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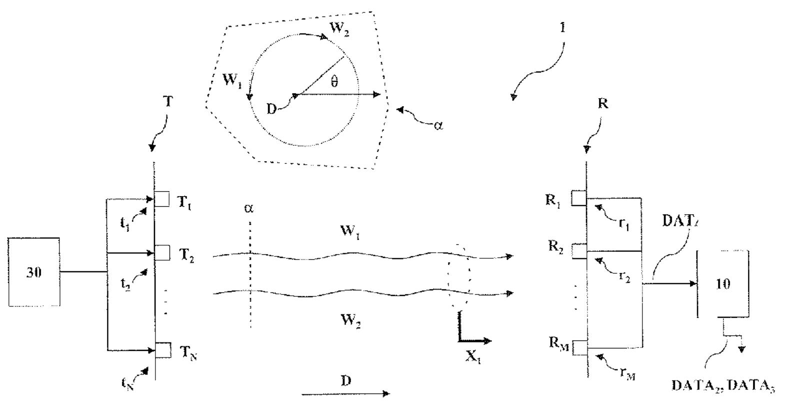

FIG. 1

(57) **Abstract**: The present invention refers to an apparatus for realizing a long-range radio link. The apparatus comprises a plurality of receiving antennas, each of which is suitable to simultaneously receive at least one pair of overlapping electromagnetic waves with the same carrier frequency but different orbital angular momenta (OAMs). The apparatus according to the invention comprises electronic means capable of obtaining data indicative of the difference between the OAMs of said electromagnetic waves. A further aspect of the present invention refers to a method for realizing a long-range radio link.

WO 2013/092470 A1

APPARATUS FOR THE REALIZATION OF A RADIO LINK AND RELATIVE METHOD

DESCRIPTION

The present invention refers to the field of telecommunication systems.

In particular, the invention refers to an apparatus and method for realizing a radio link.

It is well known that telecommunication systems are developing at an increasingly rapid rate, offering new services of interest to a large number of users and activities.

It is also known that the increasing demand for new long-distance radio links has saturated existing available frequencies, despite the fact that modern electronic technologies enable the use of increasingly broad frequency bands, and the achievement of extremely high bandwidth efficiency (in terms of bit/s per Hertz).

In such a scenario, it is particularly important to develop technological solutions that make it possible to associate several, fully independent data transmission channels with an electromagnetic wave transmitted with a given carrier frequency, within a given geographic area.

Already well known examples of this type of technology, particularly in satellite communications, include telecommunication equipment that are capable of associating a data transmission channel with each of two orthogonal states of polarization of an electromagnetic wave transmitted at a given carrier frequency.

In an attempt to achieve a more intensive use of the electromagnetic spectrum for communication purposes, and particularly to increase the data and information transmission capacity for each frequency, telecommunication systems have recently been proposed and tested, which can exploit another characteristic of electromagnetic waves, namely their Orbital Angular Momentum (in the following, OAM), to distinguish between radio signals that use the same carrier frequency but are associated with different data transmission fluxes.

As is well known in literature, the OAM of an electromagnetic wave is a physical quantity that describes in an unambiguous way the rotary movement of the wavefront around the axis of propagation of the wave, on a generic plane at right-angle to the direction of propagation.

In particular, it is customary in the literature to use the acronym OAM to designate the number of complete (i.e., 360 degrees) rotations performed by the wavefront as it advances through a distance equal to the wavelength. It is also well known from the literature that said number of complete rotations must be an integer number. In the following, for the sake of brevity, we will often call OAM this integer number, without any danger of misunderstandings.

Electromagnetic waves, which have the same frequency but a different OAM, do not interact with each other during propagation, at least in a medium having no sharp discontinuities and whose electromagnetic parameters do not greatly differ from those of vacuum.

Therefore, such electromagnetic waves are always physically distinguishable from each other.

Furthermore, the rotary movement of the wavefront of an electromagnetic wave around the axis of propagation is substantially independent of the wave polarization state.

This means that two independent data transmission channels can be associated with an electromagnetic wave having a given carrier frequency and a given OAM.

The term “data transmission channel” (or “data channel” in short) is used here to indicate a signal that carries information, without any limitation regarding the type of signal (audio, video, multimedia, etc.) or the technology used to generate or transmit it (analogue or digital).

Telecommunication systems that use OAM values to discriminate between different radio signals are able to transmit electromagnetic waves with different OAMs and to associate a different data channel to each of them, by means of a specific encryption and modulation system.

At the receiving station, the aforementioned electromagnetic waves are identified, demodulated and decrypted in order to acquire the transmitted information through the data transmission channels associated with them.

From a theoretical point of view, the basic characteristics of the propagation of radio-frequency electromagnetic waves having different OAMs, and of the electromagnetic sources suitable to generate such waves, have been studied for a long time, also with the aid of large sets of numerical simulations.

In this respect, an evidential example is represented by the Diploma thesis “Angular Momentum of Electromagnetic Radiation” by Sjoeholm Johan et al., Uppsala University (Sweden), May 2, 2009 (Cornell University Library).

Other relevant documents are represented by the publication “Radio beam vorticity and orbital angular momentum” by Thidè Bo et al, Instrumentation and Method for Astrophysics, January 31, 2011 (Cornell University Library), and the publication “Orbital Angular Momentum in a Radio System Study” by Mohammadi at al., IEEE Transactions on Antennas and Propagation, February 1, 2010 (Cornell University Library).

From the experimental point of view, the first attempts to transmit radio-frequency or microwave electromagnetic waves having different OAMs have occurred quite more recently.

Particularly known is the experiment that was carried out on June 24 2011 in Venice, Italy, which is duly described in the publication “Encoding many channels in the same frequency through radio vorticity: first experimental test” by Fabrizio Tamburini et al., July 12, 2011 (Cornell University Library).

The telecommunication systems for transmitting radio-frequency or microwave electromagnetic waves having different OAMs, which are currently available, in demonstration and/or prototype form, are all affected by a set of drawbacks.

In order to use OAM to discriminate between radio waves with the same carrier frequency but conveying different information flows, these systems perform phase measurements at different points belonging to a common receiving plane, which is perpendicular to the direction of propagation of the electromagnetic waves. This solution is theoretically justified by the correct observation that the wavefront of an electromagnetic wave with an OAM other than zero has a phase that varies continuously on the receiving plane, in proportion to a proper angular coordinate, defined on the same plane.

However, although it represents undoubtedly a valid experimental approach, carrying out phase measurements in a field-installed system is a laborious and delicate task from a practical point of view, as it was proven also during the above mentioned experiment carried out in Venice.

Up to now, such a problem has been overcome only by using relatively complex and costly electronic measurement/processing devices.

Furthermore, in order to be carried out correctly, those phase measurements require that all the measurement points lay perfectly on the same plane.

Such a requirement was laboriously satisfied during the above mentioned experiment, in which only two overlapped electromagnetic waves were transmitted, to be discriminated on the base of their OAM. However, it may become a very difficult condition to fulfill, in case electromagnetic waves having three or more OAM values are transmitted together.

Further, for the transmission of electromagnetic waves with an OAM other than zero, relatively complex antennas are commonly used, such as parabolic antennas having helical or spiral transmission or reflection surfaces, which are specially designed and built in very small numbers, which therefore makes them very expensive.

Furthermore, since the fundamental properties that characterize the OAM of a wave require a precise one-to-one relation between the pitch of the helical or spiral transmission surface and the wavelength of the radiation field, the correct operation of such transmitting and receiving antennas is limited to quite narrow frequency bands.

A further drawback consists in that electromagnetic waves, which have different OAM values and propagate in non-ideal conditions, are no more perfectly orthogonal (i.e. independent of one another), as it occurs when they propagate in free space. In particular, the reflection of an electromagnetic wave with a given OAM value either on the ground, or on the surface of a building, generates another electromagnetic wave having an OAM value with the same absolute value but opposite sign. The phase of the resulting electromagnetic field at the receiving antennas may be remarkably disturbed by this phenomenon, and consequently very difficult to identify and measure.

A further problem is the fact that, as is known, an electromagnetic wave with an OAM other than zero has an electromagnetic field whose amplitude is zero or almost zero (as regards its so-called transverse components, perpendicular to the direction of propagation) around the straight line located at the center of the wave helical vortex.

This fact is closely correlated to diffraction phenomena, associated with the transmission over long distances of the electromagnetic waves, in which the transverse dimensions of such a “dark area”, centered on the axis of propagation of the electromagnetic wave, increase with distance from the source.

This results in the need for relatively large receiving antenna systems for picking up and discriminating, at a long distance from the source, electromagnetic waves having OAMs other than zero.

Obviously, this poses considerable problems when it comes to realizing and installing a telecommunication system.

The main task of the present invention is to provide an apparatus and a method for realizing a radio link that will enable the aforementioned problems to be overcome.

In relation to this task, one aim of the present invention is to provide an apparatus and a method for realizing a radio link that are relatively simple and effective to use practically.

A further aim of the present invention is to provide an apparatus and a method for realizing a radio link that will enable relatively broad frequency bands to be used for both transmission and/or reception, in particular bands whose widths are limited by the characteristics of the transmission and/or receiving apparatuses only, but not limited by the characteristics of the antennas and/or by the features of the electromagnetic propagation, as is the case for all radio links that are in current operation nowadays.

Another aim of the present invention is to provide an apparatus and a method for realizing a radio link that will be relatively simple and economical to implement practically and to implement industrially.

The aforementioned tasks and aims, as well as other aims that will become evident from the following description and the accompanying drawings, are achieved, according to the invention, by an apparatus and method for realizing a radio link, according to the below claims 1 and 8 respectively, and the relative dependent claims which refer to preferred embodiments of the present invention.

Further characteristics and advantages of the present invention will become more apparent from the following detailed description thereof, which is illustrated by no way of limitation in the accompanying drawings, in which figures 1-5 show a schematic illustration of several practical embodiments of the apparatus and the method according to the invention.

With reference to figure 1, in one aspect the present invention refers to an apparatus 1 for realizing a radio link.

The apparatus 1 comprises a plurality of receiving antennas R_1, R_2, …, R_M, each of which is capable to simultaneously receive at least one pair C_1 of overlapping electromagnetic waves, for example a first and a second electromagnetic wave, W_1, W_2.

For the sake of clarity, the term “overlapping electromagnetic waves” refers, in this context, to electromagnetic waves that propagate during the same time interval through the same region of space.

The pair C_1 of electromagnetic waves is used for carrying at a distance a data channel X_1 associated with it. To that purpose, both electromagnetic waves W_1, W_2 may be advantageously modulated using the same modulating signal and radiated by the same source (a suitable antenna, or set of antennas). As an alternative, just one of the two electromagnetic waves W_1, W_2 may be modulated by a modulating signal while the other wave is a single-frequency, non-modulated carrier. Also such a combination is perfectly adequate to yield all the benefits entailed by the present invention.

The electromagnetic waves W_1, W_2 have the same carrier frequency, preferably within the range between 30MHz and 300GHz, and propagate along the same direction of propagation D in the same sense.

The electromagnetic waves W_1, W_2 are characterized, respectively, by different OAMs, for example a first and second OAM m_1, m_2, where m_1, m_2 are two different integer numbers, either positive or negative.

One (and only one) of the electromagnetic waves W_1, W_2 may possibly have zero OAM.

Preferably, the OAMs m_1, m_2 of the electromagnetic waves W_1, W_2 have the same absolute value but opposite signs, i.e. $m_1 = -m_2$.

As illustrated schematically in figure 1 (which refers, as an example and for the sake of simplicity only, to waves with equal amplitudes and OAMs with equal absolute value but opposite signs), on the path towards the receiving antennas R_1, R_2, …, R_M, the wavefront of each electromagnetic wave W_1, W_2 rotates around the propagation axis D, on the generic plane α perpendicular to said direction of propagation. The electric field of each of the electromagnetic waves W_1, W_2 therefore follows a helical path extending along the direction of propagation D (the helix axis).

As mentioned above, the OAMs m_1 and m_2 express the number of complete rotations made by the wavefront of the electromagnetic waves W_1, W_2, respectively, per wavelength.

The rate and the sense of rotation of the wavefront of each electromagnetic wave W_1, W_2 can therefore be expressed, respectively, by the absolute value and by the sign of the corresponding OAM number, m_1, m_2.

The receiving antennas R_1, R_2, …, R_M are placed on a receiving plane R, intersecting the direction of propagation D of the electromagnetic waves W_1, W_2 , at a distance from the transmission source T of the electromagnetic waves.

Each of the receiving antennas R_1, R_2, …, R_M is centered at a corresponding observation point r_1, r_2, …, r_M. The observation points r_1, r_2, …, r_M all belong to the receiving plane R.

Preferably, the observation points r_1, r_2, …, r_M are positioned along at least one circle or ellipse lying on said receiving plane R and centered on a rotation axis of the wavefront of said electromagnetic waves W_1, W_2, which is parallel or coinciding with the direction of propagation D.

Other embodiments (not illustrated) of the present invention may also have the observation points r_1, r_2, …, r_M arranged on several concentric (or confocal) circles or ellipses.

The number M of receiving antennas (and observation points) may vary, depending on needs. Preferably, M is an even number, greater than or equal to two.

The receiving plane R is preferably arranged so that it is substantially perpendicular to the direction of propagation D of the electromagnetic waves W_1, W_2.

According to the invention, the apparatus 1 comprises electronic means 10, operationally associated with the receiving antennas R_1, R_2, …, R_M.

The electronic means 10 may comprise any type of analogue or digital circuits, depending on needs.

The electronic means 10 are suitable to detect the amplitude of the electromagnetic field at the different observation points r_1, r_2, …, r_M, so as to acquire a first set of $DATA_1$ indicative of the amplitude of the electromagnetic field E_R which results from the overlapping (beat) of the two electromagnetic waves W_1, W_2, at different points on the receiving plane R.

The electronic means 10 are also suitable to process the $DATA_1$ obtained from the aforementioned detection of the amplitude of the electromagnetic field E_R, in order to provide a second set of $DATA_2$ which allow to identify in an unambiguous way the difference $\Delta_m = m_1 - m_2$ between the OAMs m_1, m_2 of the electromagnetic waves W_1, W_2.

The second set of data $DATA_2$ are therefore indicative of the difference $\Delta m = m_1 - m_2$ between the OAMs m_1, m_2.

The electronic means 10 are also suitable to further process the $DATA_2$ thus obtained, in order to provide a third set of $DATA_3$ that makes it possible to discriminate between different pairs of electromagnetic waves, C_1, C_2, …, C_p, if present at the same time and in the same place.

As each pair of electromagnetic waves, C_1, C_2, …, C_p carries a different data channel X_1, X_2, …, X_p, the signal reaching the end receiver of the apparatus 1 contains, thanks to this discrimination, one and only one of said data channels.

Preferably, the electronic means 10 receive from each of the receiving antennas R_1, R_2, …, R_M an amplitude signal detected at a corresponding observation point r_1, r_2, …, r_M.

Using as an input the detected signals received in this way, the electronic means 10 are able to obtain the measurement $DATA_1$ that are indicative of the amplitude of the electromagnetic field E_R actually present at all the observation points r_1, r_2, …, r_M.

Preferably, the set of $DATA_1$ also contains information about the sign (positive or negative) of the electromagnetic field at each of the observation points r_1, r_2, …, r_M.

As an example, negative and positive values of the electromagnetic field can be discriminated the ones from the others by means of a proper connection in series, with suitable polarity inversions, of the antenna terminals.

By processing the measurement $DATA_1$, the electronic means 10 are able to provide a second set of $DATA_2$ which allow to identify in an unambiguous way the difference Δ_m between the OAMs m_1, m_2 of the electromagnetic waves W_1, W_2.

Subsequent processing of the $DATA_2$ enables a single data channel to be extracted from multiple signals picked up by the receiving antennas. The process of extracting one data channel, corresponding to a given value for the difference Δ_m, may consist simply of choosing a specific configuration for the electrical network which connects the outputs of the receiving antennas R_1, R_2, …, R_M to the input of the radio receiver.

For example, if three electromagnetic waves (namely, a pair C_1 of waves consisting of two waves with the same OAM absolute value 1, and opposite signs, and another electromagnetic wave W_0 with zero OAM) impinge on the receiving antennas simultaneously, then the desired discrimination result can be achieved simply with M receiving antennas, located on a circle (centered on the rotation axis of said electromagnetic waves W_1, W_2) and equally spaced from each other, provided the signal leaving the i-th antenna is weighted by multiplying it by cos θ_i , where θ_i is the angular coordinate of the point at which the i-th antenna is centered, and then summing up all the signals weighted in this manner, with i varying from 1 to M.

Indeed, in this case, supposing that the total number of antennas is even, so that they occupy, in pairs, opposite positions, the final contribution of the wave W_0 to the weighted sum will be zero, while that of the pair of waves W_1, W_2 will be the sum of M real, non-negative terms, and therefore greater than zero.

In the general case of the simultaneous reception of two different values for Δ_m, neither of which are zero, use can also be made of the well known orthogonality of two cosine functions of different argument over the interval 0 - 2π.

A skilled technician may also find other solutions by making use of the vast body of literature available on MIMO systems.

The following considerations provide the theoretical justification for the technical solution proposed by the present invention.

On any plane perpendicular to the direction of propagation D (for example, the receiving plane R), an electromagnetic field E_R resulting from the overlapping of the electromagnetic waves W_1, W_2 (both having, for simplicity, unit amplitude) can be expressed by the following relation:

$$E_R = e^{jm_1\theta} + e^{jm_2\theta} = 2\cos(((m_1-m_2)/2)\theta)\, e^{j(m_1+m_2)\theta/2} = 2\cos((\Delta_m/2)\theta)\, e^{j(m_1+m_2)\theta/2}$$

where m_1, m_2 are the OAM numbers of the electromagnetic waves W_1, W_2, θ is the polar angular coordinate of the observation point on the plane R , and $j = (-1)^{1/2}$ is the imaginary unit. To simplify the notation without any loss of generality, in the above relation, the reference for the angular coordinate, i.e. $\theta=0$, was set at one of the straight half-lines leaving the origin, along which the two electromagnetic waves W_1, W_2 have equal phase (modulus 2π radians).

As said before, for simplicity, the amplitudes of the two electromagnetic waves W_1, W_2 are supposed to be the same. Any changes required, should this hypothesis not be satisfied, can be easily inferred from the literature (for example, from any elementary textbook on partially standing waves on transmission lines) and do not invalidate the statements made below, whose validity can substantially be ascribed to the fact that the minima of the overall electromagnetic field are no longer exactly equal to zero, but are nevertheless easy to identify and locate.

For the sake of completeness, let us notice that, as it may be obvious to the skilled person, an overlapping of the same electromagnetic waves, where the phase of one of them is delayed with respect to the other by a quarter of a period, yields a final result that differs from the relation above only in that the cosine function is replaced by the sine function. These two solutions are physically different one from the other, and there is no fundamental reason to prefer one of them, or not to make use of both of them at the same time. However, in the following, only the solution described by the above relation will be dealt with, for the purpose of simplicity.

The modulus of the resulting amplitude of the electromagnetic field E_R then varies according to the following relation:

$$|E_R|=2|\cos((\Delta_m)/2)\theta)|$$

i.e. is a periodic function of θ whose argument substantially depends on the difference Δ_m between the OAMs m_1 and m_2 of the electromagnetic waves W_1, W_2.

Schematic examples of functions that express the amplitude distribution of the electromagnetic field E_R on the receiving plane R, for different values of Δ_m, are shown in figure 4.

By processing the measurement $DATA_1$ indicative of the amplitude of the resulting electromagnetic field E_R on the receiving plane R, it is therefore possible to identify the function that expresses the amplitude distribution of the electromagnetic field on the receiving plane R, and thereby to obtain a set of $DATA_2$ indicative of the difference Δ_m between the OAMs of the electromagnetic waves W_1, W_2.

Based on the above relation, it is apparent that, if the OAMs m_1, m_2 of the electromagnetic waves W_1, W_2 have the same absolute value, n, and opposite signs, then the amplitude of the resulting electromagnetic field E_R varies according to a relationship such as $|E_R|=2|\cos(n\theta)|$, where $n = |m_1| = |m_2|$, thereby considerably simplifying the identification of Δ_m.

Furthermore, based on the above relationship, it is apparent how, in order to ensure effective recognition of the function which expresses the amplitude distribution of the electromagnetic field E_R on the receiving plane R, it is advisable to use a number M of receiving antennas, with M an even number larger than or equal to two.

It is also apparent how the positioning of the M receiving antennas R_1, R_2, …, R_M along at least one circle orthogonal to the direction of propagation D considerably simplifies recognition of the spatial distribution of the amplitude of the electromagnetic field E_R.

It is also apparent that a non-perfect perpendicularity between the receiving plane R and the propagation direction D has quite small effects on the overall result.

This is an important point of difference compared to the solutions of the state of the art, in which phase measurements are needed in order to identify the different OAMs and discriminate between the received electromagnetic waves.

In fact, the electromagnetic field amplitude at the observation points r_1, r_2, …, r_M is substantially insensitive to an imperfect planarity of the receiving system, while phase errors, with which the various contributions due to the M antennas might add up, would compensate one another (in pairs), at least partially, so that the final result would be correct, at least as a first-order approximation.

As illustrated above, the electronic means 10 are capable of acquiring the set of $DATA_2$ indicative of the difference Δ_m between the OAMs of the pair C_1 of overlapping electromagnetic waves W_1, W_2.

As mentioned above, a data channel X_1 is associated with the pair C_1 of electromagnetic waves W_1, W_2.

The difference Δ_m between the OAMs of the electromagnetic waves W_1, W_2 can therefore be advantageously used as an indicator for discriminating a given data channel X_1 from all the other ones which may be present at the same time and in the same region of space, at the same carrier frequency.

In other words, Δ_m can be thought of as a label that identifies one and only one of the data channels transmitted simultaneously on the same carrier frequency and in the same direction.

This represents a major difference compared to all known systems and apparatuses.

In fact, in systems studied and tested up to now, each electromagnetic wave received on a generic receiving plane is associated with a data channel for which the identifying value (label) consists in the OAM of the wave itself.

In order to determine the identifying value of a given data channel, it is therefore necessary to know the exact phase rotation value of the wavefront of the electromagnetic wave received on the receiving plane, and therefore to perform complex and laborious measurements of the phase of the electromagnetic field present on the receiving plane .

In apparatus 1, on the other hand, a data channel X_1 is associated with a pair C_1 of overlapping electromagnetic waves.

In order to determine the identifying value of a data channel, it is sufficient to know the amplitude of the electromagnetic field resulting from the overlapping of the electromagnetic waves, at a proper number of points on the receiving plane, and hence, to perform a relatively simple detection of the amplitude of the electromagnetic field present on the receiving plane .

In apparatus 1, acquisition of the data transmitted through the data channel X_1 can advantageously be achieved by the use of appropriate decryption means (not illustrated in the figures), including known means, which are operationally associated or integrated with the electronic means 10.

Preferably, the receiving antennas R_1, R_2, …, R_M are capable of receiving several pairs C_1, C_2 of electromagnetic waves W_1, W_2, W_3, W_4.

Each pair C_1, C_2 of electromagnetic waves is advantageously associated with a different data channel X_1, X_2 (figure 2).

As illustrated above, discrimination between each pair C_1, C_2 of electromagnetic waves, and therefore between each data channel X_1, X_2, is advantageously done by the electronic means 10, based on the set of $DATA_2$ indicative of the differences Δ_{m1}, Δ_{m2} between the OAMs of the electromagnetic waves of each pair C_1, C_2.

It should be noted that two different pairs C_1, C_2 of overlapping electromagnetic waves may advantageously share one electromagnetic wave, provided that such a wave has an OAM different from the other electromagnetic waves which overlap it.

For example, as illustrated in figure 3, the electromagnetic wave W_1 is comprised in both the pairs C_1, C_2 but has an OAM different from those of the electromagnetic waves W_2, W_3 overlapping it.

Preferably, the receiving antennas R_1, R_2, …, R_M can be moved around on the receiving plane R. The position of the observation points r_1, r_2, …, r_M on the receiving plane R can therefore vary according to needs, so as to optimize reception of the overlapping electromagnetic waves W_1, W_2.

Advantageously, in order to identify most suitable observation points r_1, r_2, …, r_M, one can first identify the points where the amplitude of the electromagnetic field E_R is minimum (ideally, zero). These minimum points can be easily localized on the receiving plane R, since, as illustrated above, the amplitude of the resulting electromagnetic field E_R on the receiving plane R is a periodic function which, at least as a first approximation, looks like a rectified sine wave, whose minima are deep and sharp, as well known in the literature and shown by way of example in figure 4.

The most suitable observation points r_1, r_2, …, r_M can therefore be identified based on the number and location of the aforementioned minimum points.

Preferably, the most suitable observation points $r_1, r_2, \ldots, r_M$ are located around the points where the amplitude of the electromagnetic field E_R reaches its maximum, each of which falls essentially half-way between two adjacent minima.

The procedure described above for identifying the most suitable observation points $r_1, r_2, \ldots, r_M$ helps to simplify the positioning of the receiving antennas $R_1, R_2, \ldots, R_M$.

For example, in the case where the receiving antennas $R_1, R_2, \ldots, R_M$ are arranged on a circle centered on the rotation axis of the wavefront, the most suitable observation points $r_1, r_2, \ldots, r_M$ will be located near the maximum points of the resulting electromagnetic field E_R, if they are rotated by an angle of π/L radians with respect to the corresponding minimum points, where $L = |\Delta_m| = |m_1-m_2|$ is the number of points of relative minimum that have been detected along the said circle.

The receiving antennas $R_1, R_2, \ldots, R_M$ may be in the form of dipoles, parabolic reflectors, or other known types of structures. Metamaterials and/or plasmonic materials can advantageously be used in their construction.

From the previous relation expressing the amplitude of the resulting electromagnetic field E_R, it is apparent that, in the region of space where said electromagnetic field is defined, there are a number – actually Δ_m – of half-planes, whose common border is the z axis, where the electromagnetic field E_R is equal to zero. In case Δ_m is an even number, then these half-planes become $\Delta_m/2$ planes, which pass through the z-axis, and correspond to values of the angular coordinate θ which are proportional to odd multiples of π/Δ_m.

Thus, referring to figure 5, if the transmitting antennas are arranged in such a way that either the horizontal plane (e.g., the plane x = 0 of figure 5), or another plane (e.g. the plane y = 0 of figure 5), parallel to the edge of an obstacle (e.g. the surface A of the building of figure 5), or both, coincide with planes on which the electromagnetic field E_R is equal to zero, then the corresponding reflection, on the ground or on said obstacle, is cancelled. This entails the benefit of suppressing the inconveniences of the state-of-the-art systems which were described at the beginning.

The electronic means 10 may be easily implemented at industrial level by means of well known design and manufacturing techniques for analogue or digital circuits.

As an example, the electronic means 10 may encompass a set of broadband attenuators and/or amplifiers, suitably arranged to provide the functionalities described above.

Aiming at maximum flexibility and integration, the electronic means 10 may be preferably implemented on a single chip, with possible inclusion of MEMS (Micro Electro-Mechanical Systems).

Preferably, the apparatus 1 comprises a plurality of transmission antennas T_1, T_2, …, T_N, arranged on a transmission plane T perpendicular to the direction D, and capable of radiating pairs of electromagnetic waves W_1, W_2 along the direction of propagation D.

Preferably, each of the transmission antennas T_1, T_2, …, T_N is centered at one of a plurality of corresponding transmission points t_1, t_2, …, t_N belonging to the transmission plane T.

Preferably, the transmission points t_1, t_2, …, t_N belong to at least one circle or ellipse lying on said transmission plane T.

Advantageously, the diameters (the axis lengths) of said circle (or ellipse) can be adjusted as a function of the difference Δ_m between the OAMs m_1, m_2 and of the distance between the receiving plane R and the transmission plane T.

The transmission points t_1, t_2, …, t_N belong preferably to only one circle or ellipse lying on the transmission plane T.

Other embodiments (not illustrated) of the present invention may however have transmission antennas T_1, T_2, …, T_N arranged on several concentric (or confocal) circles or ellipses.

The number N of transmission antennas can vary according to needs. Preferably, this number N shall be an even number, greater than or equal to two.

Preferably, second electronic means 30 are operationally associated with the transmission antennas T_1, T_2, …, T_N in order to control the transmission of the electromagnetic waves W_1, W_2.

The electronic means 30 may comprise any type of analogue or digital circuits, depending on needs.

Radiation of the transmitted electromagnetic waves W_1, W_2 can be done using known methods. For example, the electronic means 30 may drive the transmission antennas T_1, T_2, …, T_N with suitable transmission signals, each of which will have a different amplitude and/or a different phase.

In this way, the set of transmission antennas T_1, T_2, …, T_N can easily generate two electromagnetic waves W_1, W_2 that are overlapping but have different OAMs, or, in other words, have a different rotary movement of the wavefront as it travels along the direction of propagation D.

In the particular case where the two OAMs have the same absolute value but opposite signs ($m_1 = -m_2$), the driving signals of the N transmission antennas differ from one another only in terms of their amplitudes, without any difference in their phase.

This makes it particularly simple to design a feeding network for the transmission antennas, which does not need to encompass any phase shifter.

A further advantage of this type of solution consists in that it may yield a broader bandwidth of the feeding network and therefore of the entire system.

Preferably, each of the transmission antennas T_1, T_2, …, T_N is an aperture antenna, characterized by a radiating surface, like for instance a parabolic reflector.

In this case, preferably, the foci of the transmission paraboloids T_1, T_2, …, T_N belong to a circle lying on the transmission plane T, and the axes of said transmission paraboloids T_1, T_2, …, T_N are slightly tilted with respect to each other, to converge in a suitable point somewhere between the transmission plane T and the receiving plane R, along the direction of propagation D.

This makes it possible to significantly reduce the amount of power radiated in directions other than the desired direction D, and to ensure that the overall surface (on the receiving plane R) which contains all the receiving antennas R_1, R_2, …, R_M is comparable in size to the surface on which all the transmission antennas T_1, T_2, …, T_N are placed on the transmission plane T.

Thanks to the possibility of tilting the main radiation lobes of the transmission antennas T_1, T_2, …, T_N , and of a fine tuning of their power levels, the electronic means 30 can also be capable of controlling the size of the so-called "dark area" centered on the propagation axis D of the electromagnetic waves W_1, W_2.

It is therefore possible to control the size of the aforementioned "dark area" in real time, while the electromagnetic waves W_1, W_2 are being transmitted.

This offers a possibility to considerably simplify preliminary operations for the apparatus 1, i.e. to make sure that the transmitter and the receiver of the electromagnetic waves W_1, W_2 are in contact with each other, before starting the actual transmission of OAM-based signals.

In alternative embodiments of the present invention, the transmission antennas T_1, T_2, …, T_N may consist of very simple and cheap structures, like, for example, holes in metallic screens, or can antennas.

This makes it possible to cut manufacturing costs for the transmission apparatus 1.

Preferably, to further improve their directivity, the transmission antennas T_1, T_2, …, T_N may be built using metamaterials and/or plasmonic materials.

Preferably, the electronic means 30 are able to associate a data channel X_1 to the pair C_1 of overlapping electromagnetic waves W_1, W_2.

To that end, encryption means, including known means, may be operationally associated or integrated with the electronic means 30 in order to transmit data along the data channel X_1, using as a channel identifier the difference Δ_m between the OAMs of the electromagnetic waves W_1, W_2.

Preferably, means (not illustrated) of controlling the polarization state of the electromagnetic waves W_1, W_2 are operationally associated or integrated with the electronic means 30.

In this way, two distinct data channels X_1, X_2 can be associated with each pair C_1 of electromagnetic waves W_1, W_2.

Advantageously, information about the instantaneous polarization state of the electromagnetic waves W_1, W_2 can be used as an encryption/decryption key for the data transmitted via the data channels X_1 , X_2.

Preferably, the set of transmission antennas T_1, T_2, …, T_N is able to transmit simultaneously several pairs C_1, C_2 of electromagnetic waves W_1, W_2, W_3, W_4 , and to associate each pair of electromagnetic waves with a different data channel (figure 2).

As mentioned above, different pairs C_1, C_2 of transmitted overlapping electromagnetic waves can advantageously share one electromagnetic wave, provided that each of the remaining electromagnetic waves present has an OAM different from all the other electromagnetic waves overlapping it.

The electronic means 30 may be easily implemented at industrial level by means of well known design and manufacturing techniques for analogue or digital circuits.

As an example, the electronic means 30 may encompass a set of broadband attenuators and/or amplifiers, suitably arranged to provide the functionalities described above.

Aiming at maximum flexibility and integration, the electronic means 30 may be preferably implemented on a single chip, with possible inclusion of MEMS (Micro Electro-Mechanical Systems).

A further aspect of the present invention refers to a method for realizing a long-range radio link. The method according to the invention comprises the following steps:

- receiving at least one pair C_1 of overlapping electromagnetic waves W_1, W_2 with the same carrier frequency and different OAMs m_1, m_2, at a plurality of different observation points r_1, r_2, …, r_M on a receiving plane R, which intersects the direction of propagation D, and is located at a distance from at least one source T of the electromagnetic waves W_1, W_2, a data channel X_1 being associated to said pair C_1 of electromagnetic waves W_1, W_2;
- detecting the amplitude of the electromagnetic field so as to acquire a first set of $DATA_1$ indicative of the amplitude of the electromagnetic field E_R which results from the overlapping of the electromagnetic waves W_1, W_2, at said observation points on the

receiving plane R;

- processing the first set of $DATA_1$ in order to provide a second set $DATA_2$ indicative of the difference Δ_m between the OAMs m_1, m_2 of the electromagnetic waves W_1, W_2.

Preferably, the method according to the invention also comprises a step of processing the second set of $DATA_2$ to provide a third set $DATA_3$ that makes it possible to discriminate between different pairs of electromagnetic waves, C_1, C_2, ..., C_p, if present simultaneously.

Preferably, the method according to the invention also comprises the following steps:

- identifying on the receiving plane R the points where the amplitude of the electromagnetic field E_R resulting from the overlapping of the electromagnetic waves W_1, W_2 takes its minimum values;
- identifying a set of said observation points r_1, r_2, ..., r_M on said receiving plane, on the base of the number and the positions of said minimum points.

Preferably, the method according to the invention also comprises a step of transmitting at least one pair C_1 of electromagnetic waves W_1, W_2, along the direction of propagation D.

Preferably, the method according to the invention also comprises a step of receiving and/or transmitting one or more pairs C_1, C_2 of electromagnetic waves W_1, W_2, W_3, W_4 along the direction of propagation D, a data channel X_1, X_2 being associated with each pair C_1, C_2 of electromagnetic waves.

Preferably, the method according to the invention also comprises a step of orienting the whole set of transmitting antennas in such a way that the electromagnetic field E_R is set to zero (or nearly zero) on the ground plane and/or on the edge of an obstacle, e.g. a building, thereby solving the problems caused by reflections on the ground or on said obstacle.

It has been shown how, in practice, the apparatus and the method according to the invention overcome the problems suffered by known art described above, thereby achieving their aims.

The apparatus and the method according to the invention envisage the simultaneous reception (and possibly the simultaneous transmission) of one of more pairs of electromagnetic waves with different OAMs m_1, m_2.

Each pair of electromagnetic waves is identified by a characteristic value Δ_m equal to the difference between the OAMs of the electromagnetic waves that form the pair.

The apparatus and the method according to the invention envisage detecting just the amplitude of the electromagnetic field, in order to determine this characteristic identifying value Δ_m.

The characteristic value Δ_m can easily be used as a value that identifies unambiguously one and only one data channel associated with that pair of electromagnetic waves.

The apparatus and the method according to the invention are therefore of relatively simple and cost-effective practical implementation, compared to known telecommunication systems and methods.

The apparatus and the method according to the invention make it possible, by means of simple adjustments, to restrain or overcome problems caused by diffraction phenomena associated with the transmission over long distances of electromagnetic waves with a non-zero OAM.

Further, the apparatus and the method according to the invention enable the designer to set substantially at zero the electromagnetic field on the ground plane and/or on other obstacles, thereby dramatically reducing the problems which originate from the wave reflection on them.

The apparatus and the method according to the invention envisage the use of receiving/transmission antennas with very simple geometries and of easy practical use.

Since the identifying value Δ_m can be determined without determining the phase of the electromagnetic field E_R, the apparatus and the method according to the invention make it possible to build a long-range radio link with relatively broad frequency bands on both sides, i.e. transmission and reception.

Differently from the currently available OAM-based telecommunication systems, in the apparatus and the method according to the invention the bandwidth is not limited by the characteristics of the antennas and/or by the electromagnetic propagation, but it is limited by the characteristics of the transmission and/or receiving electronics only. The apparatus and the method according to the invention are thus particularly suitable for solutions which exploit the retrofitting of already existing telecommunication systems.

CLAIMS

1. An apparatus (1) for realizing a radio link characterized in that it comprises:
   - a plurality of receiving antennas ($R_1, R_2, \ldots, R_M$), each of which is suitable to receive at least one pair (C_1) of overlapping electromagnetic waves (W_1, W_2) with the same carrier frequency and different OAMs (m_1, m_2), said receiving antennas being arranged at corresponding different observation points ($r_1, r_2, \ldots, r_M$) on a receiving plane (R) which intersects the direction of propagation (D) of said electromagnetic waves and located at a distance from at least one transmission source (T) of said electromagnetic waves, a data channel (X_1) being associated with said pair (C_1) of electromagnetic waves (W_1, W_2);
   - first electronic means (10), operationally associated with said receiving antennas, said first electronic means being suitable to detect the amplitude of the electromagnetic field so as to acquire a first set of data ($DATA_1$) indicative of the amplitude of the electromagnetic field (E_R) which results from the overlapping of said electromagnetic waves (W_1, W_2), at said observation points ($r_1, r_2, \ldots, r_M$), said first electronic means being suitable to process said first set of data ($DATA_1$) in order to provide a second set of data ($DATA_2$) indicative of the difference (Δ_m) between the OAMs (m_1, m_2) of said electromagnetic waves (W_1, W_2).
2. An apparatus, according to claim 1, characterized in that said first electronic means (10) are suitable to process said second set of data ($DATA_2$) in order to provide a third set of data ($DATA_3$) that makes it possible to discriminate between different pairs (C_1, C_2) of electromagnetic waves, if present at the same time and in the same place, at said carrier frequency.
3. An apparatus, according to one or more of the previous claims, characterized in that said observation points ($r_1, r_2, \ldots, r_M$) are located along at least one circle or ellipse lying on said receiving plane (R), said receiving plane (R) being substantially perpendicular to the direction of propagation (D) of said electromagnetic waves (W_1, W_2), said circle or ellipse being substantially centered on an axis of rotation of the wave front of said electromagnetic waves (W_1, W_2).
4. An apparatus, according to one or more of the previous claims, characterized in that the OAMs (m_1, m_2) of said electromagnetic waves (W_1, W_2) have the same absolute value but opposite signs.
5. An apparatus, according to one or more of the previous claims, characterized in that it comprises a plurality of transmission antennas ($T_1, T_2, \ldots, T_N$), arranged at a plurality of

corresponding different transmission points (t_1, t_2, …, t_N) on a transmission plane (T), said transmission antennas being suitable to transmit said pair (C_1) of electromagnetic waves (W_1, W_2) along said direction of propagation (D).

6. An apparatus, according to claim 5, characterized in that said transmission antennas (T_1, T_2, …, T_N) comprise parabolic reflectors whose foci are located on a circle lying on said transmission plane (T), the axes of said parabolic reflectors being oriented so as to converge at a point located between said transmission plane (T) and said receiving plane (R), along said direction of propagation (D).
7. An apparatus, according to one or more of the claims from 5 to 6, characterized in that the set of said transmission antennas (T_1, T_2, …, T_N) is arranged in such a way that the horizontal plane, and/or another plane passing through the said direction of propagation (D) coincides with one of the planes on which the electromagnetic field (E_R) resulting from the overlapping of said electromagnetic waves (W_1, W_2) is set equal to zero, or nearly zero.
8. A method for realizing a radio link characterized in that it comprises the following steps:
   - receiving at least one pair (C_1) of overlapping electromagnetic waves (W_1, W_2) with the same carrier frequency and different OAMs (m_1, m_2), at different observation points (r_1, r_2, …, r_M) on a receiving plane (R), which intersects the direction of propagation (D) of said electromagnetic waves and is located at a distance from at least one source (T) of said electromagnetic waves (W_1, W_2), a data channel (X_1) being associated with said pair (C_1) of electromagnetic waves (W_1, W_2);
   - detecting the amplitude of the electromagnetic field so as to acquire a first set of data ($DATA_1$) indicative of the amplitude of the electromagnetic field (E_R) resulting from the overlapping of said electromagnetic waves (W_1, W_2), at said observation points (r_1, r_2, …, r_M);
   - processing said first set of data ($DATA_1$) in order to provide a second set of data ($DATA_2$) indicative of the difference (Δ_m) between the OAMs (m_1, m_2) of said electromagnetic waves (W_1, W_2).
9. A method, according to claim 8, characterized in that it comprises a step of processing said second set of data ($DATA_2$) to provide a third set of data ($DATA_3$) that makes it possible to discriminate between different pairs (C_1, C_2) of electromagnetic waves, if present at the same time and in the same place, at said carrier frequency.
10. A method, according to one or more of the claims from 8 to 9, characterized in that it comprises the following steps:

- identifying, on said receiving plane (R), the points where the electromagnetic field resulting from the overlapping of said electromagnetic waves (W_1, W_2) takes its minimum values;
- identifying, on said receiving plane (R), said observation points (r_1, r_2, …, r_M) based on the number and the positions of said minimum points;
- positioning a plurality of receiving antennas (R_1, R_2, …, R_M) at said observation points (r_1, r_2, …, r_M).

11. A method, according to one or more of the claims from 8 to 10, characterized in that it comprises a step of receiving a plurality of pairs (C_1, C_2) of overlapping electromagnetic waves (W_1, W_2, W_3, W_4), a data channel (X_1, X_2) being associated with each pair (C_1, C_2) of said electromagnetic waves.
12. A method, according to one or more of the claims from 8 to 11, characterized in that it comprises a step of transmitting one or more pairs (C_1, C_2) of overlapping electromagnetic waves (W_1, W_2, W_3, W_4) along said direction of propagation (D), a data channel (X_1, X_2) being associated with each pair (C_1, C_2) of said electromagnetic waves.
13. A method, according to one or more of the claims from 8 to 12, characterized in that it comprises a step of orienting a set of antennas transmitting said electromagnetic waves in such a way that the horizontal plane, and/or another plane passing through the said direction of propagation, coincides with one of the planes on which the electromagnetic field (E_R) resulting from the overlapping of said electromagnetic waves (W_1, W_2) is equal to zero, or nearly zero.

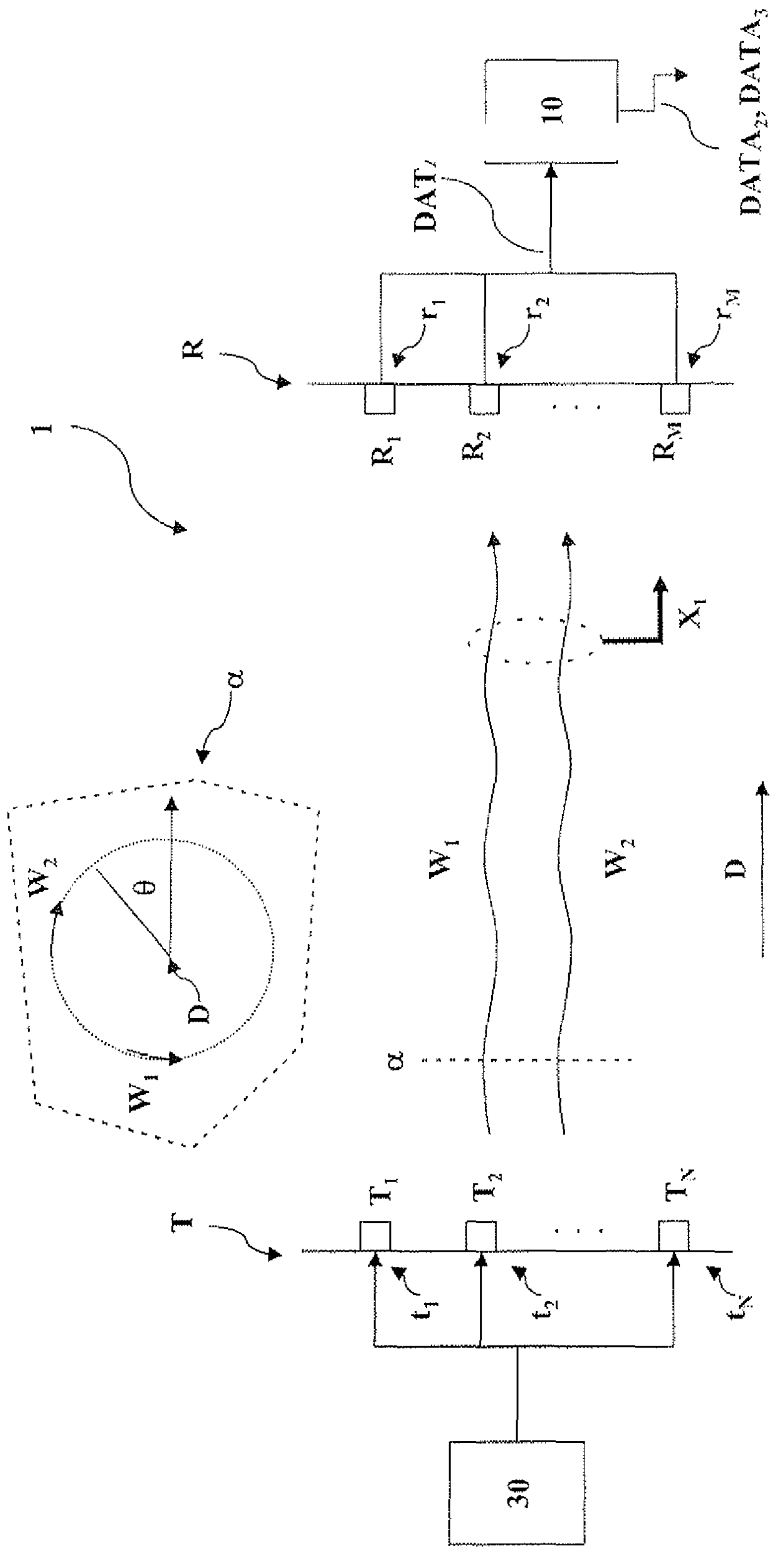
1
R
R_1
R_2
R_M
r_1
r_2
r_M
DATA
10
$DATA_2$, $DATA_3$
α
W_1
W_2
θ
D
X_1
T
T_1
T_2
T_N
t_1
t_2
t_N
30

FIG. 1

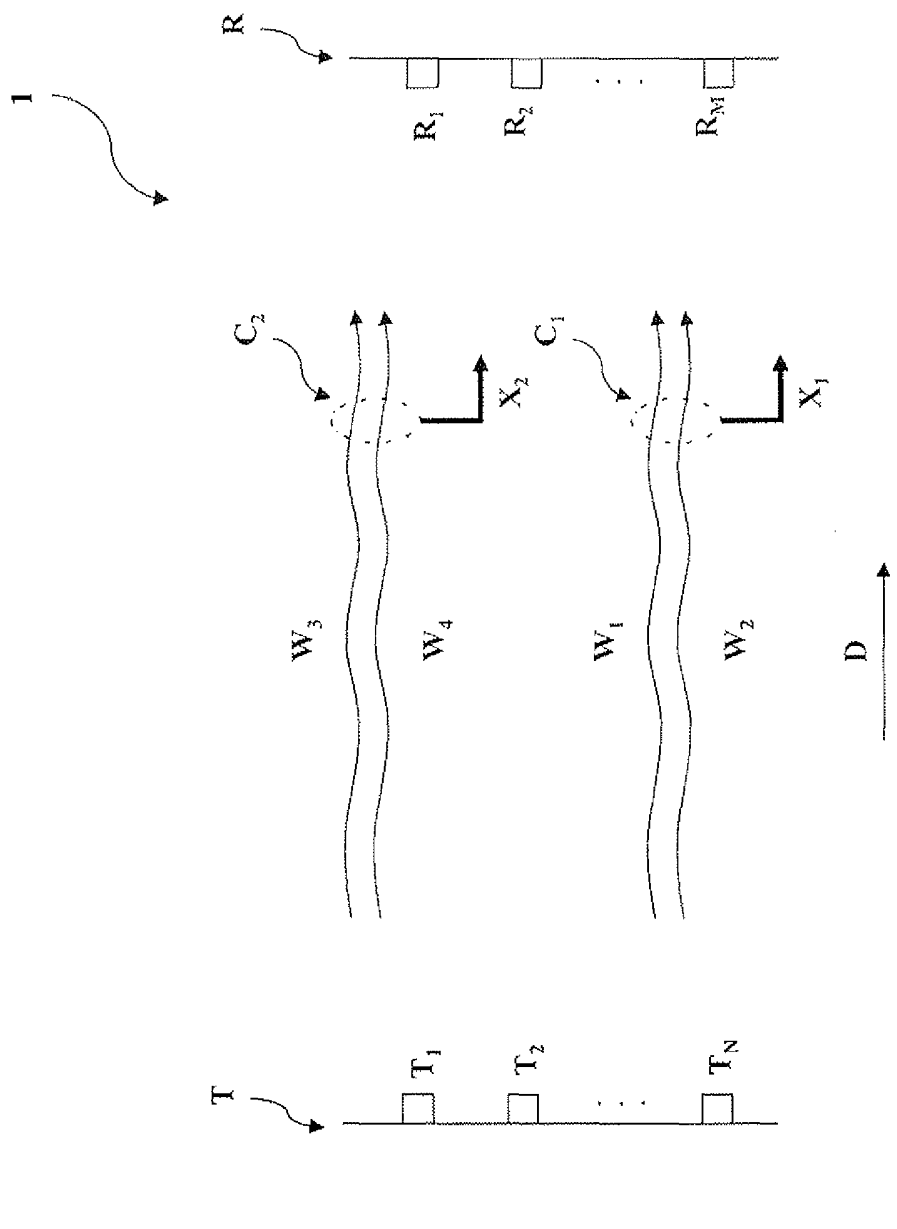

FIG. 2

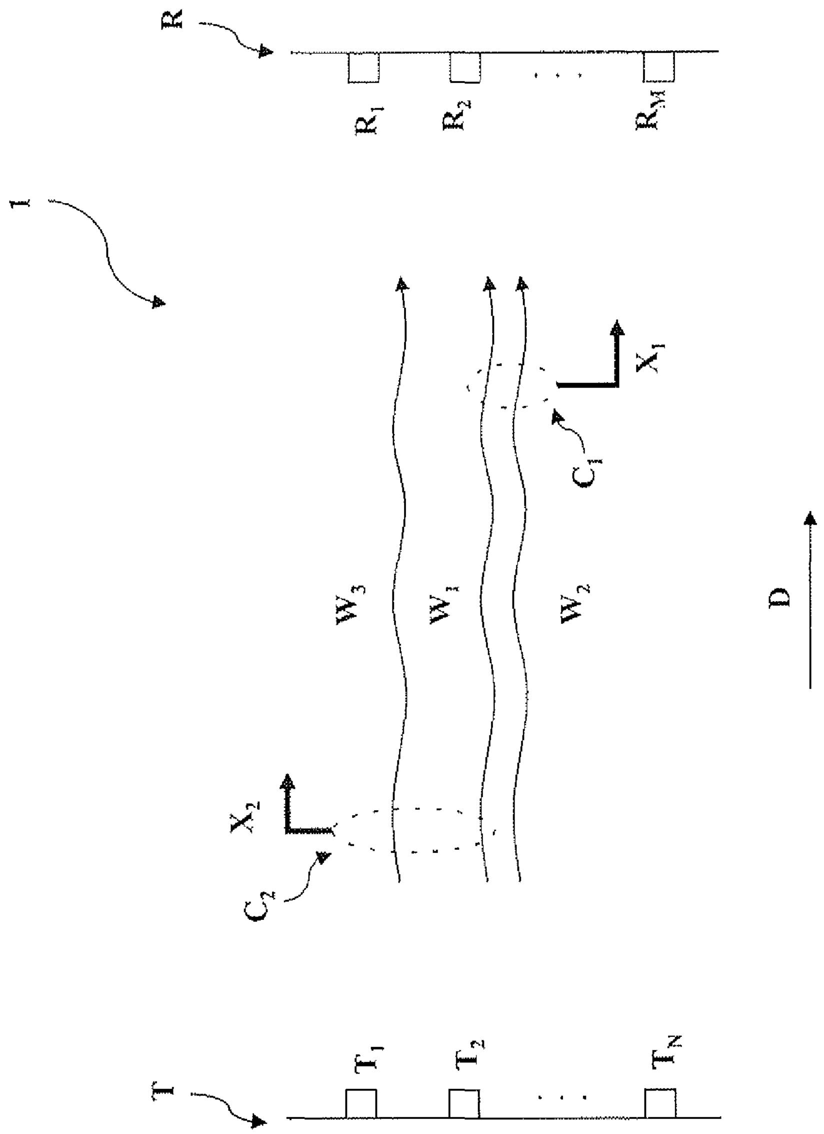

FIG. 3

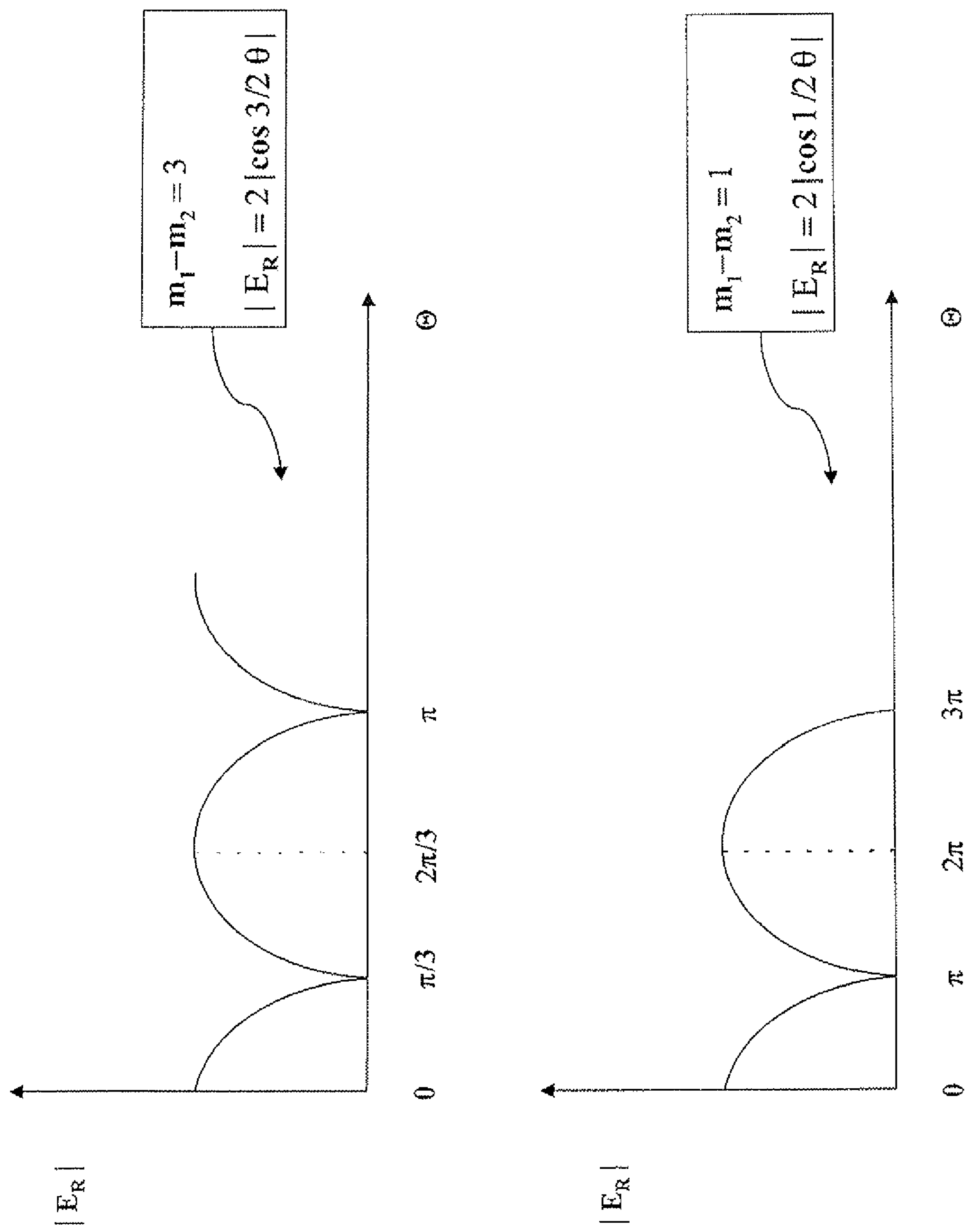
$m_1 - m_2 = 3$
$|E_R| = 2|\cos 3/2\,\theta|$
$|E_R|$
0
π/3
2π/3
π
Θ
$m_1 - m_2 = 1$
$|E_R| = 2|\cos 1/2\,\theta|$
$|E_R|$
0
π
2π
3π
Θ

FIG. 4

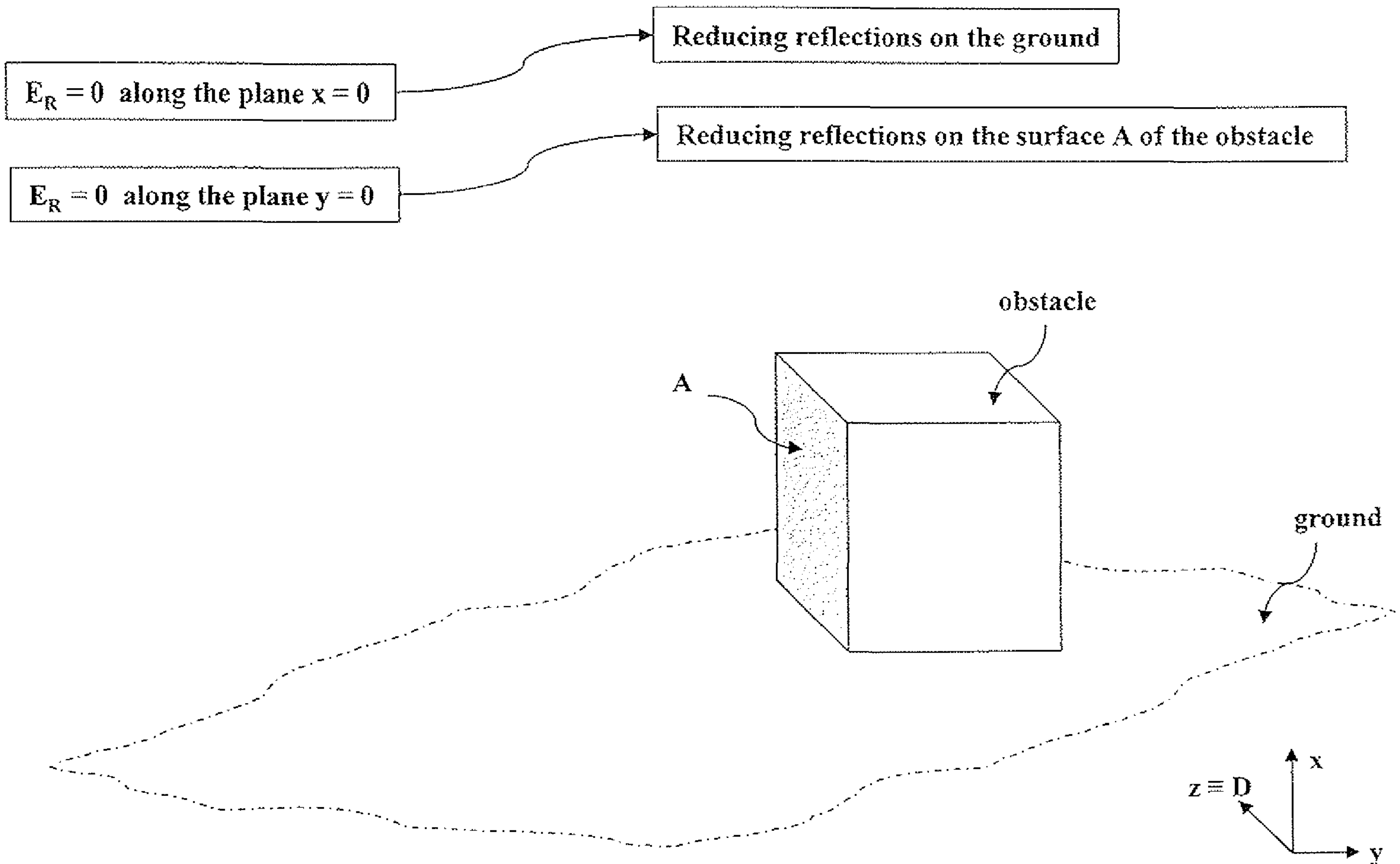
$E_R = 0$ along the plane $x = 0$
Reducing reflections on the ground
$E_R = 0$ along the plane $y = 0$
Reducing reflections on the surface A of the obstacle
obstacle
A
ground
x
$z \equiv D$
y

FIG. 5

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2012/075734

A. CLASSIFICATION OF SUBJECT MATTER
INV. H04B7/06 H04B7/08 H04B7/10
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)
H04B

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)

EPO-Internal, INSPEC, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	Fabrizio Tamburini ET AL: "Encoding many channels in the same frequency through radio vorticity: first experimental test", Cornell University Library, 12 July 2011 (2011-07-12), XP055021484, Ithaca, NY, USA Retrieved from the Internet: URL:http://arxiv.org/abs/1107.2348 [retrieved on 2012-03-09] cited in the application abstract paragraph [Introduction] paragraph [Transmittingwithradiovortices] paragraph [RadiotransmissionwithOAM] ----- -/--	1-13

[X] Further documents are listed in the continuation of Box C.

[ ] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"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

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
11 February 2013	19/02/2013

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Lustrini, Donato

1

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	Sjöholm, Johan, et. al.: "Angular Momentum of Electromagnetic Radiation", Cornell University Library Diploma thesis at Uppsala University, Sweden, 2 May 2009 (2009-05-02), pages FRONTPG.-185, XP002671614, ISSN: 1401-5757 Retrieved from the Internet: URL:http://arxiv.org/ftp/arxiv/papers/0905/0905.0190.pdf [retrieved on 2012-03-16] cited in the application abstract paragraph [Chap.6] paragraph [Chap.7] paragraph [08.2] - paragraph [08.3] -----	1-13
A	Thidé Bo, et. al.: "Radio beam vorticity and orbital angular momentum", Cornell University Library Instrumentation and Methods for Astrophysics, 31 January 2011 (2011-01-31), pages 1-3, XP002671595, Retrieved from the Internet: URL:http://arxiv.org/abs/1101.6015 [retrieved on 2012-03-15] cited in the application the whole document -----	1,8
A	MOHAMMADI S M ET AL: "Orbital Angular Momentum in Radioâ A System Study", IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, IEEE SERVICE CENTER, PISCATAWAY, NJ, US, vol. 58, no. 2, 1 February 2010 (2010-02-01), pages 565-572, XP011298052, ISSN: 0018-926X cited in the application abstract paragraphs [000I], [0III] -----	1,8

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1

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X,P	Tamburini. F, et. al.: "Encoding many channels on the same frequency through radio vorticity: first experimental test", New Journal of Physics, vol. 14 1 March 2012 (2012-03-01), pages 1-17, XP002671588, DOI: 10.1088/1367-2630/14/3/033001 Retrieved from the Internet: URL:http://iopscience.iop.org/1367-2630/14/3/033001?fromSearchPage=true [retrieved on 2012-03-15] abstract paragraph [0001] - paragraph [0004] -----	1-13

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