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(57) Abstract: A transmit antenna arrangement (100) comprising N antenna elements (110, 115, 120) arranged along a circumference (125) separated \( \frac{\alpha}{N} \) degrees. The antenna arrangement comprises an Orbital Angular Momentum encoder (105) arranged to receive N input signals (S1, S2, S3) for transmission, indexed from M=(N-1)/2 up to M=(N-1)/2 for odd N and from M=(N-2)/2 up to N/2 for even N. The Orbital Angular Momentum Encoder (105) connects each signal N (Si, S2, S3) to each antenna element (110, 115, 120), and gives each input signal M at each antenna element (110, 115, 120) a phase shift of (M \* \alpha) relative to the phase of the same input signal M at an adjacent antenna element (110, 115, 120). Two or more antenna elements (110, 115, 120) are directional and have their directivity in the same direction and have an antenna aperture of \( \geq 5 \lambda \). \( \lambda \) is the wavelength of the N input signals.

FIG. 1
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AN ANTENNA ARRANGEMENT

TECHNICAL FIELD

The present invention discloses a transmitting and a receiving antenna arrangement, as well as a radio connection using such arrangements, as well as related methods.

BACKGROUND

Orbital Angular Momentum, OAM, is an electromagnetic property which corresponds to a spiraling phase front of a propagating electromagnetic field. The creation and use of OAM-modes has mainly been discussed in the field of quantum optics, but recently also in the field of radio communication, where it has been suggested that OAM can be used to increase the capacity of a wireless communications link by creating multiple independent channels, all with the same frequency and polarization.

One possibility of creating an electromagnetic field with strong OAM is to put a spiral wedge in front of a traditional antenna, such as a reflector-, horn- or array antenna, for example, which would create a spiraling delay over the aperture. However, such a solution would only be able to support one single fixed OAM-mode.

Another possibility of creating an electromagnetic field with OAM modes is to use one or several rings of antenna elements with different phase for different elements. With such a solution, it would be possible to generate multiple OAM-modes.

Detection and reception of an electromagnetic field with multiple OAM modes has been discussed less, and mainly for radio astronomy detectors. For the astronomy application, a tri-axial dipole or loop antenna is used in
combination with extensive signal processing. Such antennas will exhibit poor sensitivity due to its local nature, but this is acceptable for the very limited information bandwidth in question in astronomy experiments.

A fundamental problem of an electromagnetic field with multiple OAM modes in a wireless communications link is that different OAM-modes will have their field strength maxima at different places at a cross section at the receiver.

SUMMARY

An object of the present invention is to present a solution by means of which an electromagnetic field with a multiple of OAM modes can be created and used for transmitting and receiving multiple independent channels in a wireless communication system, without requiring multiple frequency channels or multiple polarizations.

Such a solution is offered by the present invention in that it discloses a transmit antenna arrangement which comprises N antenna elements which are of the same polarization and are arranged along a circular circumference with an angular separation of a degrees between neighbouring antenna elements.

The transmit antenna arrangement comprises an Orbital Angular Momentum encoder which is arranged to receive N input signals for transmission. Let the N input signals be indexed from $M=-(N-1)/2$ up to $M=(N-1)/2$ for odd $N$ and from $M=-(N-2)/2$ up to $N/2$ for even $N$. The Orbital Angular Momentum Encoder is arranged to connect each of the N input signals to each antenna element, and to give each input signal $M$ at each antenna element a phase shift of $(M^*a)$ relative to the phase of the same input signal $M$ at an adjacent antenna element.
The term "adjacent antenna element" is here used to denote an antenna element which is adjacent in the clockwise direction as seen along the reverse direction of propagation of a field transmitted from the antenna arrangement. This direction can also be seen as the direction in which the antenna arrangement is seen by somebody standing in front of the antenna in the direction of propagation of its transmitted signals, facing the antenna.

In the transmit antenna arrangement, two or more of the antenna elements are directional and have their directivity in the same direction and have an antenna aperture of $\geq 5\lambda$, where $\lambda$ is the wavelength of the $N$ input signals.

The invention also discloses a receive antenna arrangement which comprises $N$ antenna elements of the same polarization and are arranged along a circular circumference with an angular separation of $\pm \frac{\theta}{2}$ degrees between neighbouring antenna elements.

The receive antenna arrangement is arranged to receive an incident field comprising up to $N$ different OAM-modes, here indexed from $M=-(N-1)/2$ up to $M=(N-1)/2$ for odd $N$ and from $M=-(N-2)/2$ up to $N/2$ for even $N$.

The receive antenna arrangement comprises an Orbital Angular Momentum decoder which is arranged to separate said OAM modes into $N$ output signals, by summing the received signal from each antenna element with a phase shift of $-M^\ast\alpha$ relative to a phase shift given to the received signal from an adjacent antenna element.

The term "adjacent antenna element" is for the receive antenna arrangement used to denote an antenna element which is adjacent in the clockwise direction as seen along the reverse direction of propagation of an incident field. This direction can also be seen as the direction in which the receive
antenna arrangement is seen by somebody standing behind the receive antenna arrangement looking at both the receiving antenna and a transmitting antenna.

In the receive antenna arrangement, two or more of the antenna elements are directional with their directivity in the same direction and have an antenna aperture of $\geq 5\lambda$, where $\lambda$ is the wavelength of the N input signals.

In one embodiment, the receive antenna arrangement is arranged to separate the OAM modes into N output signals by summing in each of N adders, indexed with the same M as the OAM modes, the received signal from each antenna element with said phase shift of $(-M^*a)$.

Also disclosed is a radio connection which comprises a transmit antenna arrangement as described above and a receive antenna arrangement as described above. In this radio connection, the transmit and the receive antenna arrangements are separated by a distance of $d_0$ meters, and the radio connection is arranged to operate at a wavelength of $\lambda$ meters. The circular circumference of each of the receive and transmit antenna arrangements corresponds to a diameter $D$ which fulfils the condition:

$$D \geq \frac{\sqrt{d_0\lambda N}}{2\pi}$$

It should be pointed out that the circular circumference $D$ of each of the receive and transmit antenna arrangements can either be the same or different, as long as the condition given above is fulfilled.

The invention also discloses a method for transmitting N signals, comprising arranging N antenna elements of the same polarization along a circular
circumference with an angular separation of a degrees between neighbouring antenna elements. The method comprises receiving the N input signals for transmission. The N input signals are here indexed from $M=-(N-1)/2$ up to $M=(N-1)/2$ for odd $N$ and from $M=-(N-2)/2$ up to $N/2$ for even $N$. According to the method, each of the input signals is connected to each antenna element, and each input signal $M$ at each antenna element is given a phase difference of $M^\ast a$ relative to the phase of the same input signal $M$ at an adjacent antenna element. The adjacent antenna element is adjacent in the clockwise direction as seen along the reverse direction of propagation of a transmitted field from the antenna arrangement. According to the method, two or more of the antenna elements are chosen as directional antenna elements which are arranged to have their directivity in the same direction and to have an antenna aperture of $\geq 5\lambda$, where $\lambda$ is the wavelength of the N input signals.

A method for receiving an incident field is also disclosed, with the incident field comprising up to N different OAM-modes, here indexed from $M=-(N-1)/2$ up to $M=(N-1)/2$ for odd $N$ and from $M=-(N-2)/2$ up to $N/2$ for even $N$. The method comprises utilizing N antenna elements of the same polarization arranged along a circular circumference with an angular separation of a degrees between neighbouring antenna elements. The method comprises separating the OAM modes into N output signals by summing the received signal from each antenna element with a phase shift of $(-M^\ast a)$ relative to the phase shift given to the received signal from an adjacent antenna element. The adjacent element is adjacent in the clockwise direction seen along the propagation direction of the incident field, and the method also comprises using directional antenna elements for two or more of the N antenna elements. The directional antenna elements are directional with their directivity in the same direction and have an antenna aperture of $\geq 5\lambda$, where $\lambda$ is the wavelength of the N input signals.
A method is also disclosed for establishing and operating a radio connection using the method for transmitting N signals described above together with the method for receiving an incident field comprising up to N different OAM-modes described above. The circumferences of the transmitting and receiving antenna elements are separated by a distance of $d_0$ meters, and the radio connection is made to operate at a wavelength of $\lambda$ meters. The circular circumference of each of the receiving and transmitting antenna elements correspond to a diameter $D$ and fulfils the condition:

$$D \geq \frac{\sqrt{d_0 \lambda N}}{2f}$$

BRIEF DESCRIPTION OF THE DRAWINGS

The invention will be described in more detail in the following, with reference to the appended drawings, in which

Fig 1 shows a schematic view of a first embodiment of an antenna arrangement of the invention, and
Fig 2 shows a schematic view of a second embodiment of an antenna arrangement of the invention, and
Fig 3 shows a schematic view of a decoder of the antenna arrangement of fig 2, and
Fig 4 shows a connection using the arrangements of figs 1 and 2, and
Fig 5 shows a simplified plan view of the arrangement of fig 1, and
Fig 6 shows a schematic view of an encoder of the antenna arrangement of fig 1, and

Figs 7-9 show flow charts of methods of the invention.

DETAILED DESCRIPTION
Embodiments of the present invention will be described more fully hereinafter with reference to the accompanying drawings, in which embodiments of the invention are shown. The invention may, however, be embodied in many different forms and should not be construed as being limited to the embodiments set forth herein. Like numbers in the drawings refer to like elements throughout.

The terminology used herein is for the purpose of describing particular embodiments only, and is not intended to limit the invention.

Fig 1 shows a first embodiment of an antenna arrangement 100 of the invention. The antenna arrangement 100 is arranged for transmission of electromagnetic fields, and is in fig 1 shown in a direction which faces "into" the antenna arrangement 100, i.e. the reverse direction of propagation of a signal or a field transmitted by the antenna arrangement 100.

As shown, the antenna arrangement 100 comprises a number of antenna elements, as an example of which three antenna elements 110, 115, 120 are shown in fig 1. The number of antenna elements can be varied, and the number three is only an example intended to illustrate a principle.

As shown in fig 1, the antenna elements are arranged along a circular circumference 125, and have an angular separation of a degrees between neighbouring antenna elements, i.e. the angular separation is essentially the same between two neighbouring antenna elements, so that the antenna elements 110, 115, 120 are distributed "equidistantly" along the circumference 125.

Regarding the nature of the antenna elements, they can be of various kinds, such as e.g. a horn antenna, a reflector antenna or a planar array antenna.
However, regardless of their nature, the antenna elements should be directional, i.e. non-isotropic, and have an antenna aperture of at least $5\lambda$, where $\lambda$ is the wavelength of electromagnetic signals which the antenna arrangement 100 is intended to transmit. In addition, the antenna elements should also be of the same polarization, i.e. in the case of transmitted signals, they should be arranged to transmit signals with the same polarization, e.g. horizontal, vertical, left or right. Thus, the antenna arrangement only requires one polarization. The transmission capacity of the antenna arrangement can of course also be doubled by using two directions of polarization.

As mentioned, the antenna arrangement 100 is arranged for transmissions of electromagnetic fields. In particular, the antenna arrangement 100 is arranged to receive up to $N$ input signals $S_1$-$S_N$, shown symbolically with $N=3$, as $S_1$, $S_2$ and $S_3$ in fig 1. It should be pointed out that $N$ can be a positive integer of which $N=3$ is only an example, although $N$ should be larger than or equal to 3, as in the example used here. The input signals can be at baseband level or at an intermediate frequency or at a final RF-frequency, and will typically carry data which has been modulated according to a certain modulation scheme such as AM, PM, QPSK, QAM, OFDM etc.

The antenna arrangement 100 is in particular arranged to transmit the $N$ input signals in $N$ modes with different orbital angular momentum, i.e. with $N$ OAM modes. This is accomplished in the following manner: the antenna arrangement 100 comprises an OAM encoder 105, which is arranged to have as its input the $N$ input signals, as shown in fig 1, and to output $N$ antenna feed signals, i.e. one to each antenna element. The antenna feed signals are in this text and in fig 1 denoted as $a_1$-$a_N$, where $N=3$ in the example used. In other words, the antenna arrangement should have at least
as many antenna elements as the amount of input signals SI-SN which it is intended to handle.

The OAM encoder 105 is thus adapted to encode the incoming N input signals into N antenna feed signals, each of which signal is connected to a different antenna element for transmission. As indicated in fig 1, by way of example, antenna feed signal 1, shown as $a_1$, is connected to antenna element 1, antenna feed signal 2, shown as $a_2$, to antenna element 2, etcetera.

The OAM encoder works as follows: each input signal SI-SN is used in each antenna feed signal $a_1$-$aN$, so that each antenna feed signal has a component from each input signal in it. Each antenna feed signal is connected to one of the antenna elements for transmission.

However, in each antenna feed signal, i.e. to each antenna element N, the "contribution" from each input signal is given a phase shift relative to the "contribution" from the same input signal at an adjacent antenna element, the term "adjacent" here being used to refer to an antenna element which is adjacent in the clockwise direction when looking at the antenna arrangement 100 as it is shown in fig 1. Since the antenna arrangement 100 is intended for transmission, the direction in which we are looking at the antenna arrangement 100 as it is shown in fig 1 can also be expressed as looking at the antenna in the reverse direction of propagation of a field transmitted from the antenna arrangement 100.

The phase shift is as follows: let the N input signals be indexed with the letter $M$, and let $M = -(N-1)/2$ up to $M = (N-1)/2$ for odd N and from $M = -(N-2)/2$ up to $N/2$ for even N. The indices $M$ will explicitly describe the rotation, i.e. the OAM mode number for the different modes. Let us also introduce a second
kind of index to the same signals, in that we let the N input signals also be
indexed as m=1, ..., N. This is a parallel representation with only positive
indices which are used in the figures and in the matrix description which will
follow. Let the smallest value of m correspond to the smallest value of M, the
second smallest value of m correspond to the second smallest value of M, etc.
As an example consider the 3-channel OAM-encoder in Fig 1. Input
signal S1 has m=1 and M=-1, while input signal S2 has m=2 and M=0, and
input signal S3 has m=3 and M=+1.

Use input signal M (S_m in Fig 1, where m thus is one of 1, 2 or 3) to illustrate
the principle used in the OAM encoder 105: input signal M is added with
complex value weights to each of the antenna feed signals a-i-aN which are
produced by the OAM encoder 105. Input signal M is given a phase shift
relative to when the same input signal, i.e. input signal M is fed to the
adjacent antenna element, the term "adjacent" being defined as above, i.e.
adjacent in the clockwise direction as seen along the reverse direction of
propagation of a field transmitted from the antenna arrangement. The phase
shift is M*a. In this manner, the total field transmitted by the antenna
elements will be a spiraling phase front, which is characteristic of an OAM
mode.

An example of an embodiment of the OAM encoder 105 is shown in fig 6:
The encoder 105 comprises three adders, 611, 612, 613, i.e. one adder for
each of the OAM modes which will be generated, which also coincides with
the minimum number of antenna elements. As mentioned above, in the case
of an odd number of input signals, which is the case here since N=3, the
input signals will be indexed as M=-(N-1)/2 up to M=(N-1)/2. For M=3, M will
thus range from -1 to 1. This is shown in fig 6, where the input signals S1-S3
which were shown in fig 1 have been shown with the indexes -1 for S1, 0 for
S2 and 1 for S3.
Each of the adders 611, 612 and 613 "produces" the signal which will be transmitted by one of the antenna elements \( a_1 \), \( a_2 \) and \( a_3 \) in fig 1, so that adder 611 produces the transmit signal for antenna element \( a_1 \), adder 612 produces the transmit signal for antenna element \( a_2 \), and adder 613 produces the transmit signal for antenna element \( a_3 \).

As shown in fig 6, each adder 611, 612 and 613 receives each of the input signals \( S_i \sim S_3 \), but gives them different phase shifts, as described above, and as will be described in more detail here: Taking the input signal \( S_i \) as an example, which has the index \( M=-1 \), the adder 611 gives it a phase shift of 0°, the adder 612 gives it a phase shift of -120° and the adder 613 gives it a phase shift of -240°. Since adder 611 feeds antenna element \( a_1 \), adder 612 feeds antenna element \( a_2 \) and adder 613 feeds antenna element \( a_3 \), this is consistent with the principle of the phase shifts explained previously: antenna element \( a_3 \) is the antenna element which is clockwise adjacent to antenna element \( a_i \) when looking at the antenna arrangement 100 in the reverse direction of propagation of a field which is transmitted from the antenna arrangement 100, and likewise, antenna element \( a_2 \) is the antenna element which is adjacent to antenna element \( a_3 \) in this sense, and \( a_i \) is the antenna element which is adjacent to antenna element \( a_2 \) in this sense.

The required phase shift is \( M \cdot \alpha \) relative to when the same input signal, i.e. input signal \( M \) is fed to the adjacent antenna element, adjacent in the above sense. In the example in Fig 6, for signal \( S_i \) we have \( M=-1 \), while the angular separation \( \alpha \) between the antenna elements is 120 degrees, so the phase shift between adjacent elements for signal \( S_i \) becomes \((-1 \cdot 120)\), i.e. -120 degrees. This is the required phase shift for \( a_i \) relative to that for \( a_3 \), and it is the phase shift for \( a_2 \) relative to that for \( a_1 \), and it is the phase shift for \( a_3 \) relative to that for \( a_2 \). An example fulfilling these phase shift requirements is
shown in Fig 6, where, for signal $S_1$, antenna element $a_i$ is fed with a zero (0 degrees) phase shift, antenna element $a_2$ is fed with a phase shift of -120 degrees relative to that for antenna element $a_i$, and antenna element $a_3$ is fed with a phase shift of -240 degrees relative that for antenna element $a_i$, i.e. -120 degrees relative to that of its clockwise adjacent neighbour $a_2$. Thus, each antenna element $a_i$, $a_2$, $a_3$ is fed with a phase shift of -120 degrees relative to its clockwise adjacent neighbour. It is possibly to add an arbitrary phase common to all these three elements without violating the requirements on relative phase shift.

Similarly, for signal $S_2$ we have $M=0$ which gives a required phase shift in the manner described above of (0°-120), i.e. 0 degrees, and for signal $S_3$ we have $M=+1$ which gives a required phase shift of (+1°-120), i.e. +120 degrees.

The antenna arrangement 100 of fig 1 will be described mathematically later in this text, but with reference to fig 2, an antenna arrangement 200 for reception of the OAM field transmitted by the antenna arrangement 100 will first be described.

As shown in fig 2, the antenna arrangement 200 also comprises $N$ antenna elements, with $N=3$ in the example of fig 2, referenced as 210, 215 and 220 in fig 2, all arranged to receive signals of the same polarization, i.e. all the antenna elements have the same polarization and are arranged along a circular circumference 225. It should be mentioned that the circumference of the antenna arrangement 200 of fig 2 need not be identical to that of the antenna arrangement 100 of fig 1, as will be explained in more detail later in this text. It can also be mentioned that the amount of antenna elements in the receiving and the transmitting antenna arrangements do not need to be the same, but in such a case the antenna arrangement with the smallest
amount of antenna elements will be the “bottle neck” for the transmission capacity of the total arrangement.

The antenna elements 210, 215, 220 are arranged along the circumference 225 with an angular separation of a degrees between neighbouring antenna elements. The reason that the angular separation of the antenna elements in figs 1 and 2 is shown as a in both figs 1 and 2 is that preferably the same angular separation should be used in both the transmit and receive antennas when they are used together for a radio connection. In addition, the “absolute angular positions” of the antenna elements along the circumferences of the transmit and receive antennas should also preferably be the same for optimum performance, as is shown in figs 1 and 2. This will also be discussed in more detail later, in connection with the description of fig 4.

As mentioned, the antenna arrangement 200 is arranged to receive an incident field comprising up to N different OAM-modes, i.e. an incident field such as that transmitted by the antenna arrangement 100. The antenna arrangement is arranged to receive this incident OAM field, and to “recover” from it the signals SI-SN which were input to the transmitting antenna, i.e. in this case the antenna arrangement 100. This is done in the following manner:

As shown in fig 2, the antenna arrangement 200 comprises an OAM decoder 205, which has N input ports, i.e. one for each antenna element N in the antenna arrangement 200. In fig 2, the signal received at each antenna element N is shown as bN, i.e. in this case b-i-b3. The OAM decoder 205 is arranged to “recover” the input signals SI-SN to the transmitting antenna 100 in the following manner:
Let the N OAM modes in the incident field here be indexed from \( M = \frac{-(N-1)}{2} \) up to \( M = \frac{(N-1)}{2} \) for odd \( N \) and from \( M = \frac{-(N-2)}{2} \) up to \( N/2 \) for even \( N \). The OAM decoder 205 comprises N adders, i.e. one for each OAM mode, and is arranged to separate the incident field into N output signals by summing in each of N adders, indexed with the same \( M \) as the OAM modes, the received signal from each of the antenna elements 210, 215, 220, with a phase shift of \(-M\) relative to the phase shift given to the received signal from an adjacent antenna element. The term "adjacent" here refers to an element which is adjacent in the clockwise direction as seen along the reverse direction of propagation of the incident field.

In addition, in the antenna arrangement 200, two or more of the antenna elements 210, 215, 220 are directional, i.e. non-isotropic, with their directivity in the same direction and have an antenna aperture of \( \geq 5\lambda \), where \( \lambda \) is the wavelength of the N input signals.

The concept of the adders in the decoder 205 is illustrated in fig 3, using an example in which there are 4 different OAM modes in the incident field, i.e. \( N=4 \), which means that there will be 4 adders, and 4 antenna elements in each of the transmit and receive antenna arrangements. Since \( N \) is even, it will be indexed with an \( M \) which ranges from \(- (N-2)/2 \) to \( N/2 \), i.e. from \(- (4-2)/2 \) to 2, in other words from \(-1 \) to 2.

As shown in fig 3, the OAM decoder 205 comprises four adders 211, 212, 213, 214. Taking the adder 211 as an example, this is the "first" adder in the range of \( M \) from \(-1 \) to 2, since each adder "corresponds to" one \( M \) in the range of \( Ms \). The \( M \) values in the range are here \(-1, 0, 1, 2 \).

Since \( M \) in the adder 211 is equal to \(-1 \), and the antenna elements in the antenna are spaced equidistantly, thus making \( a=90^\circ \), the phase shift
between the received signal from each of the antenna elements will here be 1°90° (the general expression being \(-M^a\)) relative to the phase shift given to the received signal from an adjacent antenna element.

Hence, as shown in fig 3, the phase shift applied to the signal from antenna element 1 (where one element is arbitrarily numbered as "1", so long as the same principle is adhered to for all of the adders in the decoder 205.) is 1°0°, and the phase increment to the phase shift which this applied to the signal from the adjacent antenna element, i.e. antenna element no. 2, is 1°90°, and to antenna element 3 is 2°90° =180°, and 3°90°=270 to the signals from antenna element no 4. After these phase shifts are applied, the signals from the different antenna elements are added, and the sum will then be a representation of the signal S1 which was input to a transmitting antenna such as the one 100 of fig 1, although comprising four antenna elements spaced 90 degrees apart.

The same principle is used in the other three adders, i.e. adders 212, 213, 214 in order to recreate signals S2-S4 which were input to a transmitting antenna such as the one 100 of fig 1, although comprising four antenna elements spaced 90 degrees apart.

Fig 4 shows a radio connection, a radio "hop" using a transmit antenna arrangement 100 as shown in fig 1 and a receive antenna arrangement 200 as shown in fig 2. The radio connection is arranged to operate at a wavelength of \(\lambda\) meters, and the transmit 100 and receive 200 antenna arrangements are separated by a distance of \(d_0\) meters. As explained above, the antenna arrangements 100, 200 both have a circular circumference which need not be the same for both antenna arrangements, i.e. one antenna arrangement can be larger than the other. However, the circular circumference of each of the receive 200 and transmit 100 antenna
arrangements corresponds to a diameter $D$, where $D$ thus can differ between the two antenna arrangements. In addition, the antenna arrangements 100, 200 should be arranged so that they are concentric, i.e. in parallel to each other. The transmit 100 and receive 100 antenna arrangements can be equipped with different amounts of antenna elements, but in such a case, in order to obtain optimum performance, the antenna arrangement with the smaller amount of antenna element should preferably have an antenna element at the other antenna arrangement in the same angular position; if this is not the case, the radio connection will still function, although with a degraded performance as compared to the case with antenna elements in the same angular positions. The expression "same angular position" here refers to a common coordinate system used for both antenna arrangements 100, 200. In other words, in a radio connection such as the one 400 in fig 4, each antenna element in one of the antenna arrangements should correspond in its angular position to an antenna element in the other antenna arrangement.

In a constellation such as the one shown in fig 4, in order to obtain good performance, it is necessary to fulfil the following condition:

$$D \geq \frac{\sqrt{d \lambda N}}{2\pi}$$  \hspace{1cm} (1)

Different values of $D$ can be used, and $D$ can also, as mentioned, differ between the two antenna arrangements. Certain values of $D$ will however give better performance than others, as will be explained in more detail later in this text. However, for antenna arrangements with 3 or 4 antenna elements, optimum performance is obtained when, using the notations of fig 4, and letting $N$ equal the amount of antenna elements, the following is the case:
\[ d_{12} - d_0 = \frac{1}{N}, \text{ or a multiple of } \frac{1}{N}, \text{ although this will lead to larger ring diameters.} \]

It should also be pointed out that in some embodiments of the invention, an antenna arrangement is disclosed which is arranged to transmit as the antenna arrangement 100 described above and to receive as the antenna arrangement 200 described above. Such an antenna arrangement is then both a transmit and a receive antenna arrangement.

A more mathematical explanation of the invention will now be given, with reference to a case such as that shown in figs 1, 2 and 4, i.e. a transmit antenna arrangement with 3 antenna elements and a receive antenna arrangement which also has 3 antenna elements. Reference will also be made to a constellation in which the transmitter and receiver antenna arrays are arranged along concentrically, with the distance between two elements in the different arrays denoted \( d_{w,i} \), where the first index, \( k \), identifies the element in the receive antenna, and the second index, \( i \), identifies the element in the transmit antenna, and to fig 5 which shows a front view a transmit antenna arrangement. The distance between element 1 and element 1 in the transmit antenna is denoted \( p_n \).

Thus, three input signals, \( S_1, S_2, S_3 \) are encoded into three antenna feed signals, \( a_1, a_2, a_3 \), and fed into a triangular array in a way such that three independent OAM-mode channels are excited. At the receiving end, the reverse decoding is done in order to recover the original bit streams. In the case of non-perfections in the geometry, even in the case of time dependent variations in the geometry, signal processing can be added to recover the individual channels.
We use an array of $N$ transmit antennas, all with the same polarization, arranged along a circle, with radius $R_t$, centered at $z=zt=0$, with the circle axis along the $z$-axis. In the simplest case there are 3 elements arranged in a regular triangle, as shown in fig 1. Similarly, we use an array of $N$ receive antennas arranged along a circle, with radius $R_r$, centered at $z=z_r=d_0$ (normalized to the wavelength), with the circle axis along the $z$-axis. All coordinates and dimensions are normalized to the wavelength in the following.

Transmitting and receiving elements are located at coordinates $T_i$ and $R_k$ respectively as follows:

$$T_i = (R_t \cdot \cos(a_i), R_t \cdot \sin(a_i), z_i)$$

$$R_k = (R_r \cdot \cos(\beta_k), r - \sin(\beta_k), z_r), \text{ with:}$$

$$\alpha_i = \alpha_1 + \frac{k - 1}{N} \cdot 2\pi, \text{ with } \alpha_i=0 \text{ in the simplest case.}$$

$$\beta_k = \frac{k - 1}{N} \cdot 2\pi.$$
where $s_m$ is the complex amplitude of the $m^{th}$ modulated signal we want to transmit and $c_{ml}$ describes the coding into OAM-vectors of propagation between the antennas.

$$c_{ml} = e^{j\varphi_{ml}}, \text{ with:}$$

$$\varphi_{ml} = \frac{2}{m} \cdot \left( \frac{N-1}{2} \cdot \frac{l-1}{N} \cdot 2\pi \right) \text{, for odd } N, \ m \in \{1..N\}, \ l \in \{1..N\}$$

$$\varphi_{ml} = \frac{2 \cdot m - N}{2} \cdot \frac{l-1}{N} \cdot 2\pi \text{, for even } N, \ m \in \{1..N\}, \ l \in \{1..N\}$$

In the mathematical explanation above, and in the following the small letter "m" is used instead of, as previously, a capital M to label the modes. M and m have a distinct relationship, defined as follows:

$$M = m - \frac{N+1}{2}, \text{ for odd } N, \ m \in \{1..N\},$$

$$M = \frac{N}{2}, \text{ for even } N, \ m \in \{1..N\},$$

For excitation of mode m we get the following complex amplitude at receiver element k:

$$b_{mk} = \sum_{l=1}^{N} H_{kl} \cdot a_{ml},$$

in which channel matrix element $H_{kl}$ describes the complex amplitude in receiver element $k$ due to unit excitation of transmitter element $l$. From the definitions in fig 4 we get:
$h_{kj} = H_0(d_0) \cdot e^{j2\pi(d_{kl} - d_0)}$, where:

$d_{kl} = |R_{kl} - T_{l}|$, and $H_0(i_{l0})$ is the element factor, which we assume describes a lobe with close to spherical wave front and negligible amplitude variation over the antenna array cross section in the opposite end. We will set $H_0(i_{l0}) = 1$, which implies that all amplitude predictions in the following will be in relation to the single element case.

When all OAM modes are simultaneously driven we get the following amplitude at the receiving element $k$:

$$w_k = \sum_m b_{mk}$$

Finally the output signal $u_n$ is formed by multiplication with the complex conjugate of the OAM-code:

$$u_n = \sum_k c_{nk}^* \cdot w_k.$$ 

Putting the expressions together, we get:

$$u_n = \sum_{m=1}^N u_{nm} \cdot s_m,$$ where:

$$u_{nm} = \sum_{k=1}^N \sum_{l=1}^N c_{nk}^* \cdot H_{kl} \cdot c_{ml} = \varepsilon_n \cdot \delta_{nm}.$$
In the last expression above, $\varepsilon_n$ are eigenvalues corresponding to the OAM-vectors. In the case of perfect positioning of the individual antenna elements, different modes will not interfere at all since they are orthogonal.

Typically one should choose $R_r=R_t=R$, and for maximum performance choose $\Delta \phi$ in relation to $R$ such as to maximize the smallest of the eigenvalues $\varepsilon_n$. It is possible to make one ring smaller and to compensate that by making the other ring larger, while maintaining the same performance.

Since orthogonality is guaranteed by the rotational symmetry it is possible to increase $\Delta \phi$ while $R$ is kept constant, but the gain will drop for some of the modes (and rise for others).

In order to find $H_{kl}$ in a specific case we first need an expression for $d_{kl} - d_0$. From the definitions in figs 4 and 5, we get:

$$p_{ll} = R^2 (l - \cos \beta) + \sin^2 \beta = 2R \cdot \sin \frac{\pi}{2},$$

which implies:

$$d_{kl} - d_0 = \frac{d_{ll}^2 - d_0^2}{d_{ll} + d_0} = \frac{p_{ll}^2}{d_{ll} + d_0} = \frac{\left(2 \cdot \sin \frac{\alpha_l}{2}\right)^2}{d_{ll} + d_0}.$$
It is possible to use several concentric circles with antenna elements. With the proper radial dependence one can increase the number of independent modes in order to increase capacity further. It is also possible to use linear combinations of OAM-modes, to get other sets of independent channels.

For non-ideal situations (in positioning and phase synchronization etc) it is possible to improve performance by using signal processing of the received and/or transmitted signals and restore orthogonality.

For 3-element and 4-element, optimum performance and the smallest possible antenna circumference is obtained when:

\[ d_{ij} - d_0 = \frac{1}{N} \], which together with the previous expression gives:

\[ R = \frac{1}{2 \cdot \sin \frac{\alpha_2}{2}} \cdot \sqrt{\frac{d_{ij} + d_0}{N}} \approx \sqrt{\frac{d_0}{2N \cdot \sin^2 \frac{\alpha_2}{2}}} \]

With this in mind, we come to the following expression for \( d_{ij} - d_0 \):

\[ d_{ij} - d_0 = \frac{\sin^2 \frac{\alpha_k}{2}}{\sin^2 \frac{\alpha_2}{2}} \cdot \frac{d_{ij} + d_0}{d_{ij} + d_0} \cdot \frac{1}{N} \approx \frac{\sin^2 \frac{\alpha_k}{2}}{\sin^2 \frac{\alpha_2}{2}} \cdot \frac{1}{N} \]

A 3-element ring is described in the following. In this case we have:

\[ p_{12} = R \sqrt{3}, p_{13} = R \sqrt{3}, \quad R = \sqrt{\frac{2 \cdot d_0}{9}} \quad \text{and} \quad d_{11} - d_0 = 0, d_{12} - d_0 = 1/3, \]

\[ d_{ij} - d_0 = 1/3 \], which gives the following:
and the following OAM-vectors:

\[
H = \begin{bmatrix}
    e^{j2\pi/3} & e^{j2\pi/3} & e^{j2\pi/3} \\
    e^{j2\pi/3} & e^{j2\pi/3} & e^{j2\pi/3} \\
    e^{j2\pi/3} & e^{j2\pi/3} & e^{j2\pi/3} \\
    e^{j2\pi/3} & e^{j2\pi/3} & e^{j2\pi/3}
\end{bmatrix}
\]

\[
c_{i1} = \begin{bmatrix}
    e^{j2\pi/3} \\
    e^{j2\pi/3} \\
    e^{j2\pi/3} \\
    e^{j2\pi/3}
\end{bmatrix},
\quad c_{2i} = \begin{bmatrix}
    e^{j2\pi/3} \\
    e^{j2\pi/3} \\
    e^{j2\pi/3} \\
    e^{j2\pi/3}
\end{bmatrix},
\quad c_{3i} = \begin{bmatrix}
    e^{j2\pi/3} \\
    e^{j2\pi/3} \\
    e^{j2\pi/3} \\
    e^{j2\pi/3}
\end{bmatrix}
\]

\[
e_1 = 3\sqrt{3} \cdot e^{j2\pi/4}, e_2 = 3\sqrt{3} \cdot e^{j2\pi/12}, e_3 = 3\sqrt{3} \cdot e^{j2\pi/12}
\]

5. A 4-element ring is described in the following. In this case we have:

\[
p_{12} = R \cdot 2\sqrt{2}, p_{13} = R \cdot 2, p_{14} = R \cdot 2\sqrt{2}, R = \frac{d_0}{4},
\]

\[
d_{11} - d_0 = 0, d_{12} - d_0 = 1/4 > d_{13} - d_0 = 2/4, d_{14} - d_0 = 1/4,
\]

which gives the following channel matrix:

\[
H_4 = \begin{bmatrix}
    e^{j2\pi/4} & e^{j2\pi/4} & e^{j2\pi/4} & e^{j2\pi/4} \\
    e^{j2\pi/4} & e^{j2\pi/4} & e^{j2\pi/4} & e^{j2\pi/4} \\
    e^{j2\pi/4} & e^{j2\pi/4} & e^{j2\pi/4} & e^{j2\pi/4} \\
    e^{j2\pi/4} & e^{j2\pi/4} & e^{j2\pi/4} & e^{j2\pi/4}
\end{bmatrix}
\]

, and the following OAM-vectors:
In addition to the transmit/receive antenna arrangements and the radio connection above, the invention also discloses methods for operating such arrangements and a radio connection.

As shown in fig 7, a method 700 for transmitting N signals comprises arranging, step 705, N antenna elements of the same polarization along a circular circumference with an angular separation of a degrees, step 710, between neighbouring antenna elements. The method comprises receiving, step 715, the N input signals for transmission, and the N input signals are here indexed from M=-(N-1)/2 up to M=(N-1)/2 for odd N and from M=-(N-2)/2 up to N/2 for even N. According to the method 700, each of the input signals is connected, step 720, to each antenna element, and each input signal M at each antenna element is given, step 725, a phase difference of M*’a relative to the phase of the same input signal M at an adjacent antenna element. The adjacent antenna element is adjacent in the clockwise direction as seen along the reverse direction of propagation of a transmitted field from the antenna arrangement. According to the method, two or more of the antenna elements are chosen, step 730, as directional antenna elements which are arranged to have their directivity in the same direction and to have an antenna aperture of ≥ 5λ.
Fig 8 shows steps of a method 800 for receiving, step 805, an incident field which comprises up to $N$ different OAM-modes, here indexed from $M=-(N-1)/2$ up to $M=(N-1)/2$ for odd $N$ and from $M=-(N-2)/2$ up to $N/2$ for even $N$. The method 800 comprises, step 810, utilizing $N$ antenna elements of the same polarization arranged along a circular circumference with an angular separation, step 815, of $\alpha$ degrees between neighbouring antenna elements. The method 800 comprises separating said OAM modes into $N$ output signals by summing, step 825, the received signal from each antenna element with a phase shift of $(-M^*\alpha)$ relative to the phase shift given to the received signal from an adjacent antenna element. The adjacent element is adjacent in the clockwise direction as seen along the propagation direction of the incident field, and the method 800 also comprises, step 830, directional antenna elements for two or more of said $N$ antenna elements. The directional antenna elements are directional with their directivity in the same direction and having an antenna aperture of $\geq 5\lambda$, where $\lambda$ is the wavelength of the $N$ input signals.

In one embodiment, the method 800 comprises separating the OAM modes into $N$ output signals by summing in each of $N$ adders, indexed with the same $M$ as the OAM modes, the received signal from each antenna element with the phase shift of $(-M^*\alpha)$.

Fig 9 shows a flowchart 950 of a method for establishing and operating a radio connection which comprises, step 955, using the method for transmitting $N$ signals described above and, step 960, the method described above for receiving an incident field comprising up to $N$ different OAM-modes. According to the method 950, as shown in step 965, the circumferences of the transmitting and receiving antenna elements are separated by a distance of $d_0$ meters. In addition, the radio connection is
arranged to operate at a wavelength of $\lambda$ meters, and the circular circumference of each of the receiving and transmitting antenna elements correspond to a diameter $D$ and fulfils, step 970, the condition:

$$D \geq \frac{d_0 \lambda N}{2\pi}$$

In one embodiment of the method 950, each antenna element in one of the circumferences is arranged to correspond in its angular position to an antenna element in the other circumference.

In one embodiment, the method 950 comprises using equal amounts of transmitting and receiving antenna elements.

In one embodiment, the method 950 comprises arranging the antenna elements along both circumferences with an equal angular spacing of a degrees between the antenna elements.

Embodiments of the invention are described with reference to the drawings, such as block diagrams and/or flowcharts. It is understood that several blocks of the block diagrams and/or flowchart illustrations, and combinations of blocks in the block diagrams and/or flowchart illustrations, can be implemented by computer program instructions. Such computer program instructions may be provided to a processor of a general purpose computer, a special purpose computer and/or other programmable data processing apparatus to produce a machine, such that the instructions, which execute via the processor of the computer and/or other programmable data processing apparatus, create means for implementing the functions/acts specified in the block diagrams and/or flowchart block or blocks.
These computer program instructions may also be stored in a computer-readable memory that can direct a computer or other programmable data processing apparatus to function in a particular manner, such that the instructions stored in the computer-readable memory produce an article of manufacture including instructions which implement the function/act specified in the block diagrams and/or flowchart block or blocks.

The computer program instructions may also be loaded onto a computer or other programmable data processing apparatus to cause a series of operational steps to be performed on the computer or other programmable apparatus to produce a computer-implemented process such that the instructions which execute on the computer or other programmable apparatus provide steps for implementing the functions/acts specified in the block diagrams and/or flowchart block or blocks.

In some implementations, the functions or steps noted in the blocks may occur out of the order noted in the operational illustrations. For example, two blocks shown in succession may in fact be executed substantially concurrently or the blocks may sometimes be executed in the reverse order, depending upon the functionality/acts involved.

In the drawings and specification, there have been disclosed exemplary embodiments of the invention. However, many variations and modifications can be made to these embodiments without substantially departing from the principles of the present invention. Accordingly, although specific terms are employed, they are used in a generic and descriptive sense only and not for purposes of limitation.
The invention is not limited to the examples of embodiments described above and shown in the drawings, but may be freely varied within the scope of the appended claims.
CLAIMS

1. A transmit antenna arrangement (100) comprising N antenna elements (110, 115, 120) of the same polarization and arranged along a circular circumference (125) with an angular separation of a degrees between neighbouring antenna elements (110, 115, 120), the antenna arrangement being characterised in that it comprises an Orbital Angular Momentum encoder (105) which is arranged to receive N input signals (S1, S2, S3) for transmission, said N input signals here being indexed from M=-(N-1)/2 up to M=(N-1)/2 for odd N and from M=-(N-2)/2 up to N/2 for even N, the Orbital Angular Momentum Encoder (105) being arranged to connect each of said N input signals (S1, S2, S3) to each antenna element (110, 115, 120), and to give each input signal M at each antenna element (110, 115, 120) a phase shift of (M\*a) relative to the phase of the same input signal M at an adjacent antenna element (110, 115, 120), said adjacent antenna element (110, 115, 120) being adjacent in the clockwise direction as seen along the reverse direction of propagation of a field transmitted from the antenna arrangement (100), in which antenna arrangement (100) two or more of said antenna elements (110, 115, 120) are directional and have their directivity in the same direction and have an antenna aperture of \( \geq 5\lambda \), where \( \lambda \) is the wavelength of the N input signals.

2. A receive antenna arrangement (200) comprising N antenna elements (210, 215, 220) of the same polarization arranged along a circular circumference (225) with an angular separation of a degrees between neighbouring antenna elements (210, 215, 220), which antenna arrangement (200) is arranged to receive an incident field comprising up to N different OAM-modes, here indexed from M=-(N-1)/2 up to M=(N-1)/2 for odd N and from M=-(N-2)/2 up to N/2 for even N, the antenna arrangement (200) being characterized in that it comprises an Orbital Angular Momentum Decoder
which is arranged to separate said OAM modes into N output signals by summing the received signal from each antenna element (210, 215, 220) with a phase shift of \(-M^*a\) relative to a phase shift given to the received signal from an adjacent antenna element (210, 215, 220), said adjacent element (210, 215, 220) being in the clockwise direction seen along the reverse direction of propagation of the incident field, in which antenna arrangement (200) two or more of said antenna elements (210, 215, 220) are directional with their directivity in the same direction and have an antenna aperture of \(\geq 5\lambda\), where \(\lambda\) is the wavelength of the N input signals.

3. The receive antenna arrangement (200) of claim 2, being arranged to separate the OAM modes into N output signals by summing in each of N adders, indexed with the same M as the OAM modes, the received signal from each antenna element with said phase shift of \(-M^*a\).

4. A radio connection (400) comprising a transmit antenna arrangement (100) of claim 1 and a receive antenna arrangement (200) of claim 2, in which the transmit (100) and receive (200) antenna arrangements are separated by a distance of \(d_0\) meters, the radio connection being arranged to operate at a wavelength of \(\lambda\) meters and being characterized in that the circular circumference of each of the receive (200) and transmit (100) antenna arrangements corresponds to a diameter D and fulfils the condition:

\[
D \geq \sqrt[3]{\frac{d_0 \lambda N}{\text{iff}}}
\]

5. The radio connection (300) of claim 4, in which each antenna element in one of the antenna arrangements (100, 200) corresponds in its angular position to an antenna element in the other antenna arrangement.
6. The radio connection (300) of claim 5, in which both the transmit (100) and the receive (200) antenna arrangements have equal amounts of antenna elements.

7. The radio connection (300) of claim 6, in which the antenna elements of both the transmit (100) and the receive (200) antenna arrangements are arranged with equal angular spacing (a) between the antenna elements.

8. A method (700) for transmitting N signals (S1, S2, S3), the method comprising arranging (705) N antenna elements (110, 115, 120) of the same polarization along a circular circumference (125) with an angular separation of a degrees (710) between neighbouring antenna elements (110, 115, 120), the method comprising receiving (715) said N input signals (S1, S2, S3) for transmission, the N input signals here being indexed from M=-(N-1)/2 up to M=(N-1)/2 for odd N and from M=-(N-2)/2 up to N/2 for even N, the method being characterized in that each of said input signals (S1, S2, S3) is connected (720) to each antenna element (110, 115, 120), and in that each input signal M at each antenna element (110, 115, 120) is given (725) a phase difference of M’a relative to the phase of the same input signal M at an adjacent antenna element (110, 115, 120), said adjacent antenna element (110, 115, 120) being adjacent in the clockwise direction as seen along the reverse direction of propagation of a transmitted field from the antenna arrangement (100), according to which method two or more of the antenna elements (110, 115, 120) are chosen (730) as directional antenna elements which are arranged to have their directivity in the same direction and to have an antenna aperture of ≥ 5λ.

9. A method (800) for receiving (805) an incident field comprising up to N different OAM-modes, here indexed from M=-(N-1)/2 up to M=(N-1)/2 for odd N and from M=-(N-2)/2 up to N/2 for even N, the method comprising (810)
utilizing N antenna elements (210, 215, 220) of the same polarization arranged along a circular circumference (225) with an angular separation (815) of a degrees between neighbouring antenna elements (210, 215, 220), the method being characterized in that it comprises separating said OAM modes into N output signals by summing (825) the received signal from each antenna element (210, 215, 220) with a phase shift of (-M * a) relative to the phase shift given to the received signal from an adjacent antenna element (210, 215, 220), said adjacent element (210, 215, 220) being in the clockwise direction seen along the propagation direction of the incident field, the method also comprising using (830) directional antenna elements for two or more of said N antenna elements, said directional antenna elements (210, 215, 220) being directional with their directivity in the same direction and having an antenna aperture of ≥ 5λ, where λ is the wavelength of the N input signals.

10. The method (800) of clam 9, comprising separating the OAM modes into N output signals by summing in each of N adders, indexed with the same M as the OAM modes, the received signal from each antenna element with said phase shift of (-M * a).

11. A method (950) for establishing and operating a radio connection (400) comprising using (955, 960) the method for transmitting N signals of claim 8 and the method for receiving an incident field comprising up to N different OAM-modes of claim 9, the method (950) being characterized in that the circumferences of the transmitting and receiving antenna elements are separated (965) by a distance of d0 meters, and in that the radio connection is arranged to operate at a wavelength of λ meters, with the circular circumference of each of the receiving (200) and transmitting (100) antenna elements corresponding to a diameter D and fulfils (970) the condition:
12. The method (950) of claim 11, in which each antenna element in one of the circumferences is arranged to correspond in its angular position to an antenna element in the other circumference.

13. The method (950) of claim 11 or 12, comprising using equal amounts of transmitting and receiving antenna elements.

14. The method (950) of any of claims 11-13, comprising arranging the antenna elements along both circumferences with an equal angular spacing (a) between the antenna elements.
FIG. 3
FIG. 6
Fig 7

1. Arrange N elements
2. α° separation
3. Receive N signals
4. Each signal to each element
5. M*α phase shift
6. Directional elements
Receive N OAM modes

N elements

$\alpha^\circ$ separation

$\sum$ phase shift ($-M^*\alpha$)

$M^*\alpha$ phase shift

Directional elements

Fig 8
Transmit N signals (800)

Receive N OAM modes (900)

Distance = \( d_0 \) meters

Diameter \( D = \frac{\sqrt{d_0 \lambda N}}{2\pi} \)

Fig 9
A. CLASSIFICATION OF SUBJECT MATTER
INV. H01Q21/20  H01Q3/40
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 practical, search terms used)

EPO-Internal , INSPEC, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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<th>Relevant to claim No.</th>
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<tr>
<td>A</td>
<td>GB 2 410 130 A (ROKE MANOR RESEARCH [GB]) 20 July 2005 (2005-07-20) page 4, line 18 - page 8, line 14 figures 1,2 abstract</td>
<td>1-14</td>
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X Further documents are listed in the continuation of Box C. X See patent family annex.

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Date of the actual completion of the international search
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13/09/2011

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Authorized officer
von Walter, Sven-Uwe

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