or frequency modulation of these latter, of the analog or digital type.

Preferably, the telecommunication apparatus 1 comprises first synchronization means 35 (e.g. an electronic circuit of the digital or analog type) for generating the synchronization sequences SYNC that are associated to each of the OAM modes.

Advantageously, the synchronization means 35 are operatively associated to the modulating means 301.

As mentioned above, each of the synchronization sequences SYNC is indicative of a specific OAM mode. They may be considered as particular control signals S_C that convey information on the phase shift Φ with which the transmitting antennas 21 are operated.

According to some aspects of the present invention, the transmission apparatus 1 may comprise receiving means 40 for receiving the EM waves W structured with OAM modes.

Advantageously, the control signals S_C and the data signals S_D are simultaneously received by the receiving means 40 through the reception of the EM waves W .

The receiving means 40 comprise one or more receiving devices 41.

Being positioned in a far region with respect to the transmitter devices 21, a group of M receiving devices 41 can locally sample the received EM field and reconstruct it through a superimposition of appropriate signals. The received EM field may be given by the reconstruction quantity R , according to the following relation:

$$U_\ell(\vec{r}, \omega) \approx R(r, \omega, \vartheta) = \sum_{k=0}^{M-1} v_k(r'_k, \omega, \vartheta)$$

where the parameters r'_k represent the positions of each receiving device 41.

By obtaining the phase shift of each receiving device 41 and by selecting a suitable set of functions $v_k(r'_k, \omega, \vartheta)$, it is possible to reconstruct the originally transmitted OAM mode, according to the following relation:

$$U_\ell(\vec{r}, \omega) \approx R(r, \omega) \exp(-i\ell\vartheta)$$

Of course, this procedure can be extended to any superposition of OAM states, with integer or non-integer topological charges and for any frequency of the EM spectrum.

Preferably, the receiving devices 41 comprise M receiving antennas, with $M \geq 2Lr + 1$,

where L_r is the maximum quantum number ℓ of the OAM modes that have to be received.

The number M of receiving antennas 41 limits the maximum quantum number of OAM modes that can be received including right-handed or left-handed OAM modes, preserving, as much as possible, the orthogonality between the OAM modes. Only OAM modes having a quantum number ℓ sweeping, according to a discrete spectrum, the range $[-L_r, L_r]$, can be discriminated.

Therefore, at most $M = 2\ell + 1$ receiving antennas 41 are needed to receive a spectrum of OAM states varying in the range $[-\ell, +\ell]$.

The known case of EM waves with null vorticity, i.e. with OAM modes having the sole quantum number $\ell = 0$, is the one obtained with a single ($M=1$) receiving antenna.

Of course, the number M of receiving antennas 41 may coincide with the number of transmitting antennas 21.

Possibly, the receiving antennas 41 are of the dipole type and they may be linearly distributed along one or more straight lines.

Receiving antennas 41 having three receiving dipoles oriented along three mutually orthogonal directions allow determining the direction of the EM field even in case they are in relative motion with respect to the transmitting means 20.

The receiving antennas 41 provide receiving signals I_R generated by the received OAM modes.

According to a further embodiment of the invention, each of the receiving devices 41 comprises a second phase mask operatively associated to a corresponding receiving element. Such embodiment will be useful both for broadcasting as well as for point-to-point transmission and reception of radio signals. The receiving devices 41 have a structure that is similar to the transmitting structures shown in figures 4A, 4B, even if they work in a reverse manner.

In this case, the second phase mask is illuminated by the EM waves W received from the transmitting devices 21.

The phase mask is helically shaped to properly reflect or transmit only a specific OAM mode towards the associated receiving element that works as a receiving antenna.

Also in this case, the receiving elements 41 provide receiving signals I_R generated by the received OAM modes.

According to the invention, the transmission apparatus 1 comprises decoding means 50 that are operatively associated to the receiving means 40 for decoding one or more control signals S_C and one or more data signals S_D received through the reception of the EM waves W .

Preferably, the decoding means 50 comprise demodulating means 501 that are operatively associated to the receiving means 50 to obtain the control signals S_C and the data signals S_D from the received EM waves W .

In general, the demodulating means 501 comprise an electronic device (analog or digital) capable of demodulating the receiving signals I_R (current signals) provided by the receiving devices 41.

Preferably, the telecommunication apparatus 1 comprises second synchronization means 55 (e.g. an electronic circuit of the digital or analog type) for discriminating the OAM states received by the receiving devices 41 for any relative position with respect to the transmitting devices 21.

The receiving devices 41 receive the EM waves W with a phase shift $\Phi_{TOT} = \Phi_{POS} + \Phi$, where Φ_{POS} is the positioning phase shift that is determined by the relative position of the receiving devices 41 with respect to the transmitting devices 21 and Φ is the intrinsic phase shift with which the transmitting devices 21 have been operated.

The overall phase shift $\Phi_{TOT} = \Phi_{POS} + \Phi$ between the receiving devices 41 is determined by the second synchronization means 55 thanks to the synchronization sequences SYNC.

The synchronization sequences SYNC are received by the receiving devices 41 through the reception of the OAM modes.

As mentioned above, the synchronization sequences SYNC are indicative of the specific OAM modes. In other words, they convey information on the phase shift Φ with which the transmitting antennas 21 have been operated.

Further, the synchronization sequences SYNC are preferably transmitted at predefined time intervals that are known by the first and second synchronization means 35, 55.

By comparing said predefined time intervals with the time intervals at which the synchronization sequences SYNC are actually received by the receiving devices 41, the synchronization means 55 can determine the positioning phase shift Φ_{POS} .

Since the phase shift Φ is provided by the received synchronization sequences SYNC, the synchronization means 55 are thus capable of reconstructing the correct phase shift Φ_{TOT} between the receiving devices 41.

On the base of the relations shown above, the received OAM modes can thus be correctly identified by sampling the received EM field at the positions of the receiving devices 41.

The control signals S_C and the data signals S_D , which are simultaneously received with the OAM modes, can be obtained by the demodulating means 501.

The telecommunication method and apparatus, according to the invention, allow obtaining relevant advantages with respect to the solutions of the state of the art.

The telecommunication method and apparatus, according to the invention, are particularly suitable for a broadcasting transmission and reception of radio signals.

The telecommunication method and apparatus, according to the invention, are capable of simultaneously generating and transmitting independent OAM modes that can be separately received by many independent broadcasting receivers.

However, the telecommunication method and apparatus, according to the invention, may be conveniently adopted also for implementing a point-to-point transmission and reception of radio signals.

OAM modes may be generated and transmitted for many carrying frequencies, on a large frequency band, without interference among frequencies or among OAM modes related to different carrying frequencies.

The telecommunication method and apparatus, according to the invention, thus allow adding a new degree of freedom in the process of signal multiplexing, in all kinds of radio systems.

The telecommunication method and apparatus, according to the invention, are of particularly easy and low cost industrial realization and practical implementation, at radio frequencies.

CLAIMS

1. A telecommunication method characterised in that it comprises the steps of:
 - generating EM waves (W) structured with a plurality of OAM modes, said EM waves having a same carrier frequency and one or two orthogonal polarization states;
 - encoding one or more control signals (S_C , SYNC) and one or more data signals (S_D) that are associated to said EM waves, so that a channel for transmitting and receiving information is associated to each of said OAM modes, each of said control signals being associated to a corresponding OAM mode of said EM waves, each of said data signals being one-to-one associated to a corresponding OAM mode of said EM waves;
 - transmitting said EM waves, said control signals and said data signals being simultaneously transmitted through the transmission of said EM waves.
2. Method, according to claim 1, characterised in that it comprises the steps of:
 - receiving said EM waves, said control signals and said data signals being simultaneously received through the reception of said EM waves;
 - decoding said control signals and said data signals.
3. Method, according to one or more of the previous claims, characterised in that it comprises the step of associating one or more synchronization sequences (SYNC) to each of said OAM modes, said synchronization sequences being configured to allow the identification of the OAM mode to which they are associated, at the reception of said OAM mode.
4. Method, according to one or more of the claims from 2 to 3, characterised in that it comprises the step of discriminating the received OAM modes, on the base of one or more synchronization sequences (SYNC) associated to each of said OAM modes.
5. A telecommunication method characterised in that it comprises the steps of:
 - receiving EM waves (W) structured with a plurality of OAM modes, said EM waves having a same carrier frequency and one or two orthogonal polarization states;
 - simultaneously receiving, through the reception of said EM waves, one or more encoded control signals (S_C , SYNC) and one or more encoded data signals (S_D) that are associated to said EM waves, so that a channel for transmitting and receiving information is associated to each of said OAM modes, each of said control signals being associated to a corresponding OAM mode of said EM waves, each of said data signals being one-to-one associated to a corresponding OAM mode of said EM

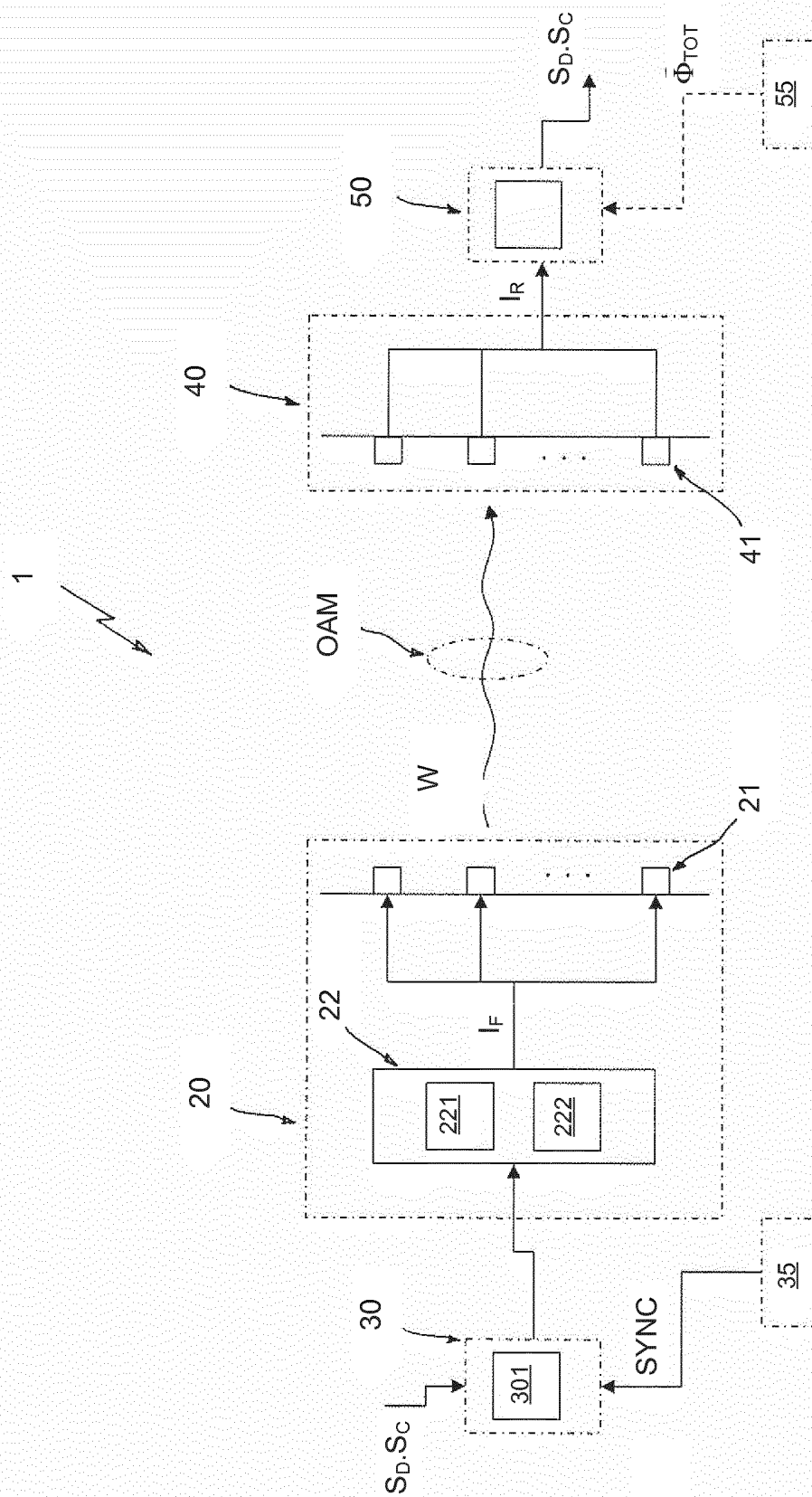
- waves, said control signals and said data signals being simultaneously transmitted through the transmission of said EM waves.
6. Method, according to claim 5, characterised in that one or more synchronization sequences (SYNC) are associated to each of said OAM modes, said synchronization sequences being configured to allow the identification of the OAM mode to which they are associated, at the reception of said OAM mode.
 7. A telecommunication apparatus characterised in that it comprises:
 - transmitting means (20) for generating and transmitting EM waves (W) structured with a plurality of OAM modes, said EM waves having a same carrier frequency and one or two orthogonal polarization states, said transmitting means comprising one or more transmitting devices (21);
 - encoding means (30) for encoding one or more control signals (S_C , SYNC) and one or more data signals (S_D) that are associated to said EM waves, so that a channel for transmitting and receiving information is associated to each of said OAM modes, each of said control signals being associated to a corresponding OAM mode of said EM waves, each of said data signals being one-to-one associated to a corresponding OAM mode of said EM waves, said control signals and said data signals being simultaneously transmitted through the transmission of said EM waves.
 8. Telecommunication apparatus, according to claim 7, characterised in that it comprises:
 - receiving means (40) for receiving said EM waves, said control signals and said data signals being simultaneously received through the reception of said EM waves, said receiving means comprising one or more receiving devices (41);
 - decoding means (50) for decoding said control signals and said data signals.
 9. Telecommunication apparatus, according to one or more of the claims from 7 to 8, characterised in that said transmitting means (20) comprise feeding means (22) for providing said transmitting devices (21) with feeding signals (I_F), said feeding means comprising phase controlling means (23) for controlling the phase of said feeding signals and amplitude controlling means (24) for controlling the amplitude of said feeding signals.
 10. Telecommunication apparatus, according to one or more of the claims from 7 to 9, characterised in that said transmitting devices (21) comprise transmitting antennas, each comprising three transmitting dipoles (21A, 21B, 21C) that are orthogonally arranged one respect to the others.

11. Telecommunication apparatus, according to one or more of the claims from 7 to 9, characterised in that each of said transmitting devices (21) comprises a first phase mask (216) operatively associated to a corresponding transmitting element (217).
12. Telecommunication apparatus, according to one or more of the claims from 7 to 11, characterised in that said transmitting devices (21) are operatively associated to an anamorphic reflector (219) for redirecting the radiation lobes of said transmitting means (20).
13. Telecommunication apparatus, according to one or more of the claims from 7 to 12, characterised in that it comprises first synchronization means (35) for associating one or more synchronization sequences (SYNC) to each of said OAM modes, said synchronization sequences being configured to allow the identification of the OAM mode to which they are associated, at the reception of said OAM mode.
14. Telecommunication apparatus, according to one or more of the claims from 8 to 13, characterised in that said receiving devices (41) comprise receiving antennas, each comprising three transmitting dipoles that are orthogonally arranged one respect to the others.
15. Telecommunication apparatus, according to one or more of the claims from 8 to 13, characterised in that that each of said receiving devices (41) comprises a second phase mask operatively associated to a corresponding receiving element.
16. Telecommunication apparatus, according to one or more of the claims from 8 to 15, characterised in that it comprises second synchronization means (55) for discriminating the OAM modes received by said receiving means (40), on the base of one or more synchronization sequences (SYNC) associated to each of said OAM modes.
17. A telecommunication apparatus characterised in that it comprises:
 - receiving means (40) for receiving EM waves (W) structured with a plurality of OAM modes, said EM waves having a same carrier frequency and one or two orthogonal polarization states, said receiving means simultaneously receiving, through the reception of said EM waves, one or more encoded control signals (S_C , SYNC) and one or more encoded data signals (S_D) that are associated to said EM so that a channel for transmitting and receiving information is associated to each of said OAM modes, each of said control signals being associated to a corresponding OAM mode of said EM waves, each of said data signals being one-to-one associated to a corresponding OAM mode of said EM waves, said control signals and said data

signals being simultaneously transmitted through the transmission of said EM waves, said receiving means comprising one or more receiving devices (41);

- decoding means (50) for decoding said control signals and said data signals.

18. Telecommunication apparatus, according to claim 17, characterised in that said receiving devices (41) comprise receiving antennas, each comprising three transmitting dipoles that are orthogonally arranged one respect to the others.
19. Telecommunication apparatus, according to claim 17, characterised in that that each of said receiving devices (41) comprises a second phase mask operatively associated to a corresponding receiving element.
20. Telecommunication apparatus, according to one or more of the claims from 17 to 19, characterised in that it comprises second synchronization means (55) for discriminating the OAM modes received by said receiving means (40), on the base of one or more synchronization sequences (SYNC) associated to each of said OAM modes.



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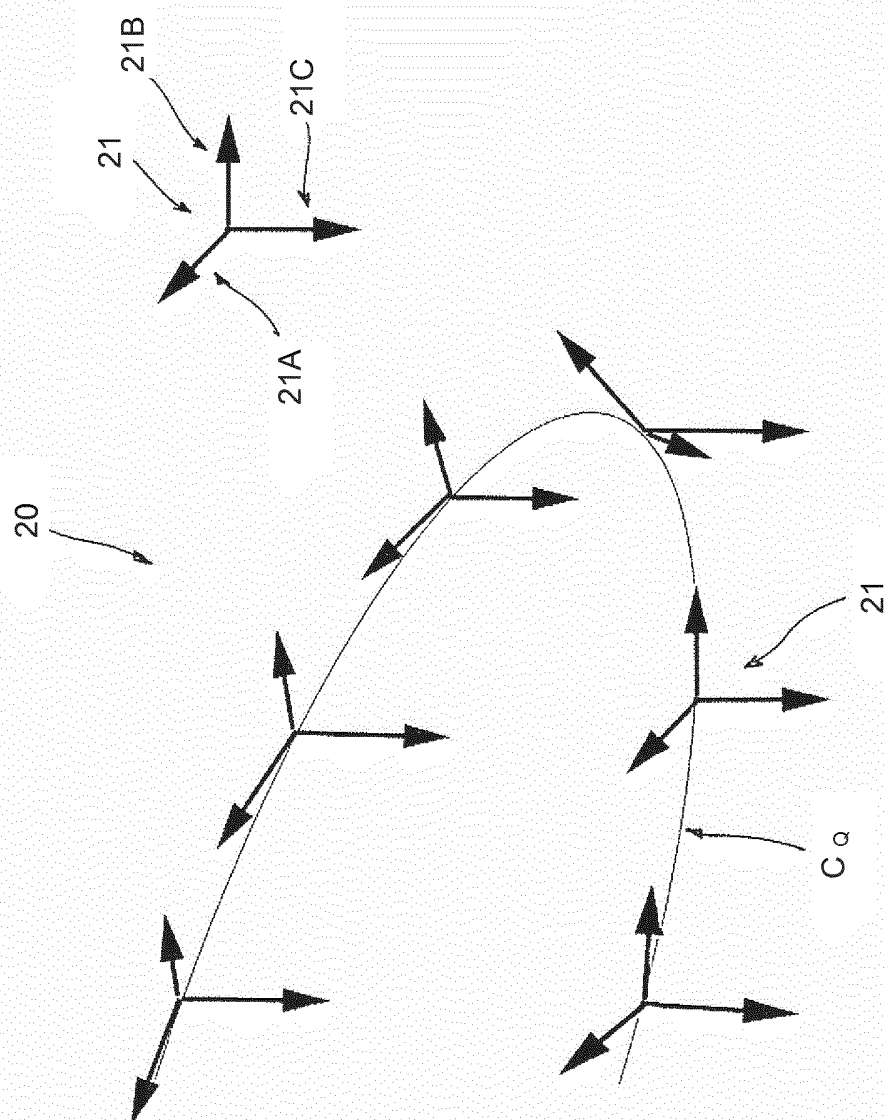


FIG. 2

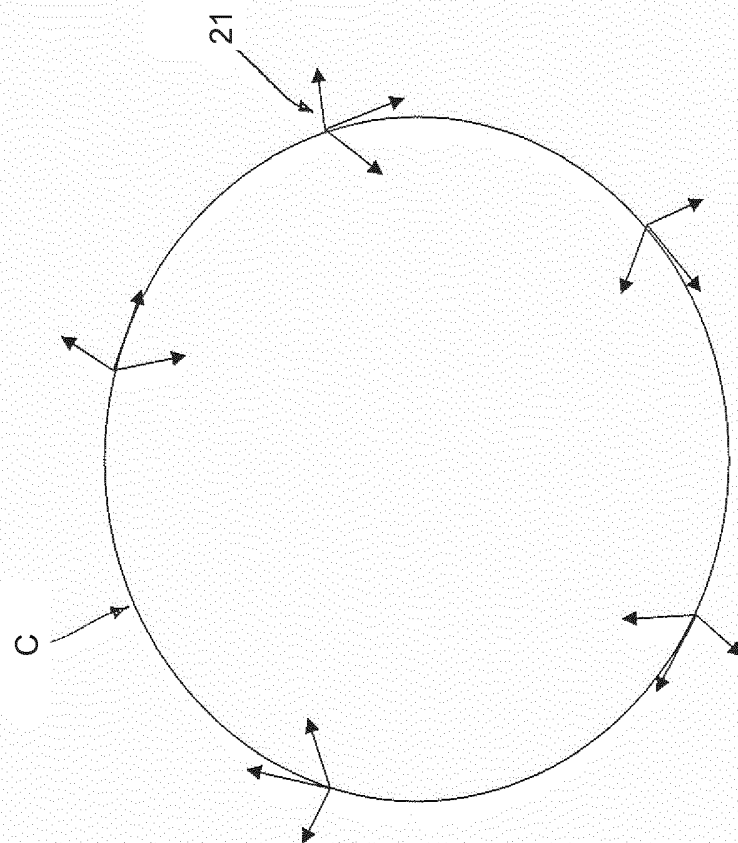


FIG. 3

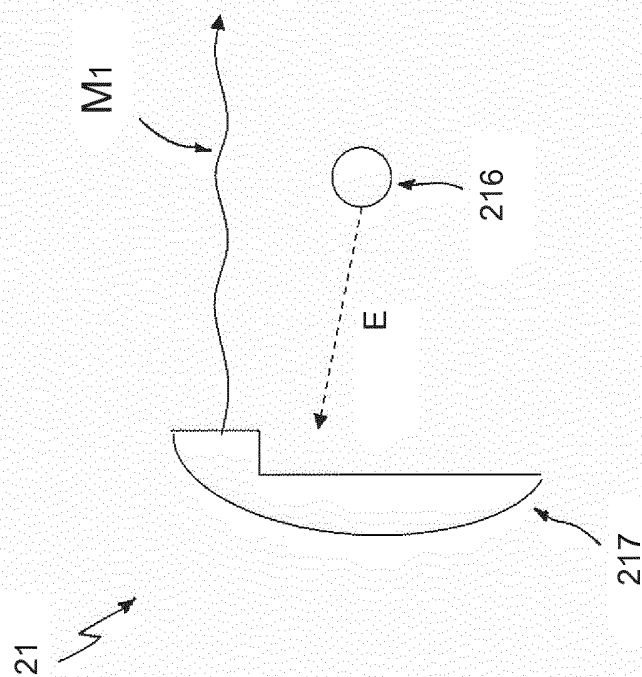


FIG. 4A

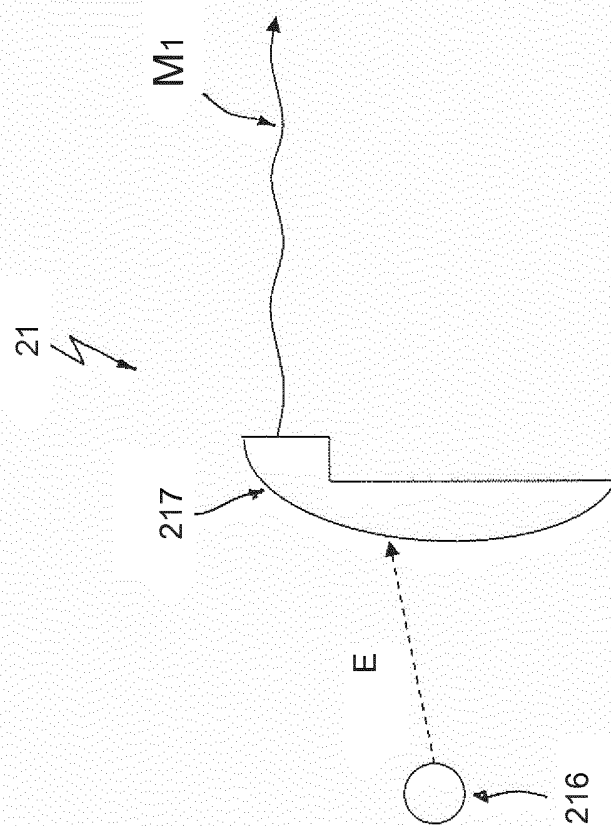


FIG. 4B

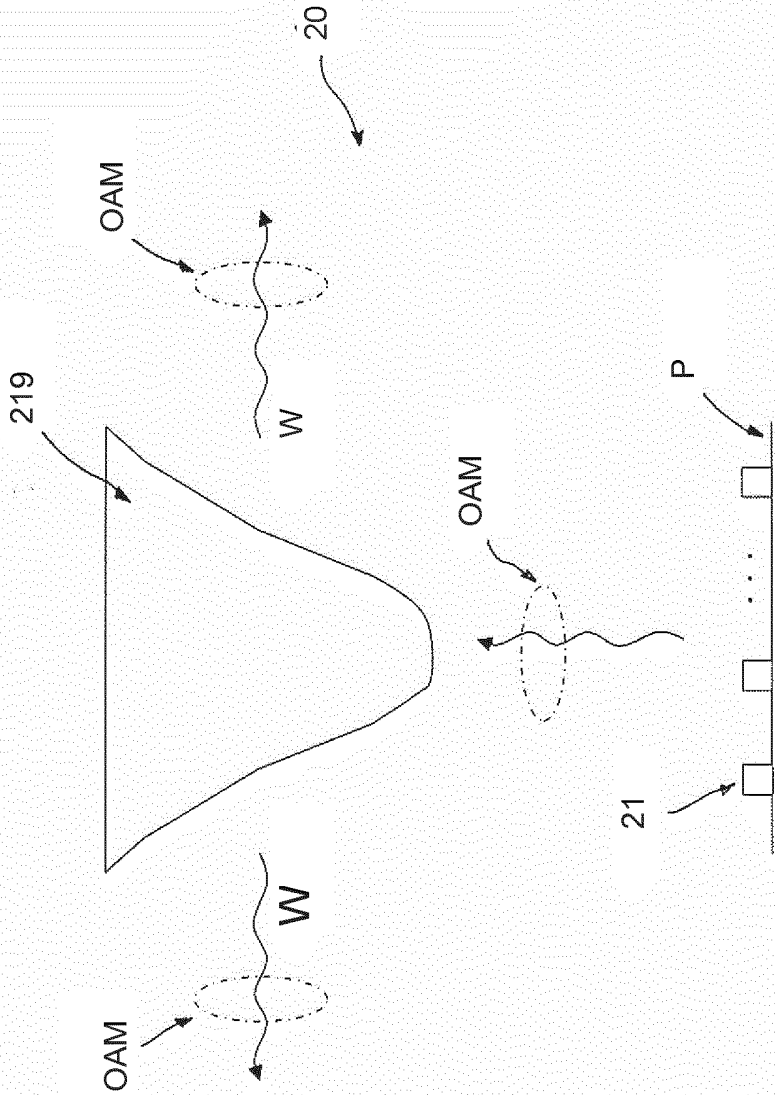


FIG. 5

INTERNATIONAL SEARCH REPORT

International application No

PCT/EP2012/062004

A. CLASSIFICATION OF SUBJECT MATTER

INV. H01Q21/20 H01Q21/08
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

H01Q

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EP0-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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Y	abstract paragraphs [0001] - [0105], [0128] - [0170]; figures 15-17 -----	10
X	GB 2 410 130 A (ROKE MANOR RESEARCH [GB]) 20 July 2005 (2005-07-20)	1-9, 11-17, 19,20
Y	abstract page 1, line 1 - page 8, line 14; claim 8; figures 1, 2 ----- -/-	10,18



Further documents are listed in the continuation of Box C.



See patent family annex.

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"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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Date of the actual completion of the international search

13 August 2012

Date of mailing of the international search report

21/08/2012

Name and mailing address of the ISA/

European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040,
Fax: (+31-70) 340-3016

Authorized officer

Sidoti, Filippo

INTERNATIONAL SEARCH REPORT

International application No

PCT/EP2012/062004

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
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X	GIBSON G ET AL: "Free-space information transfer using light beams carrying orbital angular momentum", OPTICS EXPRESS, OSA (OPTICAL SOCIETY OF AMERICA), WASHINGTON DC, (US), vol. 12, no. 22, 1 November 2004 (2004-11-01), pages 5448-5456, XP002500773, ISSN: 1094-4087, DOI: 10.1364/OPEX.12.005448 cited in the application abstract page 2, line 22 - page 9, line 10 -----	1-9, 11-17, 19,20
Y	SJÖHOLM JOHAN ET AL: "Angular Momentum of Electromagnetic Radiation. Fundamental physics applied to the radio domain for innovative studies of space and development of new concepts in wireless communications", ANGULAR MOMENTUM OF ELECTROMAGNETIC RADIATION. FUNDAMENTAL PHYSICS APPLIED TO THE RADIO DOMAIN FOR INNOVATIVE STUDIES OF SPACE AND DEVELOPMENT OF NEW CONCEPTS IN WIRELESS COMMUNICATIONS, UPPSALA UNIVE 2 May 2007 (2007-05-02), pages 1-187, XP002671614, ISSN: 1401-5757 Retrieved from the Internet: URL: http://arxiv.org/ftp/arxiv/papers/0905/0905.0190.pdf [retrieved on 2012-03-16] page 49, line 1 - page 52, line 24 page 80, line 1 - page 94, line 7; figures 7.27, 7.28 page 100, line 1 - page 102, line 5 -----	10,18
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E	WO 2012/084039 A1 (ERICSSON TELEFON AB L M [SE]; TAGEMAN OLA [SE]) 28 June 2012 (2012-06-28) abstract page 1, line 1 - page 26, line 27 ----- -/--	1-20

INTERNATIONAL SEARCH REPORT

International application No

PCT/EP2012/062004

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
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A,P	Fabrizio Tamburini ET AL: "Encoding many channels in the same frequency through radio vorticity: first experimental test", arXiv.org, 12 July 2011 (2011-07-12), XP55021484, Ithaca, NY, USA Retrieved from the Internet: URL:http://arxiv.org/abs/1107.2348 [retrieved on 2012-03-09] the whole document -----	1-20

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/EP2012/062004

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