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(54) IMPROVEMENTS IN OR RELATING TO COMMUNICATIONS LINKS

(57) Described herein is a communications link between a radiating cable (1) and a moving vehicle having an antenna (5) which can be used in locations where space is critical, such as, in tunnels. The radiating cable (1) emits radiation in a main mode (3) at an angle θ_1 and the antenna (5) is aligned so that the axis (102) of the main lobe (6) is aligned in a direction ϕ. According to the invention, both θ_1 and ϕ are between 150° and 180°.

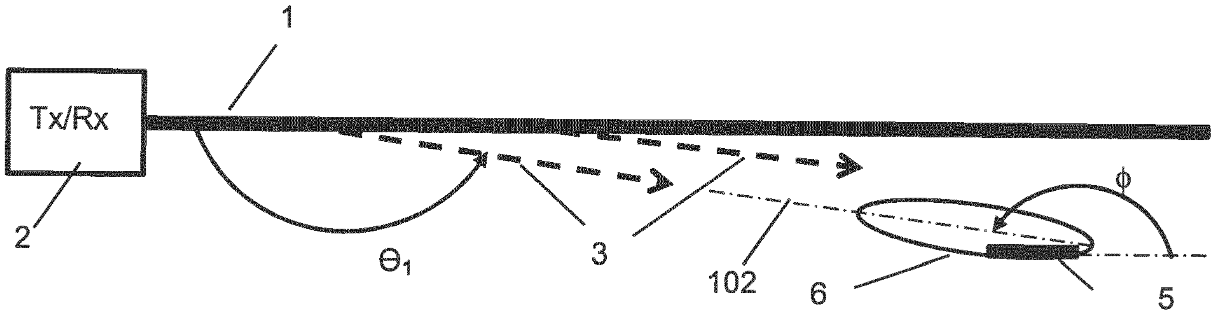

Fig. 5

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Description

Field of the invention

[0001] The present invention relates to improvements in or relating to communications links and is more particularly concerned with a method for providing wireless, short range, high throughput communication links between moving vehicles and equipment installed along the route of such vehicles.

Background of the invention

[0002] Wireless links are commonly used for communications between fixed equipment and moving vehicles such as trains, subway trains and cars. In the past, the required channel bandwidth was rather low as these wireless links were only used for voice transmission, for example, between train drivers and traffic controllers. Nowadays, wireless links are also used for transmitting and receiving control signals, video surveillance, internet access, etc. Such applications require a high data throughput and reliability, especially when safety is involved.

[0003] Wireless communications for moving vehicles can be achieved using one or more antennas mounted on each vehicle and one or more fixed antennas which are installed, for example, on masts or buildings, for providing communications coverage along the vehicle route. However, such a solution only offers limited throughput and reliability where obstacles may impair radio wave propagation.

[0004] In addition, restricting the radio coverage in a corridor along the vehicle route may be required to avoid interference with neighbouring transmitters operating at the same radio frequency. With antennas, the radio coverage cannot be restricted to a particular zone, and, the transmitted signal inevitably extends beyond the limit of the vehicle route. This inconvenience is more easily avoided if radiating cables are used instead of antennas.

[0005] Radiating cables comprise a coaxial cable comprising an inner conductor surrounded by a dielectric and an outer conductor of tubular form. The outer conductor includes apertures which generate an electromagnetic radiation. The outer conductor is covered by an insulating outer sheath.

[0006] Such radiating cables are typically used in indoor environments such as buildings and tunnels where waves radiated by antennas do not propagate well. These radiating cables can also be used outdoor in order to restrict the radio coverage in a narrow lateral corridor along a vehicle route, e.g. a railway track, a defined path in a workshop, etc., and they allow reduction of the risk of interference with neighbouring transmitters operating at the same radio frequency. Generally, one or more radiating cables are provided along the route of a moving vehicle and exchange radio signals with one antenna provided on the vehicle. Alternatively, providing several antennas on the vehicle allows improving communication reliability and throughput due to the use of more complex techniques such as transmission and/or reception diversity.

[0007] Although the use of radiating cables generally provides better radio coverage, the variations of the received signal along the vehicle route may reach 20 to 30 dB over a few wavelengths in distance.

[0008] The received signal fluctuations impair the quality of the radio channel, namely, such fluctuations increase the error rate, and they reduce the data throughput and the transmission reliability. These signal fluctuations, often called "short term fading", are due to the fact that radiating cables generally produce waves which propagate in different directions usually termed "modes". These different modes interfere with each other, either constructively or destructively, at all receiving points. The short term fading can be reduced by an appropriate radiating cable implementation which favours one (main) mode of propagation and effectively cancels (or attenuates) the secondary modes. Several solutions achieve this objective but most of them are efficient only at some distance from the radiating cable, typically, at least at a few wavelengths. At shorter distances, the received signal fluctuations may remain important, impairing the data throughput and error rate.

[0009] In all cases, the received signal fluctuations can be considerably reduced by using a directional antenna on the vehicle, provided its main lobe points in the direction of the wave emitted by the radiating cable. There exist different types of directional antennas the directivity of which would be compatible for use with some radiating cables. Unfortunately, most of them are not appropriate for use on a vehicle for various reasons (too bulky, do not resist to vibrations, aerodynamic impact, etc.). In particular, there are applications where there is not enough space available on the vehicle for bulky antennas. This is, for example, the case with small size vehicles used by conveyor systems used to transport and sort goods in workshops, luggage in airports, letters and parcels in postal sorting centres. Other examples where the available space is a critical issue are metro tunnels where the clearance between the roof of a train, on which the antenna is located, and the tunnel ceiling is very low.

[0010] Radiating cables are well known in the art, but they are rarely used with coaxial aperture antennas on vehicles. GB-A-1324180 describes a leaky coaxial type vehicle antenna whose configuration and periodicity of the array of slots in the outer conductor are substantially the same as those of the array of slots in the radiating cable. The arrays of slots on the vehicle antenna and on the radiating cable are characterized by a zigzag arrangement repeated periodically along the cable axis at an interval nearly equal to the wavelength in order that the radiated wave propagates in a direction approximately at 90° with respect to the radiating cable axis.

[0011] However, the leaky coaxial type vehicle antenna described in GB-A-1324180 is not appropriate for use in implementations where a high throughput is required, or when the vehicle antenna may come close to the radiating cable, that is, within a few wavelengths.

[0012] US-A-6091372 describes a slotted array antenna for communicating with a stationary radiating cable in a vehicle communication system where the phase velocity of the array antenna substantially matches the phase velocity of the radiating cable throughout a range of frequencies. With the solution described in US-A-6091372 the radiated wave propagates in a direction approximately at 90° with respect to the radiating cable axis and for this reason it is not appropriate for use when the vehicle antenna may come close to the radiating cable, that is, within a few wavelengths.

[0013] EP-B-1657828 describes a U-shaped slotted coaxial antenna built with two substantially parallel radiating cable lengths connected together and orientated in the longitudinal direction of the route which compensates for the location of the radiating cable either on the left side or the right side of the vehicle.

[0014] US-A- 5705967 describes a radiating line appropriate for establishing radio frequency links with mobile apparatus.

Summary of the invention

[0015] It is therefore an object of the present invention to provide a method for providing a wireless high throughput with a high reliability communication link between one or more coaxial aperture antennas installed on vehicles moving along a radiating cable in order to overcome the problems described above.

[0016] A further object of the present invention is to provide a method for providing a wireless high throughput with a high reliability communication link which can be used with one or more coaxial aperture antennas moving very close to the radiating cable, for example, at a distance of only a few centimetres.

[0017] It is also an object of the present invention to provide a compact low profile directional antenna appropriate for use on a vehicle.

[0018] It is also an object of the present invention to provide a coaxial aperture antenna with bi-directional characteristics for use on a moving vehicle.

[0019] In accordance with one aspect of the present invention, there is provided a communications link comprising:

- a radiating cable for transmitting electromagnetic radiation, having a longitudinal cable axis and comprising groups of apertures; and
- a directional coaxial aperture antenna mountable on a mobile vehicle, being operable for receiving said electromagnetic radiation transmitted by said radiating cable, configured to be substantially aligned with said radiating cable and comprising a plurality of apertures,

characterized in that the groups of apertures of the radiating cable are repeated at a constant spacing in the range of $[3.5\lambda_a, 9.1\lambda_b]$ where λ_a and λ_b are wavelength values corresponding to a frequency band of $[f_a,f_b]$ where $f_a < f_b$, in such a way that the radiating cable is able to generate a main transmission mode which has a direction of propagation at an angle between 150° and 180° to said longitudinal cable axis,
and in that the apertures of the directional coaxial aperture antenna extend over a length which is equal to or greater than $1.9\lambda_b$, in such a way that a main lobe of the directional coaxial aperture antenna is substantially aligned with the direction of propagation of said main transmission mode.

[0020] The inventors have found that a radiating cable with groups of apertures repeated at a constant spacing in the range of $[3.5\lambda_a, 9.1\lambda_b]$ generates a main transmission mode with a direction of propagation at an angle between 150° and 180° to the axis of the radiating cable. Such a main transmission mode, almost parallel to the radiating cable, provides an especially high electromagnetic field at a given power.

[0021] The inventors have also found that a directional coaxial aperture antenna with a plurality of apertures extending over a length which is equal to or greater than $1.9\lambda_b$ has a main lobe at an angle between 150° and 180° to the axis of the directional coaxial aperture antenna. Therefore, with the radiating cable and the directional coaxial aperture antenna substantially parallel, the main transmission mode of the radiating cable is substantially aligned with the main lobe of the antenna. As a consequence, the effect of the secondary modes is strongly attenuated.

[0022] By providing a main transmission mode which is at an angle between 150° and 180° to said longitudinal cable axis, it is possible to provide a communications link which is more robust against the variations of antenna position relative to the radiating cable.

[0023] In addition, such a communications link can be used in any environment, particularly, where the coaxial aperture antenna moves at a distance which is within a few centimetres of the radiating cable.

[0024] The use of a directional coaxial aperture antenna makes the antenna especially suitable for vehicle since it is aerodynamic and easy to integer in the vehicle parallel to its main motion direction. Moreover, the directional coaxial aperture antenna is especially reliable and compact.

[0025] In accordance with one aspect of the present invention, there is provided a communications link comprising:-

at least one radiating cable for transmitting electromagnetic radiation, each radiating cable having a longitudinal cable axis; and

at least one directional coaxial aperture antenna mountable on a mobile vehicle, said at least one directional coaxial aperture antenna being configured to be substantially aligned with said radiating characteristics of said radiating cable with a main lobe of said at least one antenna being aligned with said main transmission mode of the radiating cable and being operable for receiving said signals transmitted by said at least one radiating cable;

characterised in that radiating characteristics of said at least one radiating cable generates a main transmission mode which is at an angle between 150° and 180° to said longitudinal cable axis.

[0026] Each radiating cable may include groups of apertures repeated at a constant spacing in the range of [$3.5\lambda_a$, $9.1\lambda_b$] where λ_a and λ_b are wavelength values corresponding to a frequency band of [f_a,f_b] where $f_a < f_b$.

[0027] Each directional coaxial aperture antenna may include a plurality of apertures extending over a length which is equal to or greater than $1.9\lambda_b$.

[0028] In one embodiment, said radiating characteristics of said at least one radiating cable and said at least one directional coaxial aperture antenna operate at a frequency in a range between 5150MHz and 5850MHz. In other words, in this embodiment, f_a is equal to 5150MHz and f_b is equal to 5850MHz.

[0029] Said at least one directional coaxial aperture antenna may comprise an antenna longitudinal axis and a plurality of transverse apertures equally spaced along its length, the number of transverse apertures and their spacing being proportional to the wavelength of electromagnetic radiation to be transmitted or received.

[0030] One advantage which is achieved with the present invention is that said coaxial aperture antenna on the vehicle features a directivity which can be easily tailored to match the directional characteristics of the radiating cable and requires very little space.

[0031] Said transverse apertures may be identical.

[0032] In another embodiment, said plurality of transverse apertures defines a symmetrical tapered profile.

[0033] In one embodiment, said plurality of transverse apertures has different widths, at least one central transverse aperture having a first width value with other transverse apertures extending outwards on either side of said at least one central transverse aperture, said other transverse apertures having width values which are less than the first width value and which decrease symmetrically, on each side, in value from said at least one central transverse aperture. There may be one or more central apertures.

[0034] In another embodiment, said plurality of transverse apertures has different lengths, said at least one central transverse aperture having a first length value with other transverse apertures extending outwards on either side of said at least one central transverse aperture, said other transverse apertures having length values which are less than the first length value and which decrease symmetrically, on each side, in value from said at least one transverse aperture.

[0035] In a further embodiment, at least one transverse central aperture is perpendicular to said longitudinal axis and said other transverse apertures on either side thereof are angled with respect to said at least one central transverse aperture, said other angled transverse apertures having increasing angles with respect to said at least one central aperture on either side thereof.

[0036] Said other angled transverse apertures may be arranged to be identical on either side of said at least one transverse central aperture. Alternatively, said at least one central aperture defines an axis of mirror symmetry about which said other angled transverse apertures extend outwardly on either side of said at least one central transverse aperture, said other angled transverse apertures having decreasing angles with respect to said longitudinal axis.

[0037] In addition to or instead of the varying widths, lengths and angles of the transverse apertures, the directional coaxial aperture antenna may further comprise at least one shield operable for covering at least one of said transverse apertures.

[0038] In one embodiment, said at least one directional coaxial aperture antenna comprises a uni-directional antenna. In this case, the antenna receives radiation from or transmits radiation to the radiating cable. It will be appreciated that the reception and transmission of radiation refers to the reception and transmission of signals between the antenna and the radiating cable. This embodiment is useful where the transceiver on the moving vehicle always transmits/receives signals to/from the same direction (that is, either to/from the front or to/from the back of the vehicle).

[0039] In another embodiment, said at least one directional coaxial aperture antenna comprises a bi-directional antenna. This embodiment is useful where the transceiver on the moving vehicle has to transmit/receive signals to/from any direction (that is, both to/from the front and to/from the back of the vehicle).

[0040] Said at least one directional coaxial aperture antenna may operate using linearly polarized radiation or may operate with circularly (or elliptically) polarized radiation.

[0041] Another advantage achieved with the present invention is the minimum physical cross section, the low profile and the negligible aerodynamic impact of said coaxial aperture antenna.

[0042] Still another advantage of this invention is the broadband characteristic of said coaxial aperture antenna.

[0043] Still another advantage of this invention is the possibility to provide bi-directional coaxial aperture antennas.

[0044] Still another advantage of this invention is the possibility to easily tailor the field pattern of said coaxial aperture antenna to the directional characteristics of a wide range of radiating cables.

[0045] Still other advantages of said coaxial aperture antenna according to the present invention is its low cost, its robustness, its ability to be used in harsh environment (i.e. with vibrations, humidity, moisture, dust, high and low temperature, etc.).

Brief description of the drawings

[0046] For a better understanding of the present invention, reference will now be made, by way of example, to the accompanying drawings in which:-

Figure 1 illustrates schematically a conventional radiating cable with its main mode;
Figure 2 illustrates schematically a conventional radiating cable with both its main mode and its secondary mode;
Figure 3 illustrates the directionality of the main lobe of a directional antenna;
Figure 4 illustrates schematically a first embodiment of a uni-directional linear polarization coaxial aperture antenna in accordance with the present invention;
Figure 5 illustrates schematically the main mode of a radiating cable and the main lobe of a directional antenna;
Figure 6 illustrates schematically how the radiations from the aperture configuration contribute to the directivity of the antenna;
Figure 7 illustrates schematically a first embodiment of an aperture configuration for the directional antenna of Figure 4;
Figures 8 and 9 illustrate array factor against elevation angle ϕ in an axial half plane located above the aperture configuration of Figure 7 at 5850MHz and 5150MHz respectively;
Figure 10 is similar to Figure 7 but illustrates schematically a second embodiment of an aperture configuration for the directional antenna of Figure 4;
Figure 11 illustrates array factor against the elevation angle ϕ in an axial half plane located above the aperture configuration of Figure 10 at 5850MHz;
Figure 12 is similar to Figure 7 but illustrates schematically a third embodiment of an aperture configuration for the directional antenna of Figure 4;
Figure 13 is similar to Figure 12 but illustrates schematically a fourth embodiment of an aperture configuration for the directional antenna of Figure 4;
Figure 14 illustrates array factor against elevation angle ϕ in an axial half plane located above the aperture configuration of Figure 13 at 5850MHz;
Figure 15 is similar to Figure 13 but illustrates schematically a fifth embodiment of an aperture configuration for the directional antenna of Figure 4;
Figure 16 illustrates array factor against elevation angle ϕ in an axial half plane located above the aperture configuration of Figure 15 at 5850MHz;
Figure 17 is similar to Figure 10 but illustrates schematically a sixth embodiment of an aperture configuration for the directional antenna of Figure 4;
Figure 18 illustrates schematically a seventh embodiment of an aperture configuration in accordance with the present invention;
Figure 19 is similar to Figure 18 but illustrates schematically an eighth embodiment of an aperture configuration for the directional antenna of Figure 4;
Figures 20a and 20b illustrate schematically one embodiment of an antenna comprising a shield located over a portion of the aperture configuration for the directional antenna of Figure 4;
Figures 21 a and 21 b are similar to respective ones of Figures 20a and 20b but illustrating a second embodiment of a shield located over a portion of the aperture configuration for the directional antenna of Figure 4;
Figures 22a and 22b are similar to respective ones of Figures 20a and 20b but illustrating a third embodiment of a shield located over a portion of the aperture configuration for the directional antenna of Figure 4;
Figures 23a and 23b are similar to respective ones of Figures 20a and 20b but illustrating a fourth embodiment of a shield located over a portion of the aperture configuration for the directional antenna of Figure 4;
Figures 24a to 24c illustrate various cable-antenna relative positions;
Figures 25a and 25b schematically illustrate how circular (or elliptical) polarization is achieved;
Figure 26a and 26b schematically illustrate an embodiment of an aperture configuration for a directional antenna

which achieves circular polarization;
Figure 26c is similar to Figure 26b but for a spacing of $d_{270°}$;
Figure 27 illustrates schematically the effect of a spacing of $d_{90°}$ to produce circular (elliptical) polarisation;
Figure 28 schematically illustrates an embodiment of an aperture configuration for a directional antenna which achieves circular polarization;
Figure 29 illustrates an embodiment where there are two radiating cable sections;
Figure 30 illustrates an embodiment achieving bi-directionality by using two antenna elements connected to a power splitter;
Figure 31 illustrates an embodiment achieving bi-directionality by using transceivers working in Multiple Input - Multiple Output (MIMO) scheme;
Figures 32a and 32b respectively illustrate a bi-directional antenna embodiment for linear polarization and for circular (or elliptical) polarization;
Figure 33 illustrates a variation of Figure 32a;
Figure 34a and 34b illustrate bi-directional antenna embodiments where there is no matching load;
Figure 35a and 35b are similar to Figures 34a and 34b but with only one connector; and
Figure 36 schematically illustrates a radiating cable and a mobile vehicle involved in an embodiment of the invention.

Description of the invention

[0047] The present invention will be described with respect to particular embodiments and with reference to certain drawings but the invention is not limited thereto. The drawings described are only schematic and are non-limiting. In the drawings, the size of some of the elements may be exaggerated and not drawn on scale for illustrative purposes.

[0048] In the context of the present invention, the vehicles may be trains, subway trains, cars, carriages, containers or any conveyor systems used for the transport of people, animals or goods. Such vehicles exchange radio signals with fixed equipment provided along their route, even when they move.

[0049] In accordance with the present invention, at least one radiating cable generates radiation in a direction which is at an angle of between 150° and 180° to its longitudinal axis.

[0050] The term "radiating cable" as used herein refers to a coaxial cable having an inner conductor surrounded by a dielectric and an outer conductor with an outer insulating sheath. Such a coaxial cable has a generally tubular form with a longitudinal cable axis. The outer conductor is configured to define a plurality of apertures along its length which are spaced at a predetermined distance apart through which radiation is generated. It will readily be appreciated that the properties of the apertures define radiating characteristics of the radiating cable.

[0051] A coaxial aperture antenna is generally tubular and comprises an inner conductor surrounded by a dielectric layer, an outer conductor and an insulating outer sheath. The outer conductor includes a plurality of transverse apertures equally spaced along its length and by way of which radiation is transmitted or received.

[0052] In accordance with the present invention, coaxial aperture antennas feature two different directivities and two different polarizations which provide four possible combinations. These four possibilities are identified as follows:

1) uni-directional linear polarization coaxial aperture antenna: it is a directional antenna which has one main lobe and which generates a linear polarization;
2) uni-directional circular polarization coaxial aperture antenna: it is a directional antenna which has one main lobe and which generates a circular or elliptical polarization;
3) bi-directional linear polarization coaxial aperture antenna: it is a directional antenna which has two main lobes orientated in nearly opposite directions and which generates a linear polarization; and
4) bi-directional circular polarization coaxial aperture antenna: it is a directional antenna which has two main lobes orientated in nearly opposite directions and which generates a circular or elliptical polarization.

[0053] The terms "coaxial aperture antenna according to the invention" and "antenna according to the invention" as used herein refer generally to all four antenna types described above. When this is not the case, the specific antenna type will be given.

[0054] A directional coaxial antenna comprises an antenna longitudinal axis with a plurality of transverse apertures arranged therealong, the number and spacing of the transverse apertures depending on the wavelength of electromagnetic radiation to be transmitted or received.

[0055] The term "transverse aperture" as used herein refers to an aperture or slot which extends at an angle to the antenna longitudinal axis. In some embodiments, the strict literal meaning of the term transverse is applied, that is, perpendicular to the antenna longitudinal axis, but, in other embodiments, the strict literal meaning does not apply, that is, the apertures are at an angle between 0° and 90° to the antenna longitudinal axis.

[0056] In addition, in the following description of the present invention, it is assumed that the wireless link uses radio signals in the $[f_a,f_b]$ frequency band (with $f_a < f_b$). These frequencies f_a and f_b (in MHz) are linked to the corresponding wavelengths in the air λ_a and λ_b by

$$\lambda_a = \frac{300}{f_a} \text{ and } \lambda_b = \frac{300}{f_b} \text{ with } \lambda_a > \lambda_b \quad (1)$$

[0057] The objects of the present invention can be accomplished by providing :

along the moving vehicle route, a radiating cable in which the outer conductor includes groups of apertures, which are reproduced with a constant spacing *s*, in the range $[3.5\lambda_a, 9.1\lambda_b]$; and
on the moving vehicle, one or more coaxial aperture antennas which comprise an inner conductor surrounded by a dielectric and an outer conductor of tubular form which includes at least one plurality of transverse apertures extending over a length greater than or equal to $1.9\lambda_b$, the outer conductor being covered by an insulating outer sheath.

[0058] The characteristics of the radiating cable and coaxial aperture antenna used in the present invention are described hereafter. Although both the radiating cable and the coaxial aperture antenna can transmit and receive radio waves, it is be noted that, for simplification purposes, only one transmission direction is described below. However, it will readily be understood that the description below will also apply to each transmission direction. Therefore, when the radiating cable is being described, it will be described as transmitting and the vehicle antenna will be described as receiving. Similarly, when the vehicle antenna is being described, it will be described as transmitting and the radiating cable will be described as receiving.

[0059] The radiating cable radiation characteristics are mostly determined by the type of apertures in the outer conductor and the aperture spacing. The present invention requires cables known as "radiated mode cables" in which the outer conductor includes groups of apertures which are reproduced with a constant spacing s, this spacing being several times the wavelength of the radiated signal.

[0060] There also exists cables in which the total length of the outer conductor includes apertures separated by a distance considerably shorter than the wavelength of the radiated signal. One characteristic of these cables is the large received signal fluctuations when the receiving antenna is moved along a path parallel to the cable. For this reason, these cables are not suitable for the present invention.

[0061] Figure 1 illustrates a conventional arrangement in which a radiating mode cable 1 is fed by a transceiver 2 at one end. It is known by those having ordinary skill in the art that such a cable generates a main mode, as indicated by dotted lines 3, which propagates in a direction forming an angle θ_1 with the cable axis lying between 0° and 180°; this angle is given by

$$\theta_1 = arcos\left(\frac{\lambda}{s} - \sqrt{\varepsilon_{rc}}\right) \quad (2)$$

where:

θ_1 is the propagation direction of the main mode with respect to the direction of the cable end connected to the transceiver;
s is the radiating cable aperture group spacing;
λ is the signal wavelength in air; and
ε_{rc} is the relative dielectric constant of the insulator between the radiating cable inner and outer conductors.

[0062] With the dielectric usually used, $\sqrt{\varepsilon_{rc}}$ generally lies between ≅ 1.11 and ≅ 1.15.

[0063] A radiated mode cable operates in this way at wavelengths less than $\lambda_{\theta 1\text{-}0°}$ where $\lambda_{\theta 1\text{-}0°}$ is the wavelength (in the air) corresponding to θ_1 = 0° and which is given by

$$\lambda_{\theta 1-0^\circ} = \left(1 + \sqrt{\varepsilon_{rc}}\right)s \quad (3)$$

[0064] This wavelength $\lambda_{\theta 1\text{-}0°}$ is linked to the frequencies $f_{\theta 1\text{-}0°}$ (in MHz) by

$$f_{\theta 1-0^\circ} = \frac{300}{\lambda_{\theta 1-0^\circ}} \quad (4)$$

[0065] However, as illustrated in Figure 2, it is also known that, when the frequency is greater than or equal to $2f_{\theta 1\text{-}0^\circ}$, there is a secondary mode 4 propagating in a direction θ_2 which is different to θ_1. As before, the radiating cable 1 is connected to a transceiver 2 and generates a main mode 3 as well as the secondary mode 4. If the secondary mode is not cancelled by appropriate means, it interferes with the main mode resulting in large field strength fluctuations.

[0066] According to equation (2) above, $\theta_1 \cong 93°$ or 94° when $f = 2f_{\theta 1\text{-}0^\circ}$ for any $\sqrt{\varepsilon_r}$ lying between $\cong 1.11$ and $\cong 1.15$. If f continues to increase, a third mode appears when $f = 3f_{\theta 1\text{-}0^\circ}$ and so on for all the $f_{\theta 1\text{-}0^\circ}$ multiples. As a consequence, the higher the frequency, the more numerous are the secondary modes, all propagating in different directions θ_k given by

$$\theta_k = arcos\left(\frac{k\lambda}{s} - \sqrt{\varepsilon_{rc}}\right) \text{ with } k = 2, 3, \text{etc.} \quad (5)$$

[0067] These interferences between the main and secondary modes result in large received signal fluctuations along the cable. Several solutions have been proposed to cancel or to reduce the intensity of the secondary modes, at least on a frequency band from $2f_{\theta 1\text{-}0^\circ}$ to $nf_{\theta 1\text{-}0^\circ}$ where n depends on the efficiency of the solution. However, although the intensity of the secondary modes can be significantly attenuated, some of them could still be present, at least at a certain level, and they would interfere with the main mode causing received signal variations.

[0068] As illustrated in Figure 3, the use of a directional antenna 5 on a vehicle (not shown) rejects, at least partly, the effect of the secondary modes provided its lobe 6 substantially points in the direction of the main mode 3. As before, the radiating cable 1 is connected to a transceiver 2 and generates, in addition to the main mode 3, secondary modes 4. In addition, when propagating between the radiating cable and the vehicle antenna, the main mode experiences multipath due to the reflections on ground, walls, ceiling, surrounding objects, etc. These multipaths also cause received signal variations. With the directional antenna pointing in the direction of the main mode, the effect of the multipath is reduced as well.

[0069] It will readily be understood that the terms "multipath" and "multipaths" refer to signals which are received as echoes or time delayed signals due to reflections as described above.

[0070] In addition, by using a directional antenna orientated in the direction of the desired radio signal on the vehicle reduces the level of interfering signals emitted by neighbouring transmitters operating at the same frequency. This feature contributes to improve the transmission reliability.

[0071] As described in EP-B-1742298, radiated mode cables may radiate a stronger electromagnetic field if they are designed so that the main mode propagates in a direction θ_1 lying between 150° and 180°.

[0072] Thus, setting θ_1 = 150° in equation (2) yields

$$\cos 150° = \frac{\lambda_a}{s} - \sqrt{\varepsilon_{rc}} \quad (6)$$

[0073] As cos 150° = - 0.866, $\theta_1 \geq 150°$ for frequencies $\geq f_a$ provided that:

$$s \geq \frac{\lambda_a}{\sqrt{\varepsilon_{rc}} - 0.866} \quad (7)$$

[0074] As $\sqrt{\varepsilon_{rc}}$ lies in the interval [1.11, 1.15], the minimum radiating cable apertures group spacing is obtained for $\sqrt{\varepsilon_r} = 1.15$. Then, equation (7) yields:

$$s \geq \frac{\lambda_a}{0.284} \cong 3.5\lambda_a \quad (8)$$

[0075] If $\sqrt{\varepsilon_r}$ differs from 1.15, the minimum apertures group spacing should be calculated with equation (7).

[0076] There is a second condition which requires that θ_1 is less than 180° in the [f_a,f_b] frequency band. This is the case if

$$\cos 180° \leq \frac{\lambda_b}{s} - \sqrt{\varepsilon_{rc}} \qquad (9)$$

[0077] As cos 180° = - 1, equation (9) becomes

$$s \leq \frac{\lambda_b}{\sqrt{\varepsilon_{rc}}-1} \qquad (10)$$

[0078] Depending on the exact value of $\sqrt{\varepsilon_r}$ in the [1.11, 1.15] interval, the maximum apertures group spacing *s* must be in the [6.7λ_b, 9-1λ_b] range.

[0079] As there are numerous values which satisfy the conditions of equations (7) and (10), s can be chosen to avoid having resonant frequencies in the bands of interest.

[0080] The example described below shows how to calculate the spacing *s* for a radiating cable optimized for the frequency band allocated to Wireless Local Area Network (WLAN) which extends from 5150MHz to 5850MHz. It will be assumed that the radiating cable has a dielectric whose $\sqrt{\varepsilon_{rc}} = 1.13$. The wavelengths, in air, λ_a and λ_b are respectively 5.8cm and 5.1cm. A spacing *s* within the range [≅22cm, ≅39cm] satisfies the conditions of equations (7) and (10).

[0081] For example, for a spacing where s equals 32cm, θ_1 varies between 161.6° and 166.1 in the frequency band from 5150MHz to 5850MHz. It will be appreciated that this characteristic can be achieved for other frequency bands by changing the spacing between the groups of apertures in the radiating cable.

[0082] Radiating cables where the outer conductor includes groups of apertures reproduced with a constant spacing *s* which satisfies the conditions of equations (7) and (10) generates, at wavelengths in the range [λ_a, λ_b], a main mode which propagates in a direction forming an angle θ_1 with the longitudinal axis of the cable which lies between 150° and 180°. Secondary modes may also be generated and which could destructively interfere with the main mode resulting in impaired transmission quality. The effect of insufficiently attenuated secondary modes can be reduced or cancelled with the use, on a vehicle, of a directional antenna 5 the main lobe 6 of which substantially points toward the radiating cable main mode as shown in Figure 3.

[0083] There exist many different types of directional antennas. Unfortunately, most of them are not appropriate for use on a vehicle for various reasons (too bulky, do not resist to vibrations, aerodynamic impact, etc.). In accordance with the present invention, a compact low profile directional antenna appropriate is provided for use on a vehicle. This directional antenna can be easily tailored in order that:

- its main lobe is substantially orientated in the direction of the radiating cable main propagation mode;
- the secondary modes which are insufficiently attenuated are reduced or cancelled.

[0084] Such a low profile directional antenna comprises a coaxial aperture antenna including an inner conductor extending over a certain length surrounded by a dielectric and an outer conductor of tubular form. The outer conductor includes at least one plurality of transverse apertures which generate an electromagnetic radiation. The outer conductor is covered by an insulating outer sheath. One end is provided with a connector used for feeding the antenna with the signal from the transmitter. The other antenna end can be either open or short circuited, or provided with a connector alone, or provided with a connector and a load which matches the characteristic impedance of the short coaxial line formed by the inner and outer conductor.

[0085] Such a coaxial aperture antenna can be manufactured at rather low cost with a commercially available coaxial cable in which the apertures have been machined in the outer conductor. Alternatively, the apertures can also be made by piercing the outer conductor before it is placed around the dielectric.

[0086] The type of apertures in the outer conductor and their orientation with respect to the antenna longitudinal axis controls the polarization of the radiated signal, and, the number of apertures and their size control the radiated field strength when the coaxial aperture antenna is transmitting. The length of the plurality of apertures in the antenna outer conductor also determines the angle of the aperture of the main lobe of the antenna when the coaxial aperture antenna is receiving.

[0087] The general principle of one embodiment of a uni-directional linear polarization coaxial aperture antenna 100 is shown in Figure 4 where an outer sheath has been removed so that outer conductor 7 is visible. This outer conductor 7 includes one plurality of N equally spaced identical transverse apertures 8 arranged in a line which is parallel to the antenna longitudinal axis 101, the spacing between the apertures 8 being denoted by d. A connector 9 is provided at each end of the antenna 100. One connector is used for feeding the antenna with a signal from a transceiver 10. A matching load 11 (typically having an impedance of approximately 50Ω) is mounted to the other connector at the other end of the antenna 100 as shown. As a result, a signal fed by the transceiver 10 propagates in the antenna and the fraction of energy which has not been radiated by the apertures is then fully absorbed in the matching load 11.

[0088] In Figure 5, as previously described with reference to Figures 1 to 3, a radiating cable 1 is connected to a transceiver 2 and from which a main mode 3 propagates in a direction θ_1 with respect to a longitudinal axis of the radiating cable 1. A coaxial aperture antenna 5 mounted on a vehicle (not shown) is assumed to have its longitudinal axis substantially parallel to the radiating cable 1. The coaxial aperture antenna 5 can be positioned to be either below or above the radiating cable 1, but in the present embodiment, it is shown to be below the radiating cable. Typically, the radiating cable and the antenna can be separated by a distance ranging from a few centimetres to several metres.

[0089] It will readily be appreciated that the antenna 5 can also be positioned to be side by side with the radiating cable, but not necessarily at the same height.

[0090] As shown in Figure 5, the main lobe 6 of the antenna 5 has its axis 102 substantially aligned with the propagation direction of the main mode 3 of the radiating cable 1 which is at an angle of θ_1 with respect to the longitudinal axis of the radiating cable (not shown but described above).

[0091] As a result, in a plane defined by the longitudinal axis of the radiating cable and the longitudinal axis 101 of the antenna, any direction referenced by θ (measured with respect to the radiating cable axis) can also be referenced by the elevation angle ϕ (measured with respect to the antenna longitudinal axis 101). It is obvious that θ and ϕ are equal for any direction in the above defined plane as the longitudinal axis of the radiating cable and the longitudinal axis 101 of the antenna are parallel.

[0092] The plurality of N equally spaced identical apertures 8 of the antenna 100 described with reference to Figure 4 may be considered to be equivalent to a linear array of N sources of equal amplitude and spacing. In Figure 6, the antenna 100 of Figure 4 is shown schematically where the directions of the radiations emitted by the different apertures in the direction of the elevation angle ϕ are indicated by dotted arrows 12. As described above, the apertures 8 are spaced by a distance d.

[0093] In a half plane above the apertures 8, at a distant point in the direction forming an angle ϕ with the coaxial aperture antenna axis 101 (where ϕ = 0° effectively corresponds to the direction of the end of the antenna connected to the transceiver 10), the phase difference ψ (in radians) of the wave radiated by two adjacent apertures is given by

$$\psi = 2\pi \frac{d}{\lambda}\left(\sqrt{\varepsilon_{ra}} + cos\phi\right) \tag{11}$$

where:

d is the coaxial antenna aperture spacing; and

$\sqrt{\varepsilon_{ra}}$ is the coaxial aperture antenna relative dielectric constant With the dielectric usually used, $\sqrt{\varepsilon_{ra}}$ generally lies between ≅1.11 and ≅1.15.

[0094] If the normalized field pattern is the field strength divided by its maximum value in the half plane above the apertures, the normalized field pattern of a linear array of N isotropic sources of equal amplitude and spacing is given by

$$\frac{1}{N}\left|\frac{sin\,N\psi/2}{sin\psi/2}\right| \tag{12}$$

referred to hereinafter as "array factor".

[0095] The field pattern of a plurality of apertures comprising an array of N identical equally spaced apertures is obtained by multiplying the aperture field pattern by the array factor as given in equation (12). The maximum value of equation (12) approaches 1 when $\psi/2$ approaches 0.

[0096] It is clear however from equation (11) that $\psi/2$ never reaches 0 because $\sqrt{\varepsilon_{ra}}$ is greater than 1 and cos ϕ is greater than or equal to -1. However, the minimum value of $\psi/2$ is attained when cos ϕ = -1, that is, when ϕ =180°. Consequently, the maximum value of the array factor as defined by equation (12) is reached for ϕ = 180°.

[0097] As ϕ decreases from 180°, $\psi/2$ increases and the numerator of equation (12) becomes equal to 0 when

$$\frac{N\psi}{2} = k\pi \text{ with } k = 1, 2, 3, \text{etc.} \quad (13)$$

[0098] As $\psi/2$ never reaches 0, N $\psi/2$ is never cancelled and this is why $k = 0$ is not considered in equation (13). Consequently, N $\psi/2 = \pi$ is actually the null direction with the highest angle for ϕ (the numerator of equation (12) cancels but its denominator, equal to sin π/N, does not). This first null of the array factor occurs for an angle ϕ_0 given by

$$\frac{N\psi}{2} = N\pi\frac{d}{\lambda}\left(\sqrt{\varepsilon_{ra}} + cos\phi_0\right) = \pi \quad (14)$$

[0099] Rearranging equation (14), the product *Nxd* is given by

$$Nxd = \frac{\lambda}{\sqrt{\varepsilon_{ra}}+\cos\phi_0} \quad (15)$$

[0100] It is to be noted that A and ε_{ra} are known. Thus, the array factor starts at its maximum for ϕ = 180° and drops to zero when ϕ attains ϕ_0.

[0101] According to the present invention, this angle ϕ_0 should be chosen so as the array factor:

- is as low as possible in the direction of the remaining radiating cable secondary modes;
- is as high as possible (that is, as close to 1 as possible) in the direction of the radiating cable main mode.

[0102] The angle ϕ_{3dB} corresponding to a 3dB attenuation with respect to the array factor maximum is linked to ϕ_0 by equation (16) below which has been inferred from numerical simulations.

$$\phi_{3dB} \cong 81° + 0.55\phi_0 \quad (16)$$

[0103] According to the present invention, the radiating cable is designed in order that the main mode propagates in a direction θ_1 which lies between 150° and 180° to the longitudinal axis of the radiating cable as described above. For the embodiment shown in Figure 5, the value of ϕ_{3dB} should be chosen substantially equal to 150° in order that the main mode attenuation is less than or equal to 3dB.

[0104] From equation (16), this requires that

$$\phi_0 \cong \frac{150-81}{0.55} \cong 125° \quad (17)$$

[0105] As $\sqrt{\varepsilon_{ra}}$ lies in the range [1.11, 1.15] and $\lambda_a > \lambda_b$, introducing this into equation (15) gives

$$Nxd = \frac{\lambda}{\sqrt{\varepsilon_{ra}}+\cos 125°} \geq \frac{\lambda_b}{1.11-0.57} \cong 1.9\lambda_b \quad (18)$$

[0106] The length of the plurality of apertures of a coaxial aperture antenna according to the present invention is greater than or equal to $1.9\lambda_b$.

[0107] If at the lowest frequency f_a used by the wireless link, the main mode propagates in a direction where θ_1 is greater than 150°, ϕ_0 can be chosen to be greater than 125° to provide a lower value for cos ϕ_0. Then equation (15) yields a higher *Nxd* product.

[0108] An additional condition is that the denominator of equation (12) does not cancel when ϕ varies from ϕ_0 to 180°. Otherwise, at least one strong secondary lobe would appear.

[0109] As $\psi/2$ never cancels, the first zero of the denominator of equation (12) occurs for $\frac{\psi}{2} = \pi$. In particular, it is desirable that the denominator absolute value is not too low, that is to say, greater than 0.7, when $\phi = 0°$ in order that the antenna side lobes amplitude decreases as ϕ decreases from ϕ_0 to 0°. This will be the case if $\psi/2 \leq 3\pi/4$ when $\phi = 0°$. Replacing $\psi/2$ and ϕ by these values in equation (11) yields

$$\mathrm{d} \leq \frac{3}{4}\frac{\lambda}{\sqrt{\varepsilon_{ra}}+1} \qquad (19)$$

[0110] With $\sqrt{\varepsilon_{ra}}$ lying in the [1.11, 1.15] range and as $\lambda_a > \lambda_b$, the condition $\psi/2 \leq 3\pi/4$ is satisfied if the aperture spacing is less than or equal to d_{max} where d_{max} is given by

$$\mathrm{d}_{max} = 0.35\lambda_b \qquad (20)$$

[0111] The aperture spacing d and the length of the plurality of apertures are two parameters which determine the directivity of the array factor. For a coaxial aperture antenna according to the present invention, these two parameters must be determined as follows:

- the maximum aperture spacing d_{max} is determined in accordance with equation (20); and
- the *Nxd* product in equation (21) enables the calculation of the minimum number of apertures N_{min}, namely,

$$\mathrm{N}_{min} \times \mathrm{d}_{max} = \frac{\lambda}{\sqrt{\varepsilon_{ra}}+\cos\phi_0} \qquad (21)$$

[0112] The actual number of apertures N must be an integer which is preferably greater than or equal to N_{min}. Then, d is recalculated in order that the *Nxd* product is substantially equal to the result of equation (15).

[0113] The calculation of d and N is described below using a continuation of the previous example for a wireless link working in the frequency band between 5150MHz and 5850MHz for which it has been showed that a radiating cable with $\sqrt{\varepsilon_{rc}} = 1.13$ and an aperture group spacing equal to 32cm satisfies the conditions defined by equations (7) and (10) according to the present invention.

[0114] According to equations (1) and (4), the main, secondary and the tertiary modes produced by the radiating cable propagate in the following directions indicated by θ_1, θ_2 and θ_3:

at 5150MHz, θ_1 = 161.6°, θ_2 = 140.1° and θ_3: = 125.9°; and
at 5850MHz, θ_1 = 166.1°, θ_2 = 144.2° and θ_3: = 130.7°.

[0115] To illustrate the possibilities offered by the present invention, it will be assumed that the secondary and tertiary modes are present at a level sufficient to interfere with the main mode and that they have to be attenuated by the coaxial aperture antenna.

[0116] The following calculations are based on the angles θ_1, θ_2 and θ_3 at 5850MHz. As shown hereafter, the *Nxd* product obtained with equation (15) would be identical if the wavelength and the angles at 5150MHz had been used instead.

[0117] The angle ϕ_0 is chosen in order to reduce, as much as possible, the secondary modes without attenuating the main mode. There is a certain range for ϕ_0 which achieves this goal. One possibility is to choose ϕ_0 approximately half-way between θ_2 and θ_3, that is, at ≅137°. Introducing this value into equation (16) gives ϕ_{3dB} = 156.4° which insures that the main mode at 166.1° is not significantly attenuated.

[0118] The calculations are based on the assumption that the coaxial aperture antenna has a value for $\sqrt{\varepsilon_{ra}} = 1.15$. Hence, equations (20) and (21) yield

$$\mathrm{d}_{max} = 0.36 \times 5.1 \cong 1.84 \text{ cm}$$

$$\mathrm{N}_{min} \times \mathrm{d}_{max} = \frac{5.1}{1.15 - 0.73} = 12.18\ \mathrm{cm}$$

[0119] These two results lead to a minimum number of apertures

$$\mathrm{N}_{min} = \frac{12.18}{1.21} = 6.62$$

[0120] The number of apertures can, for example, be chosen equal to 10 and the aperture spacing equal to 1.2cm.

[0121] Figure 7 shows a first embodiment of an aperture configuration 7A for an antenna according to the above calculations. The aperture configuration 7A includes 10 identical transversal slots 8A arranged along a line parallel to the antenna axis and repeated at a spacing or distance of 1.2cm.

[0122] Other embodiments may include a different number of apertures N, preferably where N is greater than or equal to 7, providing that the *Nxd* product satisfies the condition defined by equation (15).

[0123] Figure 8 shows a graph or plot illustrating the calculated array factor (in rectangular coordinates) at 5850MHz in an axial half plane above the slots corresponding to the embodiment shown in Figure 7. The graph shows that there are 4 side lobes. The position of each vertical arrow corresponds to the frequency of the main, secondary and tertiary modes emitted by the radiating cable at 5850MHz. The length of each arrow represents the value of the array factor in the corresponding direction. It appears that the array factor in the direction of the secondary mode is about 28% of its value in the direction of the main mode, hence a power ratio equal to 11.1dB.

[0124] Figure 9 shows the calculated array factor for the embodiment shown in Figure 7 and the main, secondary and tertiary modes of the radiating cable recalculated for 5150MHz. The main lobe is slightly wider at 5150MHz than at 5850MHz as the first null direction has shifted from 138° to ≅133°, that is, still halfway between θ_2 = 140.1° and θ_3 = 125.9°. However, all the radiating cable modes have shifted to the left. For example, the angle θ_1 of the main mode has moved from 165.9° to 161.4°.

[0125] Figures 8 and 9 demonstrate the broadband character of a wireless link according to the present invention, as the angle of the main and secondary modes of the radiating cable relative the array factor pattern of the antenna apertures is frequency independent between at least between 5150MHz and 5850MHz.

[0126] The *Nxd* product for the embodiment of Figure 7 has been chosen in order to have ϕ_0 approximately halfway between θ_2 and θ_3. As stated above, there are other possibilities. For example, if the secondary mode is much stronger than the tertiary mode, it is preferable that ϕ_0 is closer to θ_2. Conversely, if the secondary mode is much weaker than the tertiary mode, ϕ_0 should be chosen closer to θ_3.

[0127] The advantages and possibilities of the present invention are illustrated by a second example based on the same assumptions as above, that is, a frequency band between 5150MHz and 5850MHz for a radiating cable whose aperture group spacing is equal to 32cm and whose $\sqrt{\varepsilon_{rc}} = 1.13.$ However, it will be assumed that the aperture pattern of the radiating cable totally cancels the secondary mode but only attenuates the tertiary mode.

[0128] According to equations (1) and (4):

at 5150MHz, θ_1 = 161.4° and θ_3 = 125.7°; and
at 5850MHz, θ_1 = 165.9° and θ_3 = 130.5°.

[0129] As in the previous example, the calculations are based on the angles θ_1 and θ_3 at 5850MHz. Given the broadband nature of the coaxial aperture antenna according to the invention, the *Nxd* product obtained with equation (15) would be identical if the wavelength and the angles at 5150MHz had been used instead.

[0130] The angle ϕ_0 is chosen to cancel the tertiary mode, that is, in order that ϕ_0= 130.5°. Again, it will be assumed that $\sqrt{\varepsilon_{ra}} = 1.15.$ Hence, equations (20) and (21) yield

$$\mathrm{d}_{max} = 0.36 \times 5.1 \cong 1.84\ \mathrm{cm}$$

$$\mathrm{N}_{min} \times \mathrm{d}_{max} = \frac{5.1}{1.15 - 0.65} = 10.19\ \mathrm{cm}$$

[0131] These two results lead to a minimum number of apertures

$$N_{min} = \frac{10.19}{1.84} = 5.54$$

[0132] The number of apertures can, for example, be chosen to be equal to 9 and the aperture spacing equal to 1.13cm.
[0133] Figure 10 shows a second embodiment of an aperture configuration 7B for an antenna according to the above calculations. Aperture configuration 7B includes 9 identical transversal slots 8B arranged along a line parallel to the antenna axis (not shown) and repeated at a spacing or distance of 1.13cm. Other embodiments may include another number of apertures N, preferably where N is greater than or equal to 6, provided the *Nxd* product satisfies the condition defined by equation (15).
[0134] Figure 11 shows a graph or plot of the array factor of the aperture configuration 7B shown in Figure 10 at 5850MHz in an axial half plane above the slots. The graph shows that the tertiary mode of the radiating cable at 130.7° coincides with the first null direction of the array factor of the coaxial aperture antenna according to the invention.
[0135] The embodiments of aperture configurations shown in Figures 7 and 10 include identical apertures with equal spacing. With these embodiments, all apertures radiate equal field amplitude. Some arrays of apertures radiating different field amplitudes may decrease the level of the side lobes. In particular, symmetrical tapered field amplitude profiles may be rather efficient to produce this effect, for example, with equally spaced apertures of variable size or with apertures of variable size and spacing.
[0136] Figure 12 shows a third embodiment of an aperture configuration 7C where equally spaced apertures 8C comprise slots transverse to the coaxial antenna axis (not shown), the slot width of each slot varying according a symmetrical tapered profile as shown. Nine slots are spaced a distance d, from one another along the length of the aperture configuration 7C. The slot width is equal to W_{min} at each antenna end and increases progressively to reach W_{max} at the centre of the antenna. In this way, the field amplitude profile is symmetrical about the centre of the array of slots.
[0137] The field pattern of an array of N equally spaced apertures of variable size can be calculated with

$$E(\phi) = \sum_{i=1}^{N} A_i \cos\frac{ix\psi}{2} \qquad (22)$$

where ψ is defined by equation (11) and A_i is the amplitude of the field (in volt/m) generated by aperture number i.
[0138] If the apertures are slots, the amplitude A_i is substantially proportional to the slot width.
[0139] Figure 13 shows a fourth embodiment according to the principle described above with reference to Figure 12 but in which the aperture configuration 7D comprises 10 slots. The slot spacing d is equal to 1.9cm, the widths of the 10 slots are given in Table 1 where U is an arbitrary unit, W_{min} = 0.2U and W_{min} = 1 U.

Table 1

1	2	3	4	5	6	7	8	9	10
0.2U	0.4U	0.7U	0.9U	U	U	0.9U	0.7U	0.4U	0.2U

[0140] Figure 14 shows a graph or plot of the array factor at 5850MHz in an axial half plane above the slots for the embodiment of Figure 13 having a slot width profile according to Table 1. The first null direction is approximately at 137° and the all secondary lobes are significantly weaker than those illustrated in Figures 8, 9 and 11.
[0141] The vertical arrows indicate the frequency of the main, secondary and tertiary modes emitted by the radiating cable in the above example, that is, with θ_1 = 166.1°, θ_2 = 144.2° and θ_3 = 130.7° at 5850MHz. It appears that the array factor in the direction of the secondary mode is about 18% of its value in the direction of the main mode, hence a power ratio equal to 14.9dB.
[0142] Figure 15 shows fifth embodiment of aperture configuration 7E with 10 slots according to the principle described in Figure 12. The slot spacing is equal to 1.9cm, the widths of the 10 slots are given in the Table 2 below where U is an arbitrary unit, W_{min} = 0.25U and W_{max} = 1 U.

Table 2.

1	2	3	4	5	6	7	8	9	10
0.25U	0.5U	0.75U	U	U	U	U	0.75U	0.5U	0.25U

[0143] Figure 16 shows a graph or plot of the array factor at 5850MHz in an axial half plane above the slots for the embodiment of Figure 15 and having a slot width profile as shown in Table 2. The first null direction is approximately at 139° and the all secondary lobes are also significantly weaker than in Figures 8, 9 and 11.

[0144] The vertical arrows indicate the frequency of the main, secondary and tertiary modes emitted by the radiating cable of the above example. It appears that the array factor in the direction of the second mode is about 14% of its value in the direction of the main mode, hence a power ratio equal to 17.3dB.

[0145] While the present invention is described herein with reference to illustrative embodiments of symmetrical tapered field amplitude profiles, it should be understood that that the invention is not limited thereto as there are many other similar profiles which allow reducing the array factor side lobes. For example, triangular shaped, cosine shaped or $\cos^2$ shaped profiles may be as efficient that the profiles shown in Tables 1 and 2.

[0146] Symmetrical tapered field amplitude profiles may be realised by principles other than the one described above with reference to Figure 12. For example, Figure 17 illustrates a sixth embodiment of an aperture configuration 7F where 9 slots 8F are equally spaced by a distance d, each slot having the same width but is of variable length. The lengths are chosen in order to realise a tapered symmetrical field amplitude profile.

[0147] The transversal slots described above with reference to Figure 12 can be replaced by equally spaced slanted slots of variable width and equal length. Likewise, the transversal slots described above with reference to Figure 17 can be replaced by equally spaced slanted slots of equal width but variable length.

[0148] Figure 18 illustrates a seventh embodiment of an aperture configuration 7G where 9 slots 8G are equally spaced at a distance d, each slot having the same width and length but is slanted with respect to the axial direction to provide the desired side lobe attenuation as described above. Figure 18 shows that the slanting angle is at a minimum at each end of the aperture configuration 7G and reaches a maximum (equal to 90°) at the centre relative to the longitudinal axis of the antenna (not shown). In this embodiment, the slots on either side of the centre slot are slanted in the same way. As shown, the two slots nearest the end of the antenna are the same and moving inwards from each end of the antenna, each slot is the same as the corresponding slot on the other side of the centre slot as shown.

[0149] A variation of the aperture configuration 7G shown in Figure 18 is shown in Figure 19, where aperture configuration 7H comprises slots 8H are slanted in a different way. Here, the slots are slanted inwards with respect to the centre slot, the centre slot forming an axis of mirror symmetry so that the slots to the left of the centre slot are mirrored to the right of the centre slot.

[0150] Although they may have no practical interest, side lobe attenuation may also be obtained with many arrays of apertures of variable size and separated by a variable distance provided they implement a tapered and symmetrical field amplitude profiles.

[0151] In the embodiments described above with reference to Figures 12, 17, 18 and 19, the apertures may also have rounded corners. Each single aperture may also have an elliptical or oval shape with its main axis aligned to be either perpendicular or slanted with respect to the axial direction, that is, with respect to the longitudinal axis of the antenna. Each single aperture may also be replaced by a plurality of smaller apertures.

[0152] It will readily be understood that the aperture configurations described above are by way of example only and that other numbers of slots are possible.

[0153] Figures 20 to 23 show other embodiments in accordance with the present invention where some apertures are covered, either partly or completely, with a metal plate 12 placed at very short distance or against an outer sheath 13 (which covers the outer conductor 7 as shown in Figure 4). The shape of the plate can be flat or curved with a radius of curvature substantially equal to the radius of the outer sheath 13. It has indeed been found surprisingly, in accordance with the present invention, that the gain of the coaxial aperture antenna is increased by providing a metal plate directly against, or nearly against, the insulating outer sheath 13.

[0154] Figures 20 to 23 illustrate embodiments of aperture configurations of antennas in accordance with the present invention according to the principle described with reference to Figure 4 above in which:

a plurality of apertures in the outer conductor extending over a length which is greater than or equal to 1.9 λ_b;
the apertures being arranged along a line parallel to the longitudinal axis of the coaxial antenna;
a matching load 11;
the main lobe, in the half plane above the apertures, being between the directions ϕ_{3dB} and 180° with ϕ_{3dB} being chosen in order to attenuate or cancel the remaining secondary modes generated by the radiating cable without much reduction in its main mode.

[0155] Generally, in Figures 20 to 23, respective aperture configurations 103, 104, 105, 106 are shown in which an outer sheath 13 covers ten slots 8 and one or more metal plates 12A, 12B, 12C, 12D are positioned on the outside of the outer sheath 13 to partially shield selected slots.

[0156] In Figures 20a and 20b, an aperture configuration 103 is shown in which a single metal plate 12A is positioned over the first three slots from the left end of the antenna. The length of the metal plate 12A is chosen to cover the three slots and has a width which is less than the length of the slots as shown. The metal plate 12A has a radius of curvature which is similar to that of the outer sheath 13 as shown in more detail in Figure 20b.

[0157] The aperture configuration 104 shown in Figures 21 a and 21 b is similar to the antenna configuration 103 but having a metal plate 12B which has a width which is greater than the length of the slots. The metal plate 12B has a radius of curvature which is similar to that of the outer sheath 13 as shown in more detail in Figure 21 b.

[0158] In the aperture configuration 105 shown in Figures 22a and 22b, metal plate 12C has a width which is greater than the length of the slots. In this case, the metal plate 12C is flat as is shown more clearly in Figure 22b.

[0159] Aperture configuration 106 as shown in Figures 23a and 23b is similar to aperture configuration 103 but includes two metal plates 12D each having a radius of curvature similar to that of the outer sheath as shown more clearly in Figure 23b.

[0160] It will readily be appreciated that the aperture configuration shown in Figure 23a is symmetrical about a line between the two central apertures. However, the aperture configurations shown in Figures 20a, 21 a and 22a are not symmetrical.

[0161] The aperture configuration described above with reference to Figures 20 to 23 provides coaxial aperture antennas which generate a linear polarization when transmitting. In particular, this is the case with the embodiments according to Figure 4 provided with the aperture configurations of the antennas described above with reference to Figures 12, 17, 18, 19, 20, 21, 22 and 23.

[0162] It is also an object of the present invention to provide a coaxial aperture antenna which generates a circular polarization. Such circular polarization provides significant advantages in some situations or with some radiating cable types as will be described in more detail below. In the following description, it is assumed that the coaxial aperture antenna is moving below the radiating cable as described above with reference to Figure 5 with Figures 24a, 24b and 24c illustrating side views thereof.

[0163] In Figure 24a, radiating cable 1 is substantially vertically aligned with an antenna 5. The radiating cable 1 has apertures 18A which generate a vertical polarization as indicated by the arrows in elliptical contour 19A. It is also assumed that the electric field propagates in the direction nearly normal to Figure 24a (more precisely at an angle θ_1 in the [150°, 180°] range). For the antenna 5, if its apertures are slots 25 which are elongated in the direction transverse to antenna axis, they also generate or transmit a vertical polarization as indicated by vertical arrows in elliptical contour 20. If the antenna 5 is receiving instead of transmitting, it will mostly be sensitive to an electric field vertically polarized. As the polarizations produced by the radiating cable and coaxial aperture antenna are perfectly aligned as shown in Figure 24a, the received signal will be at its maximum.

[0164] Figure 24b illustrates another situation where, for practical reasons, the entire length of the radiating cable 1 cannot be installed just above the coaxial aperture antenna 5. It is also assumed that the radiating cable 1 has been rotated through 45° around its axis. Consequently, its apertures 18B are positioned with the linear polarization slanted at an angle of 45° as indicated by arrows in elliptical contour 19B. If the coaxial aperture antenna 5 is in the same orientation as in Figure 24a, it will deliver a lower signal as the polarization to which it is mostly sensitive is not aligned with the one produced by the radiating cable 1.

[0165] Figure 24c illustrates another situation where the radiating cable 1 generates a horizontal polarization as indicated by arrows in elliptical contour 19C. Again, if the coaxial aperture antenna is in the same orientation as shown in Figure 24a, it will deliver a weak response as it is not sensitive to a horizontal polarization.

[0166] The examples shown in Figures 24b and 24c illustrate the advantage of an antenna which is sensitive to both vertical and horizontal polarizations. This is the case with the antennas which operate on a circular (or elliptical) polarization which can be produced by two antennas generating two linear polarizations perpendicular to another and fed by two signals in phase quadrature (that is, having a phase difference of 90°).

[0167] Figures 25a and 25b illustrate side views of how circular polarization is achieved according to the present invention. Figure 25a shows an antenna 5 having two rows of apertures 25a, 25b located on either side of a vertical axis 107. More precisely, the centres 108a, 108b of the apertures of each of the rows 25a and 25b are aligned along a direction parallel to the antenna longitudinal axis (not shown). As shown, the angle formed by the centres 108a of the apertures in row 25a of the coaxial antenna outer conductor and the vertical axis 107 is substantially equal to -45°. Likewise, the angle formed by the centres 108b of the apertures in row 25b of the coaxial antenna outer conductor and the vertical axis 107 is substantially equal to +45°. It should be noted that the angles are measured positively in the clockwise direction and negatively in the counterclockwise direction. The row of apertures 25a on the left of the vertical axis 107 produces a polarization indicated by arrows in elliptical contour 21. Likewise, the row of apertures 25b on the right of the vertical axis 107 produces a polarization indicated by dotted arrows in elliptical contour 22.

[0168] If the phase difference of the electric fields produced by the two sets of arrows is 0°, the resulting polarization would be linear. In particular, as shown in Figure 25a, the linear polarization would be vertical, that is, substantially aligned with vertical axis 107 where the two rows of apertures 25a, 25b have equal field strengths. The linear polarization would be slanted where this is not the case. If the two signals are in phase quadrature (that is, having a phase difference of 90° or 270°), the resulting polarization is circular at places where the amplitude of the electric fields produced by the two series of arrows are equal. Where this is not the case, the polarization is elliptical. Circular and elliptical polarization are respectively indicated by the circle 23 and the ellipses 24a and 24b in Figure 25b.

[0169] Figures 26a and 26b illustrate the principle of a circular polarization coaxial aperture antenna according to the present invention. The antenna has an aperture configuration 7J includes two rows 25a and 25b of apertures in the outer conductor as described above. Axes 109a, 109b, as indicated by the dotted lines, of the rows 25a and 25b of apertures, when passing through longitudinal axis 110 of the antenna configuration 7J, form an arc of 90° as shown in Figure 26b. The beginning of the row 25a and 25b apertures are separated by a distance $d_{90°}$ as will be described below.

[0170] In Figure 26a, the two rows 25a, 25b of apertures are shown to be overlapping in length. However, this is not essential and an embodiment as shown in Figure 26c, where there is no overlap between the two rows 25a, 25b, is also possible.

[0171] Figure 27 shows the propagation paths of the waves emitted by respective first apertures 111 a, 111 b of the two rows 25a, 25b of apertures in the direction ϕ. As before, the transceiver 10 and matching load 11 is also shown at respective ends of the antenna, and both rows of apertures are fed from the same transceiver 10. The phase of the field from the first aperture 111 a of the row 25a is taken as the reference. Then, at a distant point in the direction ϕ, the phase of field from first aperture 111b of the row 25b is retarded by an angle ψ given by

$$\psi = \frac{2\pi}{\lambda}\left(d_{90°}\sqrt{\varepsilon_{ra}} - d_{90°}cos\alpha\right) \qquad (23)$$

[0172] As $cos\alpha = -cos\phi$, equation (23) may be rewritten as

$$\psi = \frac{2\pi d_{90°}}{\lambda}\left(\sqrt{\varepsilon_{ra}} + cos\phi\right) \qquad (24)$$

[0173] The circular (or elliptical) polarization is generated if $\psi = \pi/2$. Introducing this condition into equation (2) and solving for $d_{90°}$ yields

$$d_{90°} = \frac{\lambda}{4\left(\left(\sqrt{\varepsilon_{ra}} + cos\phi\right)\right)} \qquad (25)$$

[0174] The calculation of $d_{90°}$ is described below as a continuation of a previous example for a wireless link working in the frequency band between 5150MHz and 5850MHz for which it has been showed that a radiating cable with $\sqrt{\varepsilon_{rc}} = 1.13$ and an aperture group spacing equal to 32cm satisfies the conditions of equations (7) and (10) according to the present invention.

[0175] According to equation (1), the main mode produced by the radiating cable propagates in the following direction as given by θ_1 as described above:

at 5150MHz, θ_1 = 161.6°; and
at 5850MHz, θ_1 = 166.1°.

[0176] The calculation made for 5150MHz and 5850MHz yield respectively:

$$d_{90°} = \frac{5.8}{4(1.13 + \cos 161.6°)} = \frac{5.8}{0.72} = 8\ cm$$

$$d_{90°} = \frac{5.1}{4(1.13 + \cos 166.1°)} = \frac{5.8}{0.64} = 8\ cm$$

[0177] The fact that the calculations for both frequencies yield exactly the same results confirms the broadband character of the wireless link which uses an antenna generating a circular polarization according to the invention.

[0178] The general principle of a uni-directional circular polarization coaxial aperture antenna described in Figures

26a, 26b and 26c can be applied to any one of the embodiments described above with reference to Figures 7, 10, 12, 13, 15, 17, 18, 19, 20, 21, 22 and 23. For example, the apertures can be identical and equally spaced or they can be configured to produce a symmetrical tapered field amplitude profiles.

[0179] For example, Figure 28 shows an aperture configuration for a circular polarization antenna which uses apertures as described above with reference to Figure 10. In the axial direction, the row 25b is shifted by 8cm with respect to the row 25a. In the transverse direction, the distance between the axis of the rows 25a and 25b is equal to C/4 where C is the circumference of the outer conductor.

[0180] Figure 28 also shows that the two rows 25a, 25b of apertures overlap over a certain length. This could weaken the antenna if the apertures are large. A solution which avoids this problem in shown in Figure 26c as described briefly above. In Figure 26c, the beginning of rows 25a, 25b is separated by a distance $d_{270°}$ which is equal to $3xd_{90°}$. As a result, at a distant point in the direction ϕ, the phase of the field from first aperture (not shown) of the row 25b is retarded by an angle ψ equal to 270°, that is, the first aperture of the row 25b is in phase quadrature with respect to the field from first aperture (also not shown) of the row 25a.

[0181] Uni-directional coaxial aperture antennas are appropriate for the situations described above with respect to Figure 3 where the main mode of the radiating cable is always orientated in the same direction relative to the vehicle antenna.

[0182] Figure 29 illustrates another embodiment where adjacent radiating cable sections 1 a, 1 b are fed from the same common transceiver 2. As a result, the main modes 3a, 3b generated by these two radiating cable sections 1 a, 1 b propagate in nearly opposite directions. In such situations, the performances of a wireless link using any uni-directional antenna orientated as described above with reference to Figure 3 will be rather poor when the vehicle antenna moves along the radiating cable section 1 a unless it has bi-directional functionality as indicated by antenna 14. As shown, antenna 14 has two main lobes 113a, 113b which are arranged to be substantially aligned with the main propagation modes generated by the radiating cable sections 1 a, 1 b respectively as described in more detail below.

[0183] When used on a vehicle (not shown) moving along the radiating cable sections 1a, the main lobe 113b points toward the main mode 3a generated by the radiating cable section 1a, and, while the vehicle is moving along the radiating cable section 1 b, the main lobe 113a points toward the main mode 3b generated by the radiating cable section 1 b.

[0184] Such a problem can be solved in various ways, for example, with the use of two directional antennas 114, 115 linked to a single transceiver 10 through a power splitter 15, as shown in Figure 30. The inconvenience of this solution is the loss in the power splitter 15.

[0185] Some modern transceivers can work in a Multiple Input - Multiple Output (MIMO) scheme which uses several antennas. Figure 31 illustrates the principle of such a solution. Here, two directional antennas 116, 117 are connected directly to a single transceiver 16 for receiving signals from radiating cables (not shown) as described above. Unfortunately, the amplitudes of signals received by the two antennas 116, 117 are so different that the advantage of the real MIMO scheme, that is, a throughput increase due to different propagation paths is lost.

[0186] Naturally, although not shown in Figure 29, the coaxial aperture antenna 14 with bi-directional characteristics is aligned such that $-\theta_1$ for radiating cable section 1 a and θ_1 for radiating cable section 1b are substantially the same as the directions of - ϕ and ϕ respectively for main lobes 113b and 113a thereof.

[0187] Figures 32a and 32b show respectively embodiments of linear and circular polarization bi-directional coaxial aperture antennas. Features which have been described previously bear the same reference numerals. The outer sheath of the antennas is not shown in each case. In both embodiments, two parallel coaxial aperture antennas 5a, 5b are connected together with a short coaxial cable 17. Each antenna 5a, 5b has a pair of connectors 9a, 9a' and 9b, 9b' as described above with reference to connector 9 of Figure 4. Here, connectors 9a, 9b are connected to respective ones of transceivers 10 and load 11 with connectors 9a', 9b' connecting to the coaxial cable 17.

[0188] As shown, a first antenna 5a is connected to the transceiver 10 at one end. The second end of this first antenna 5a is connected to one end, on the same side, of the second antenna 5b. The second end of the second antenna 5b is connected to a matching load 11. In such an embodiment, the main lobe of the first and second antennas 5a, 5b are orientated to the right and left side respectively.

[0189] In the embodiment shown in Figure 32a, a linear polarization is generated because the outer conductors 7a and 7b are provided with a plurality of apertures arranged along a line parallel to the antenna longitudinal axis as indicated by rows 25a and 25b respectively.

[0190] In the embodiment shown in Figure 32b, a circular (elliptical) polarization is generated because the outer conductors 7a and 7b are provided with apertures arranged in two rows 25a, 25b for outer conductor 7a and two rows 25a', 25b' for outer conductor 7b as described above with reference to Figures 26a and 26b.

[0191] In the embodiments of Figures 32a and 32b, the power radiated by the antenna further from the transceiver is slightly weaker than the power radiated by the antenna nearer to the transceiver. This imbalance may be compensated, for example, by providing the antenna further from the transceiver with a different aperture configuration to that of the antenna nearer to the transceiver. In one example, more apertures may be provided in row 25b (Figure 32a) and rows 25a', 25b' (Figure 32b) of the antenna 5b further from the transceiver than those provided in row 25a (Figure 32a) and rows 25a, 25b (Figure 32b) of the antenna 5a nearer to the transceiver. Alternatively, or in addition, larger apertures may be provided in row 25b (Figure 32a) and rows 25a', 25b' (Figure 32b) of the antenna 5b further from the transceiver than those provided in row 25a (Figure 32a) and rows 25a, 25b (Figure 32b) of the antenna 5a nearer to the transceiver.

[0192] Although two connectors are shown for each antenna in Figures 32a and 32b, it will readily be appreciated that other configurations are possible where one or no connectors are provided.

[0193] Figure 33 shows an antenna 118 which is a variation of the antenna shown in Figure 32a. Components which have previously been described bear the same reference numerals. In this embodiment, the antenna 118 comprises two antennas sections 118a, 118b which are manufactured in a single length of cable. Here, only two connectors 9a, 9b instead of the four connectors shown in Figure 32a. Depending on the number of rows of apertures and their configuration, antenna 118 generates linear or circular (elliptical) polarization as described above with reference to Figures 32a and 32b.

[0194] Figures 34a and 34b show other embodiments of linear and circular polarization bi-directional coaxial aperture antenna configurations 119, 120 without matching load 11 as described above with reference to Figures 4, 6, 27, 32a, 32b and 33 connected to a second end of the antenna 5.

[0195] When the matching load 11 is present, it absorbs the signal delivered by the transceiver in transmission mode and which has propagated between the coaxial antenna inner and outer conductors. Without the presence of a matching load, the signal is reflected at the end of the antenna and returns to the transceiver where it is normally absorbed. This is effectively an open circuit.

[0196] In Figure 34a, the antenna configuration 119 is for linear polarization and comprises a single row 25a of apertures formed in the antenna portion 5 thereof. Connector 9a connects the antenna portion 5 to the transceiver 10 and connector 9b forms an end which reflects the signal back to the transceiver 10.

[0197] In Figure 34b, the antenna configuration 120 is for circular polarization and comprises two rows 25a, 25b of apertures formed in the antenna portion 5 thereof and spaced apart by a suitable distance as described above. As before the connector 9a connects to the transceiver and connector 9b forms an end.

[0198] The bi-directionality results in the fact that the signal which travels back to the transceiver generates a second main lobe which mirrors the image of the first main lobe which is between ϕ_0 and 180°. Thus, the second main lobe is between 0° and (180° - ϕ_0). As described above with reference to Figures 32a and 32b, the number of aperture pluralities and their configuration determine the type of polarization (linear or circular) which is produced.

[0199] Variations of the embodiments shown in Figures 34a and 34b can be realised if the connector 9b is connected to a 0Ω impedance to provide a short circuit. Such a short circuit produces the same reflection as the open circuit described above.

[0200] Figures 35a and 35b show further antenna configurations 121, 122 which are also variations of the open circuit embodiments of Figures 34a and 34b where there is no connector on the second end of the antenna. As described above with reference to Figures 32a and 32b, the number of apertures and their configuration will determine the type of polarization which is produced. In Figure 35a, which is similar to Figure 34a and having a single row 25a of apertures, linear polarization is produced, and, in Figure 35b, which is similar to Figure 34b and having two rows 25a, 25b of overlapping apertures, circular or elliptical polarization is in operation depending on signal strengths.

[0201] In the embodiments described with reference to Figures 32a, 32b, 33, 34a, 34b, 35a and 35b, row 25a (Figures 32a, 34a and 35a) and rows 25a, 25b (Figures 32b, 33, 34b and 35b) of apertures may comprise identical, equally spaced apertures (as described above with reference to Figures 4, 7, 10, 20a, 20b, 21 a, 21 b, 22a, 22b, 23a and 23b), or they can be configured to produce a symmetrical tapered field amplitude profiles as described above with reference to Figures 12, 13, 15, 17 to 19).

[0202] Figure 36 illustrates a radiating cable 1 and a directional coaxial aperture antenna 5 mechanically coupled to a mobile vehicle 1004. The radiating cable 1 is arranged parallel to a road on which the mobile vehicle 1004 is moving. The axis of the directional coaxial aperture antenna 5 is arranged on the mobile vehicle 1004 parallel to the main direction of motion of the mobile vehicle 1004. Therefore, the directional coaxial aperture antenna 5 is substantially parallel to the longitudinal cable axis 1001 of the radiating cable 1.

[0203] The radiating cable 1 comprises groups 1002 of apertures 1003 that are repeated at a constant spacing s 1006. This spacing s 1006 can be seen as the spatial period of the aperture pattern on the radiating cable 1. The radiating cable 1 comprise preferably no other aperture than the apertures 1003 of the groups 1002. The spacing s 1006 is measured parallel to the longitudinal cable axis 1001.

[0204] As described above, the directional coaxial aperture antenna 5 comprises apertures 1005. These apertures 1005 are distributed along the directional coaxial aperture antenna 5 over a length 1007. These apertures 1005 can, for example, be arranged as illustrated on any of Figures 4, 7, 10, 12, 13, 15, 17, 18, 19, 20, 21, 22, 23 and 28.

[0205] In other words, the invention relates to a communications link between a radiating cable 1 and a moving vehicle having an antenna 5 which can be used in locations where space is critical, such as, in tunnels. The radiating cable 1 emits radiation in a main mode 3 at an angle θ_1 and the antenna 5 is aligned so that the axis 102 of the main lobe 6 is aligned in a direction ϕ. Both θ_1 and ϕ are between 150° and 180°.

[0206] While the present invention is described herein with reference to illustrative embodiments for particular applications, it should be understood that the invention is not limited thereto. Those having ordinary skill in the art and access to the teachings provided herein will recognize additional modifications, applications and embodiments within the scope thereof and additional fields in which the present invention would be of significant utility.

Claims

1. A communications link comprising:

- a radiating cable (1) for transmitting electromagnetic radiation, having a longitudinal cable axis (1001) and comprising groups (1002) of apertures (1003); and
- a directional coaxial aperture antenna (5) mountable on a mobile vehicle (1004), being operable for receiving said electromagnetic radiation transmitted by said radiating cable (1), configured to be substantially aligned with said radiating cable (1) and comprising a plurality of apertures (1005),

characterized in that the groups (1002) of apertures (1003) of the radiating cable (1) are repeated at a constant spacing (1006) in the range of $[3.5\lambda_a, 9.1\lambda_b]$ where λ_a and λ_b are wavelength values corresponding to a frequency band of $[f_a, f_b]$ where $f_a < f_b$, in such a way that the radiating cable (1) is able to generate a main transmission mode (3) which has a direction of propagation at an angle between 150° and 180° to said longitudinal cable axis (1001), and **in that** the apertures (1005) of the directional coaxial aperture antenna (5) extend over a length (1007) which is equal to or greater than $1.9\lambda_b$, in such a way that a main lobe (6) of the directional coaxial aperture antenna (5) is substantially aligned with the direction of propagation of said main transmission mode (3).

2. A communications link according to claim 1, wherein said radiating cable (1) and said directional coaxial aperture antenna (5) operate at a frequency in a range between 5150MHz and 5850MHz.

3. A communications link according to any one of claims 1 or 2, wherein said directional coaxial aperture antenna (5) comprises an antenna longitudinal axis and said apertures (1005) of the directional coaxial aperture antenna (5) are transverse apertures (8) equally spaced along the length of the directional coaxial aperture antenna (5), the product of the number of transverse apertures (8) by their spacing being proportional to the wavelength of electromagnetic radiation to be transmitted or received.

4. A communications link according to claim 3, wherein said transverse apertures (8) are identical.

5. A communications link according to claim 3, wherein said transverse apertures (8) define a symmetrical tapered profile.

6. A communications link according to claim 5, wherein said transverse apertures (8) have different widths, at least one central transverse aperture (8) having a first width value with other transverse apertures (8) extending outwards on either side of said at least one central transverse aperture (8), said other transverse apertures (8) having width values which are less than the first width value and which decrease symmetrically, on each side, in value from said at least one central transverse aperture (8).

7. A communications link according to claim 6, wherein said at least one central transverse aperture (8) comprises one central aperture (8).

8. A communications link according to claim 6, wherein said at least one central transverse aperture (8) comprises two central apertures (8).

9. A communications link according to claim 6, wherein said at least one central transverse aperture (8) comprises four central apertures (8).

10. A communications link according to any one of claims 3 to 9, wherein said transverse apertures (8) have different lengths, at least one central transverse aperture (8) having a first length value with other transverse apertures (8) extending outwards on either side of said at least one central transverse aperture (8), said other transverse apertures (8) having length values which are less than the first length value and which decrease symmetrically, on each side, in value from said at least one transverse aperture (8).

11. A communications link according to any one of claims 3 to 10, wherein at least one transverse central aperture (8) is perpendicular to said longitudinal axis and said other transverse apertures (8) on either side thereof are angled with respect to said at least one central transverse aperture (8), said other angled transverse apertures (8) having increasing angles with respect to said at least one central aperture (8) on either side thereof.

12. A communications link according to claim 11, wherein said other angled transverse apertures (8) are arranged to be identical on either side of said at least one transverse central aperture (8).

13. A communications link according to claim 11, wherein said at least one central aperture (8) defines an axis of mirror symmetry about which said other angled transverse apertures (8) extend outwardly on either side of said at least one central transverse aperture (8), said other angled transverse apertures (8) having decreasing angles with respect to said longitudinal axis.

14. A communications link according to any one of claims 5 to 13, further comprising at least one shield operable for covering at least one of said transverse apertures (8).

15. A communications link according to any one of claims 1 to 14, wherein said directional coaxial aperture antenna (5) comprises a unidirectional antenna.

16. A communications link according to any one of claims 1 to 14, wherein said directional coaxial aperture antenna (5) comprises a bidirectional antenna.

17. A communications link according to any one of claims 1 to 16, wherein said directional coaxial aperture antenna (5) operates with linearly polarized radiation.

18. A communications link according to any one of claims 1 to 16, wherein said directional coaxial aperture antenna (5) operates with one of: circularly and elliptically polarized radiation.

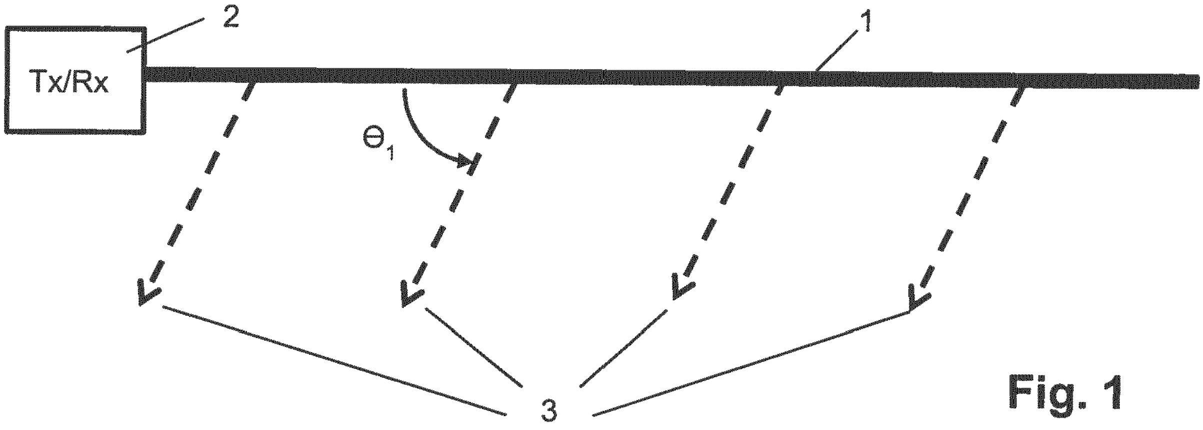


Fig. 1

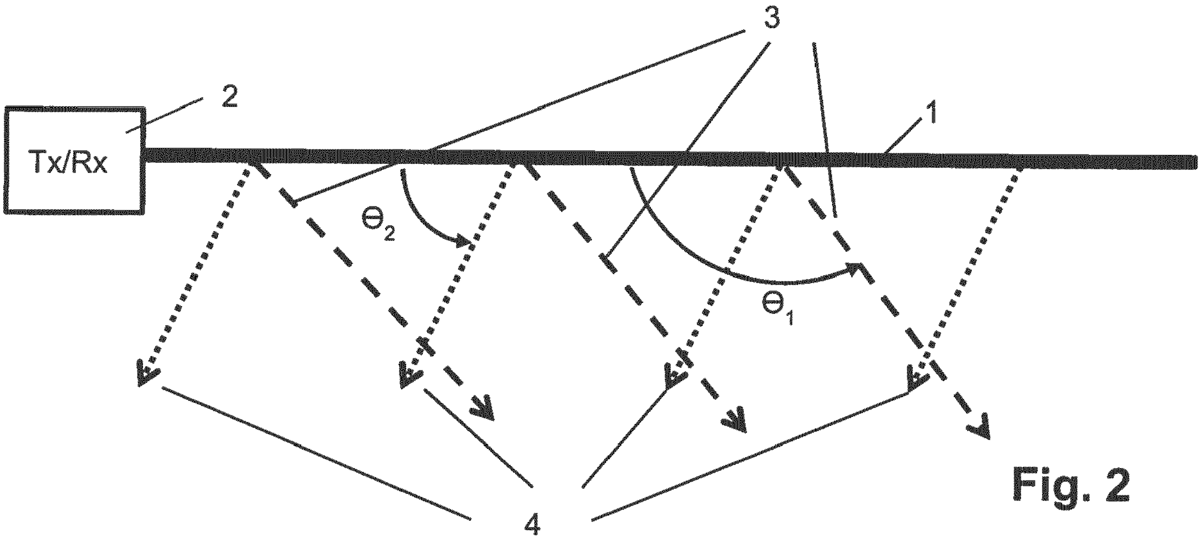


Fig. 2

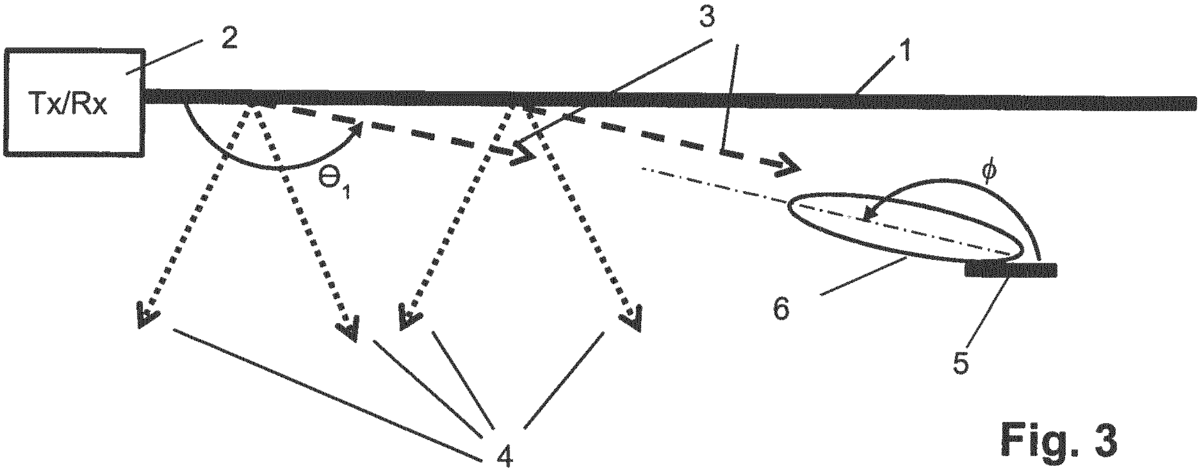


Fig. 3

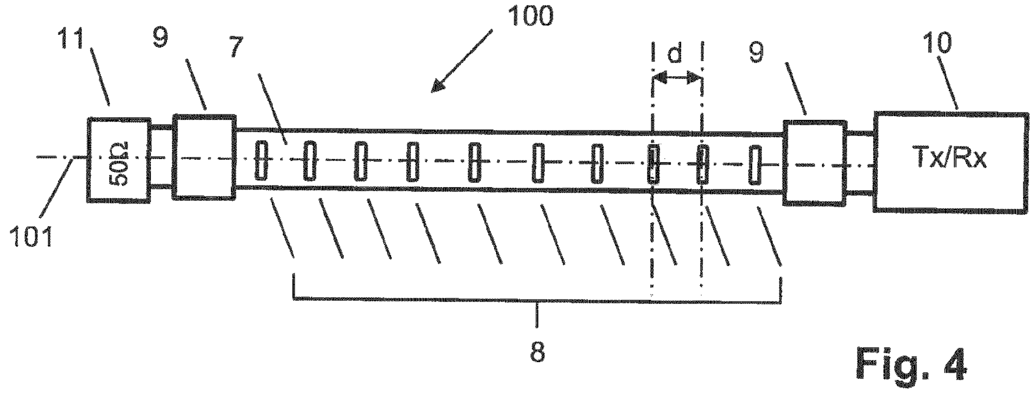


Fig. 4

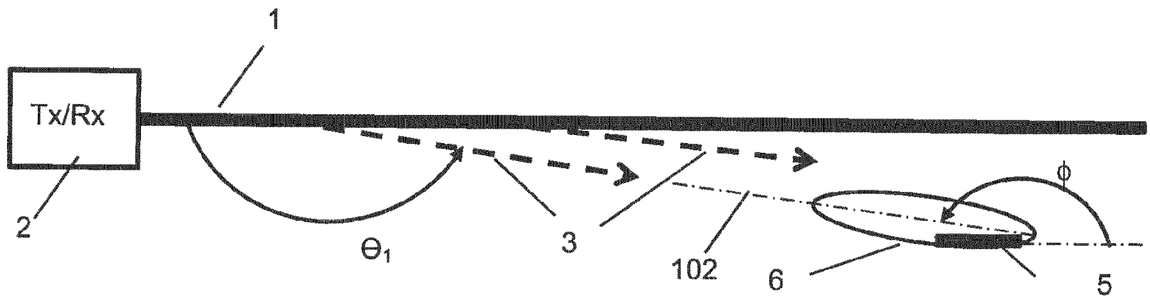


Fig. 5

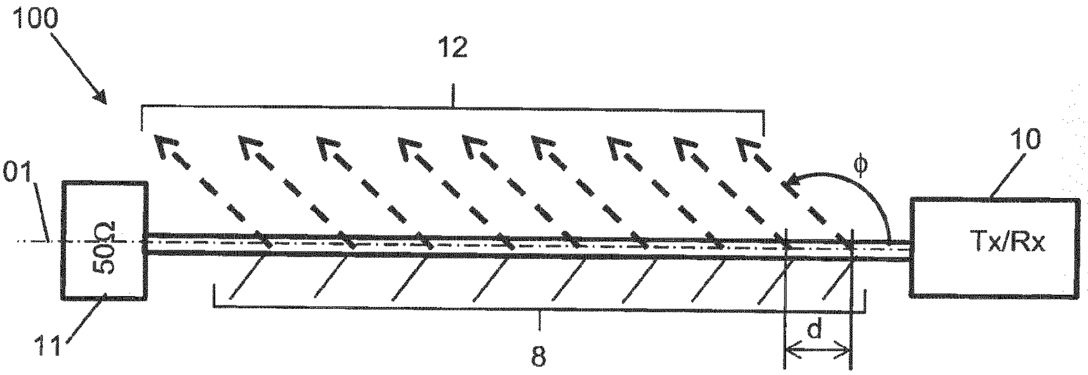


Fig. 6

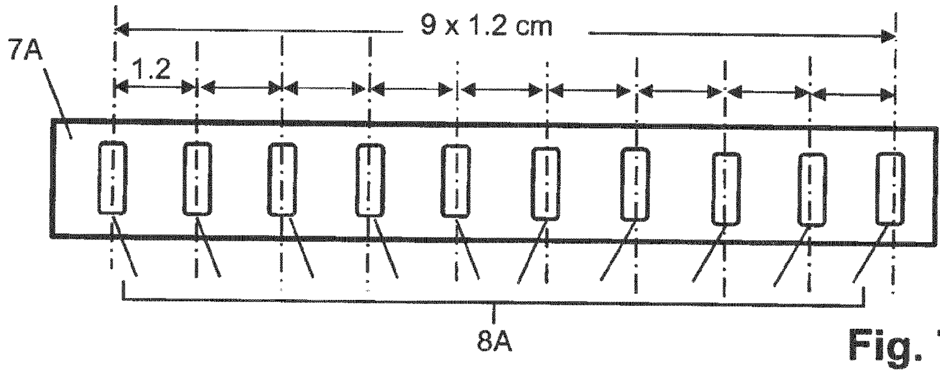
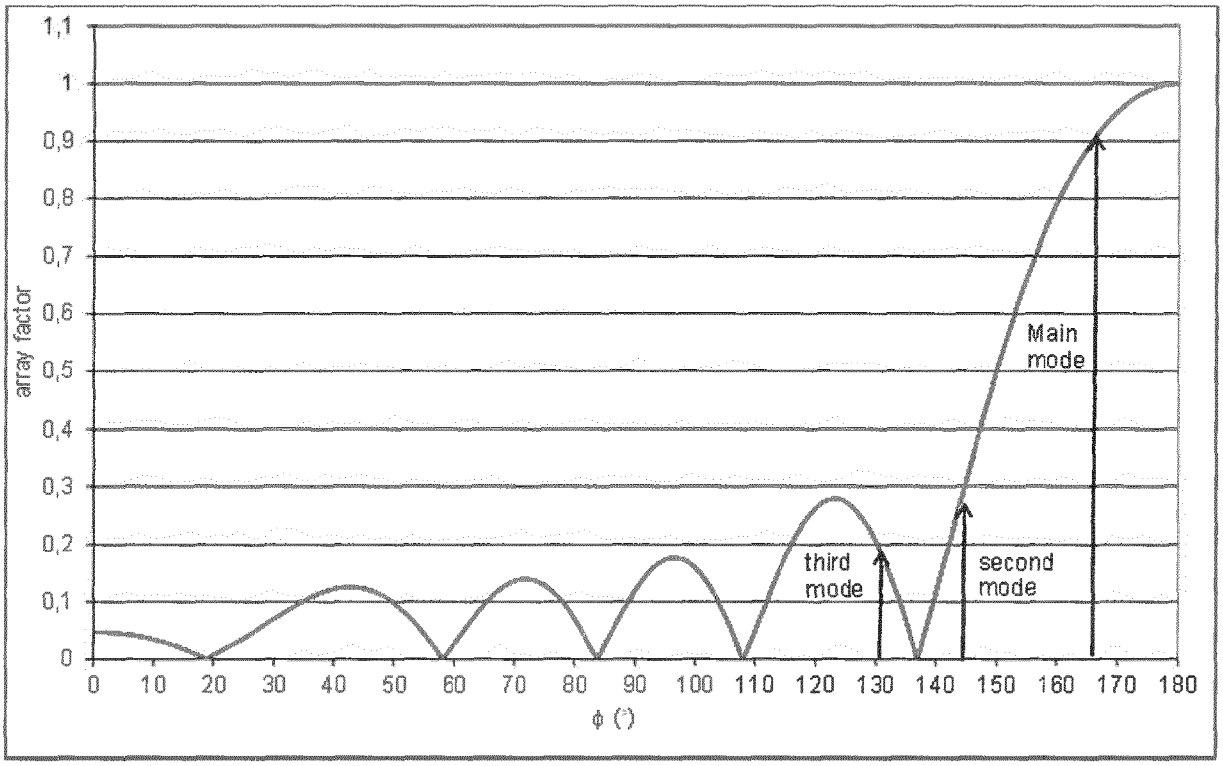


Fig. 7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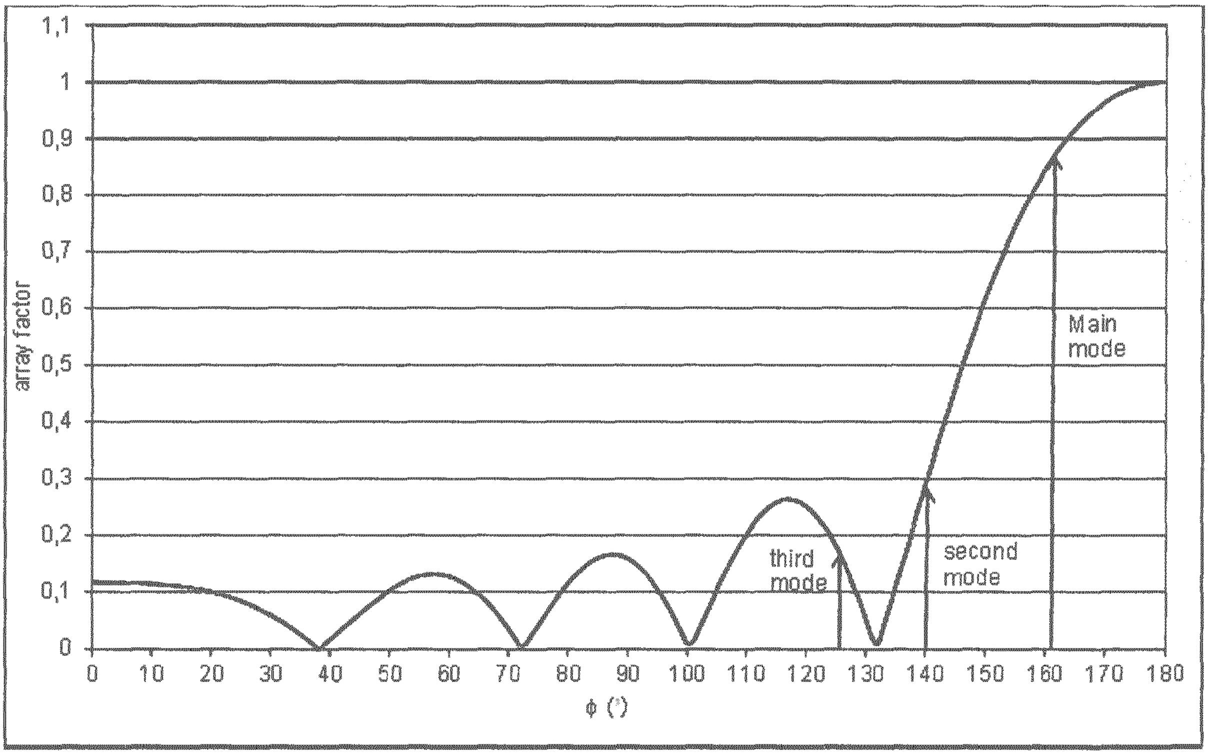
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
array factor
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180
ϕ (°)
Main mode
second mode
third mode

Fig. 8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0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
array factor
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180
ϕ (°)
Main mode
second mode
third mode

Fig. 9

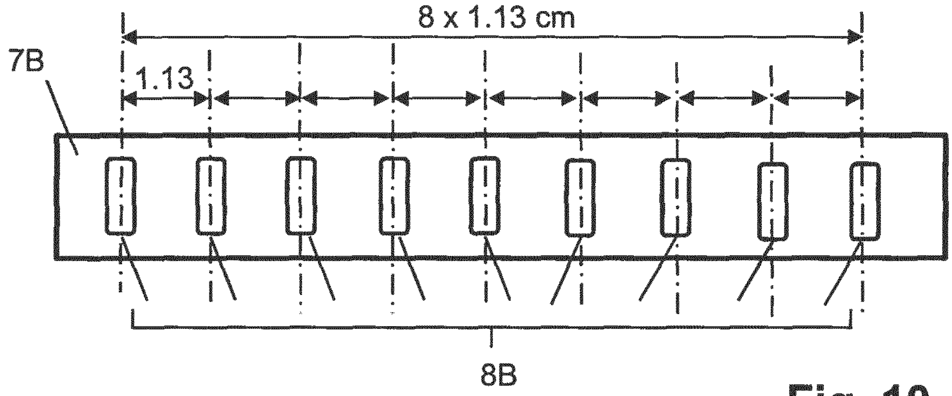
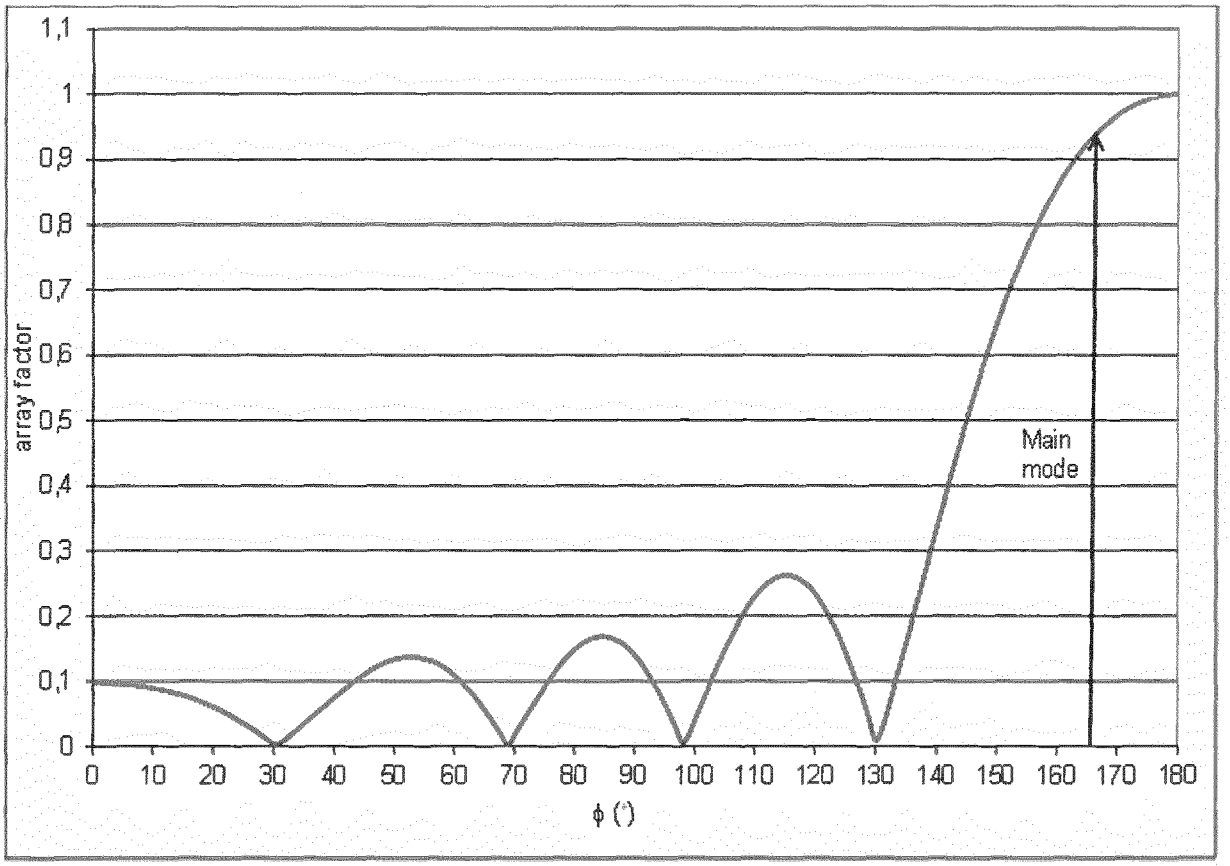

8 x 1.13 cm
7B
1.13
8B

Fig. 10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0,7
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0,5
0,4
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0,2
0,1
0
array factor
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180
ϕ (°)
Main mode

Fig. 11

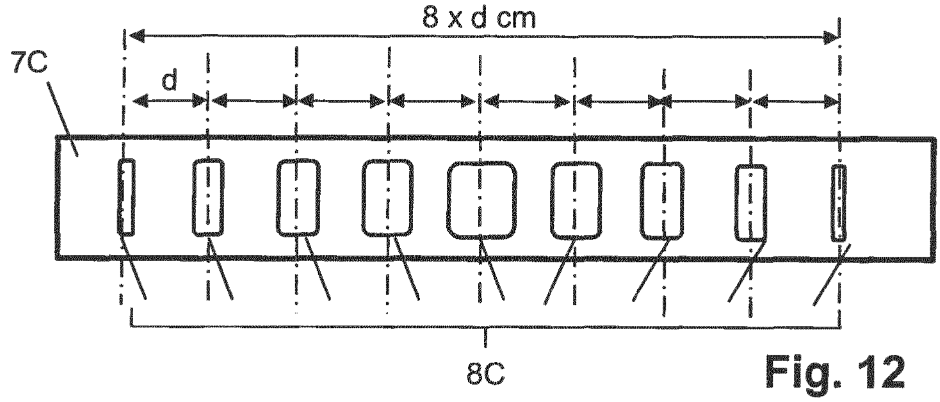


Fig. 12

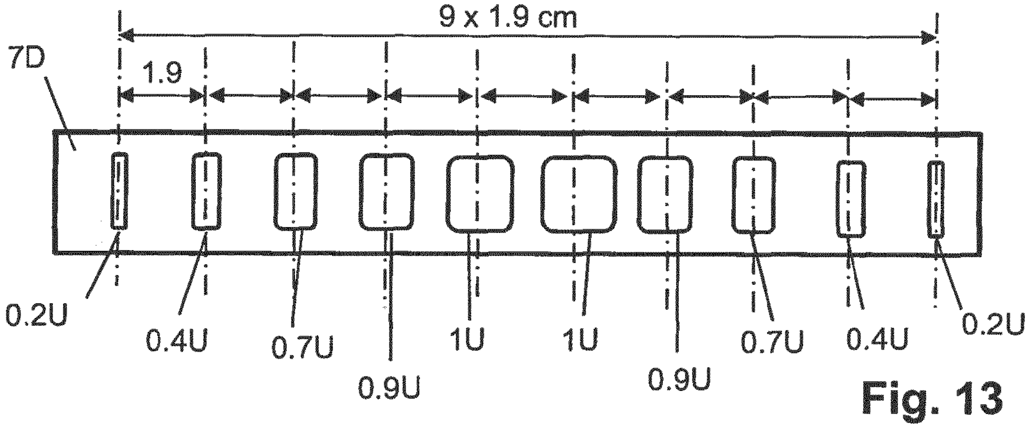


Fig. 13

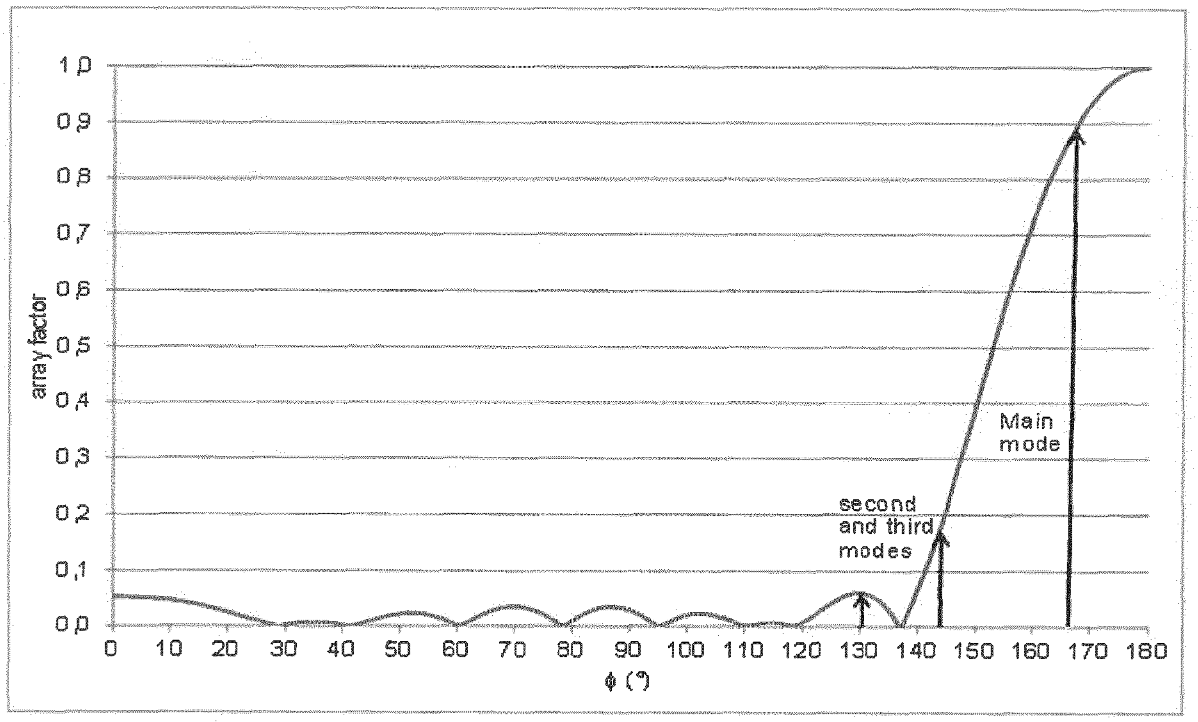
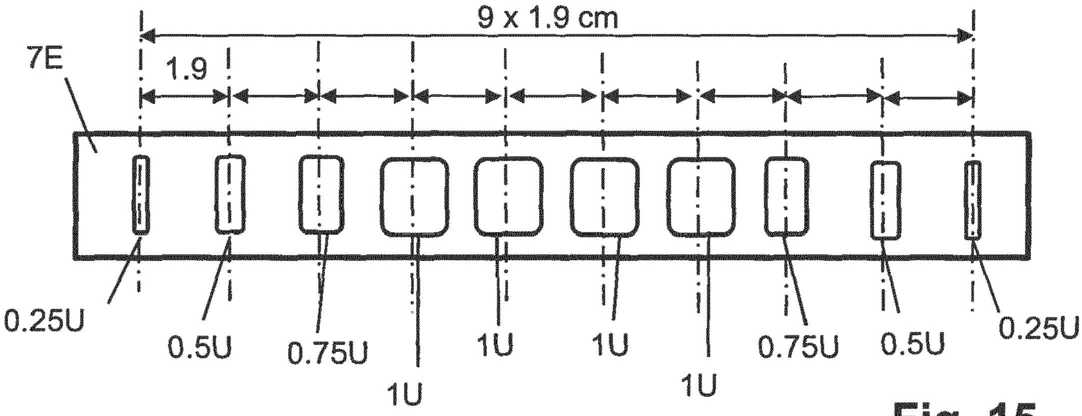


Fig. 14


9 x 1.9 cm
7E
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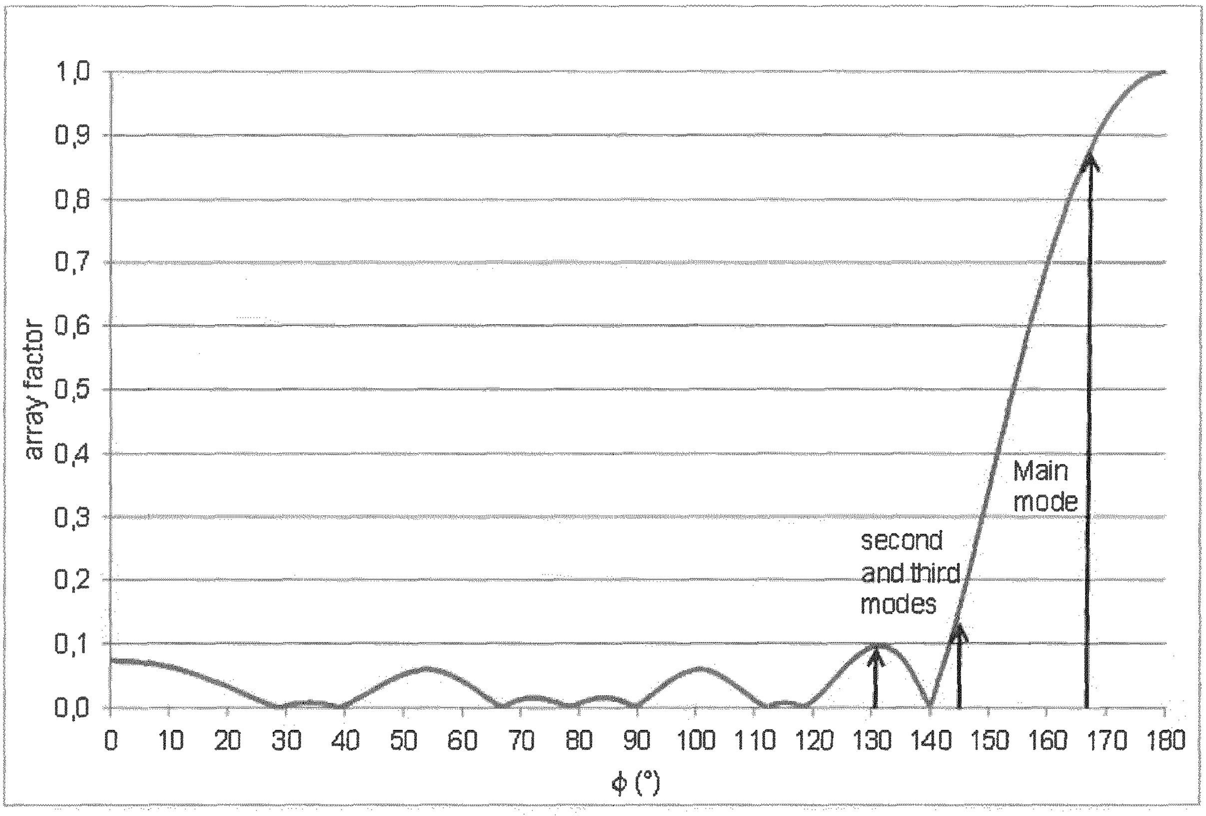
1U
1U
1U
1U
0.75U
0.5U
0.25U

Fig. 15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0,7
0,6
0,5
0,4
0,3
0,2
0,1
0,0
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180
ϕ (°)
Main mode
second and third modes

Fig. 16

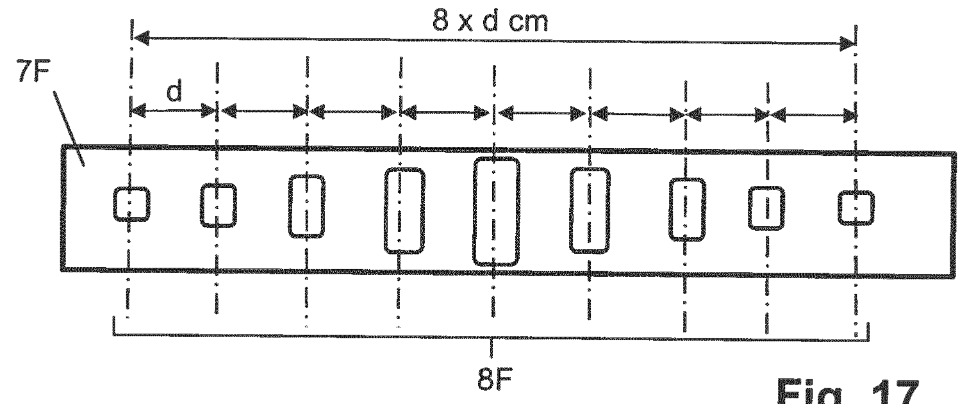


Fig. 17

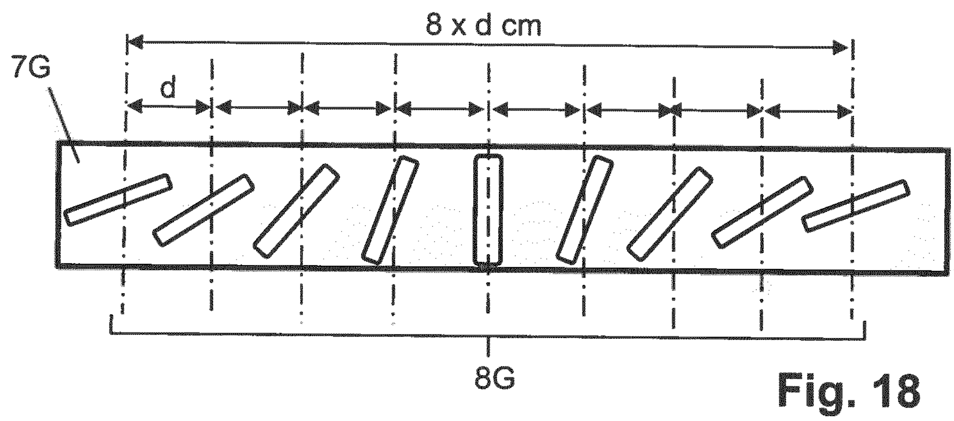


Fig. 18

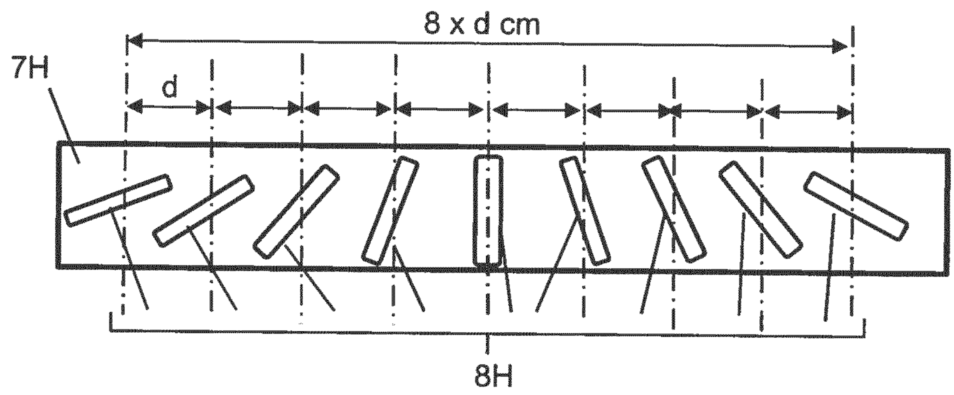


Fig. 19

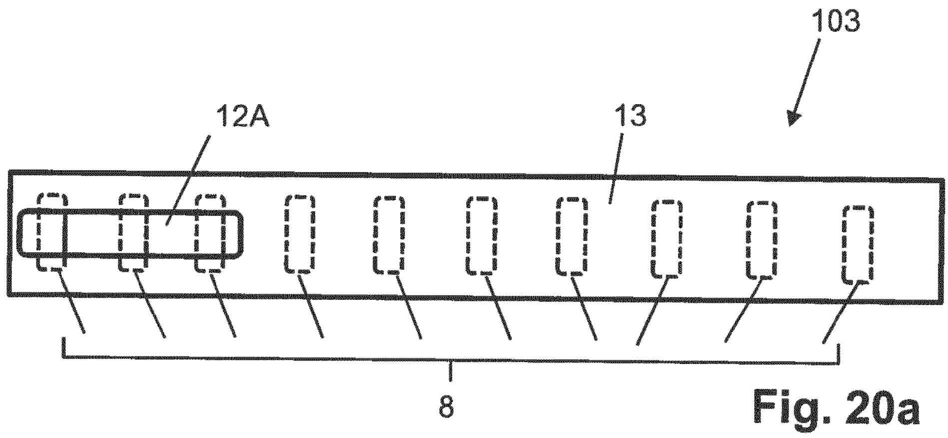


Fig. 20a

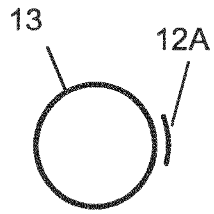


Fig. 20b

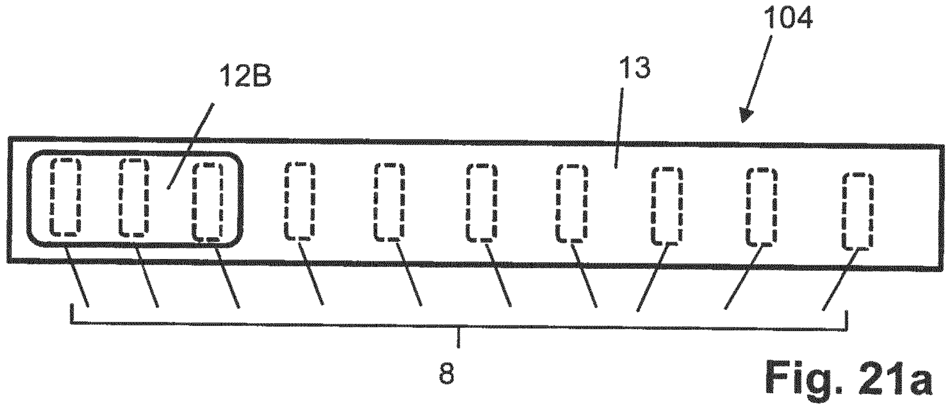


Fig. 21a

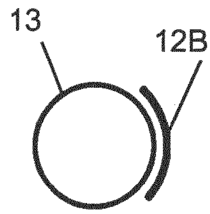


Fig. 21b

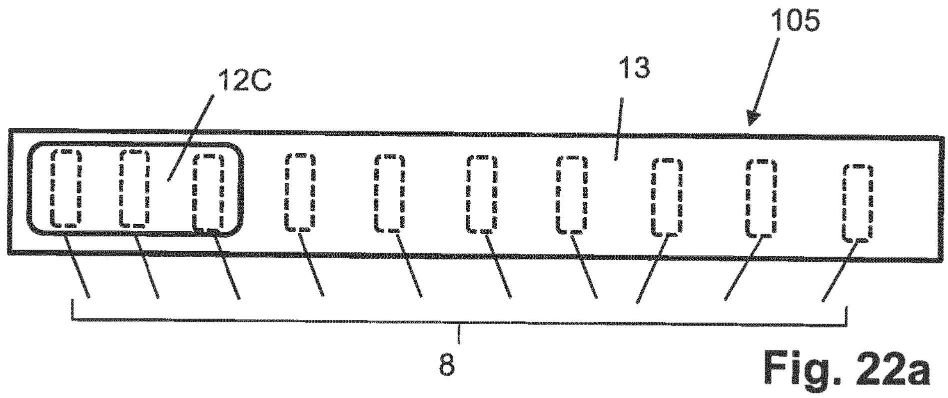


Fig. 22a

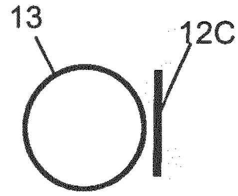


Fig. 22b

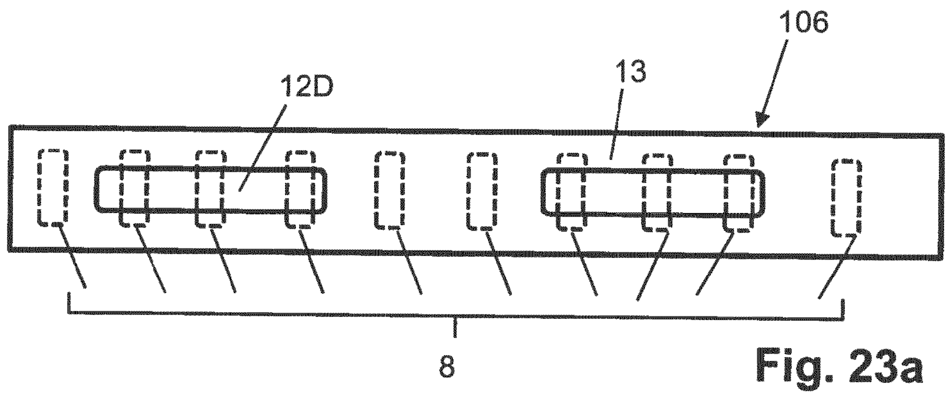


Fig. 23a

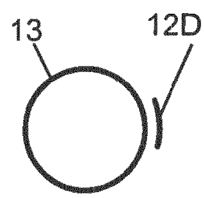


Fig. 23b

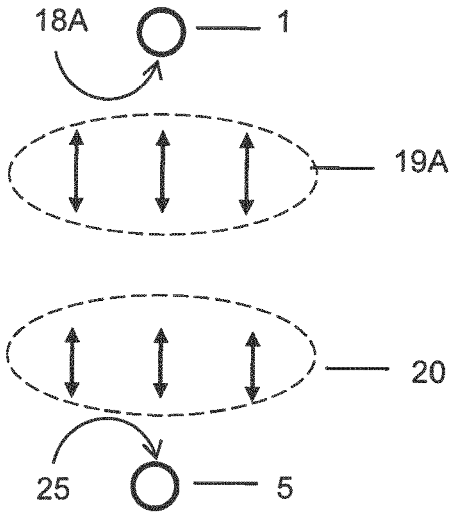


Fig. 24a

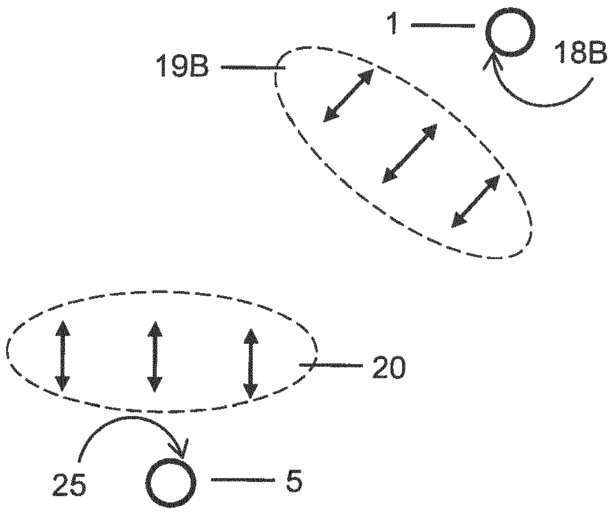


Fig. 24b

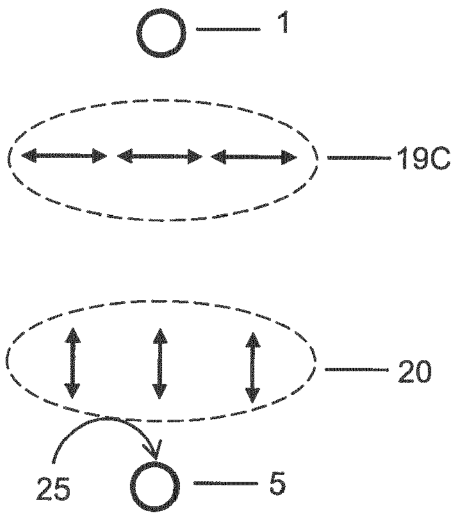


Fig. 24c

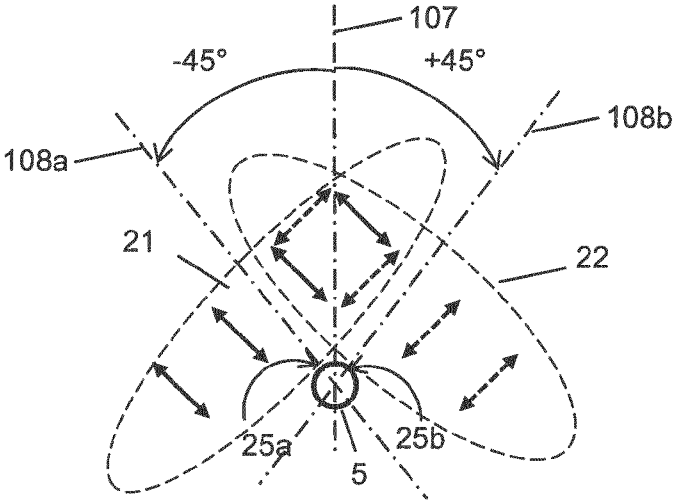


Fig. 25a

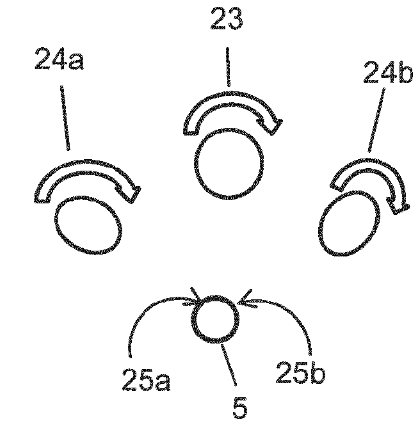


Fig. 25b

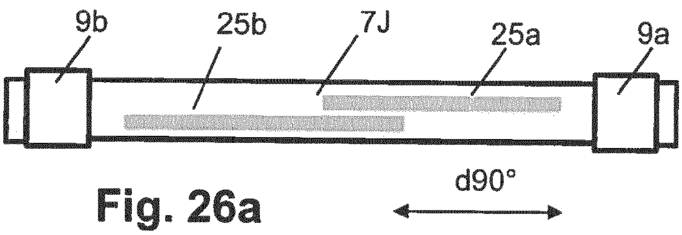


Fig. 26a

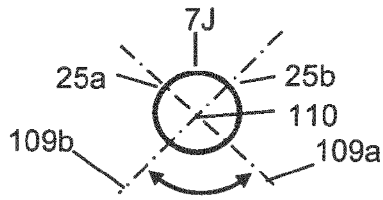


Fig. 26b

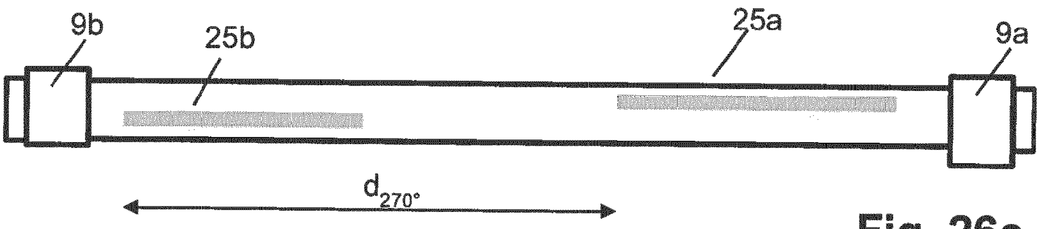


Fig. 26c

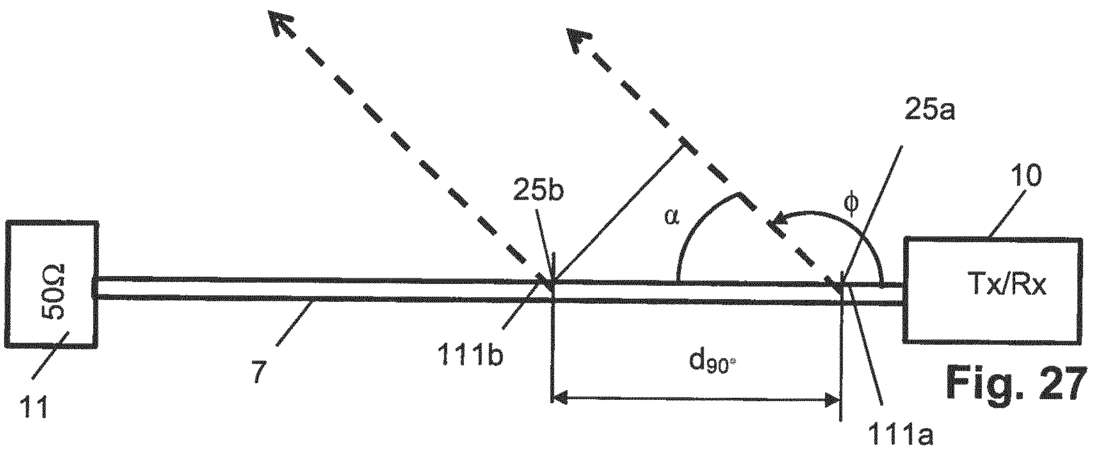


Fig. 27

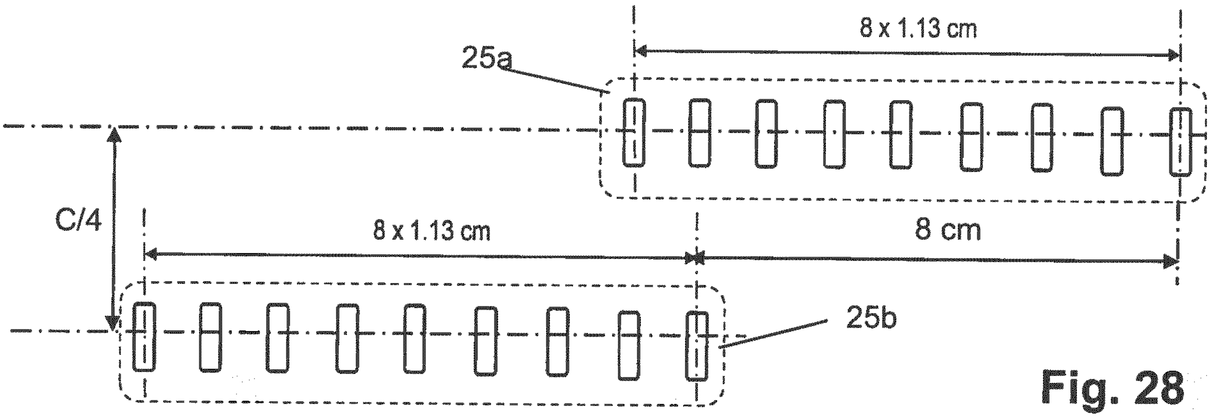


Fig. 28

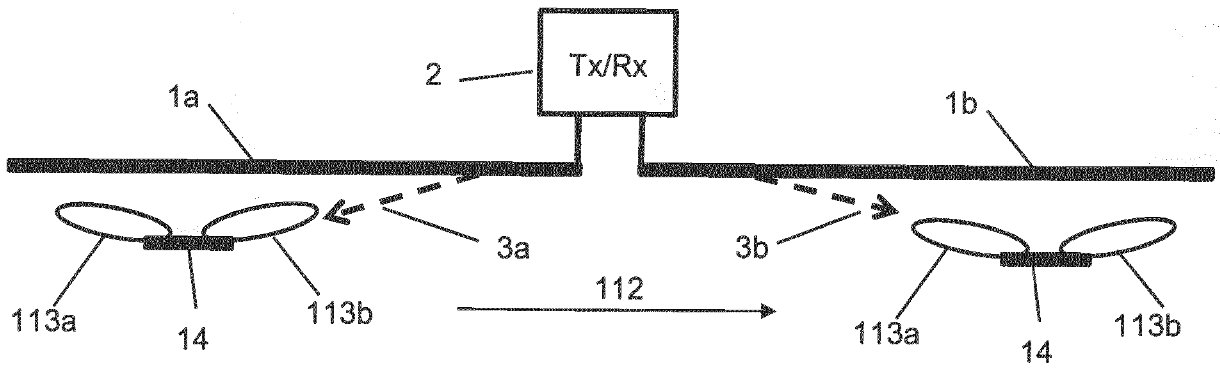


Fig. 29

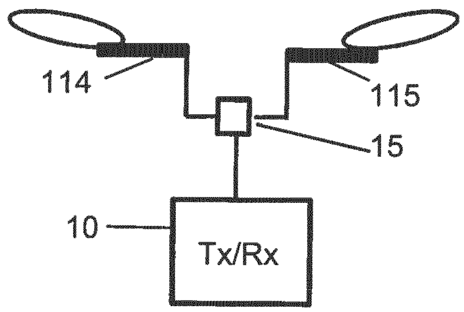


Fig. 30

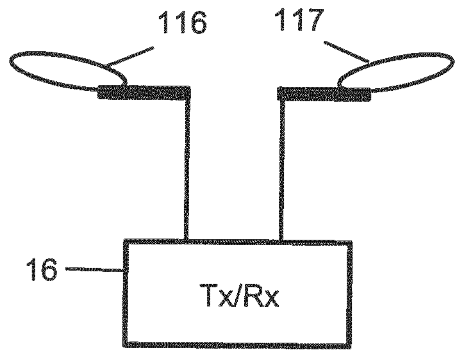


Fig. 31

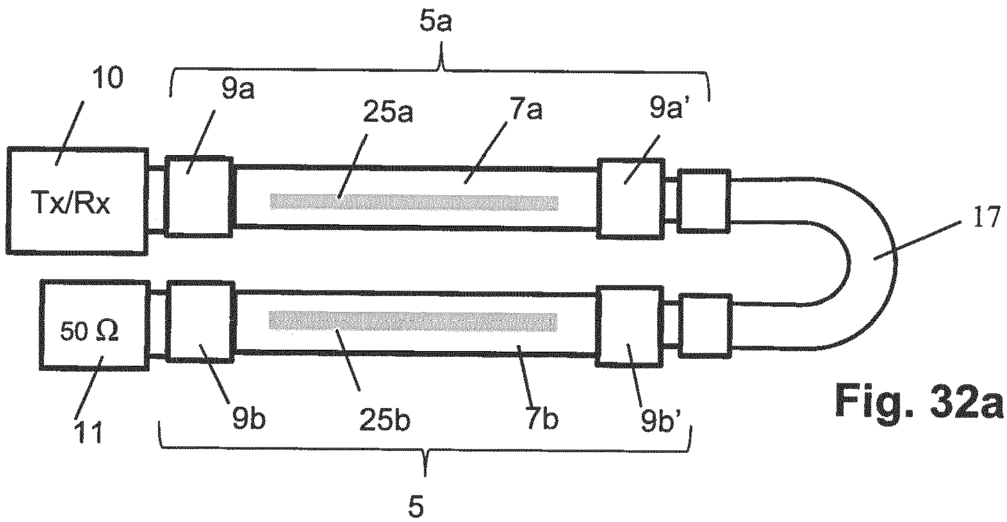


Fig. 32a

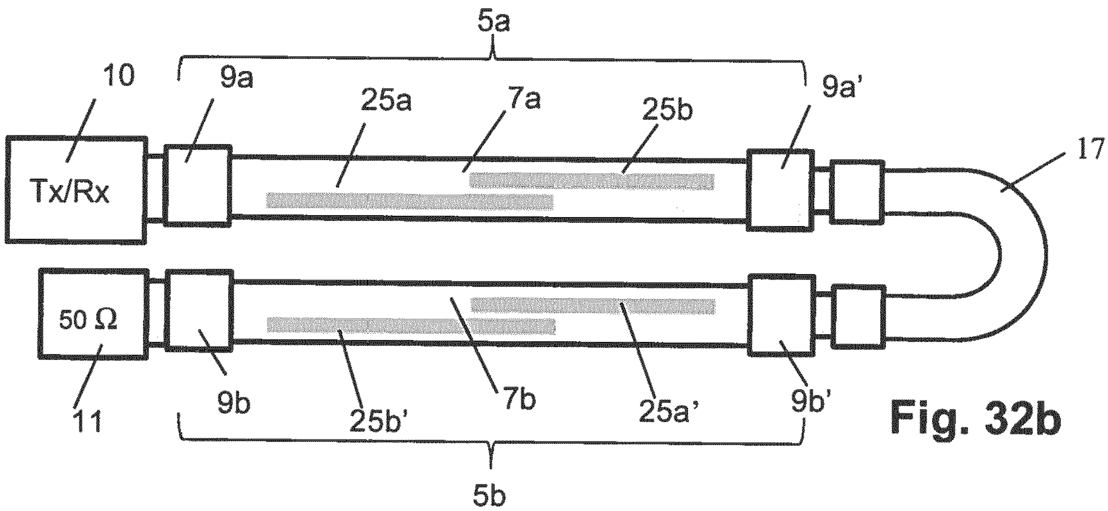


Fig. 32b

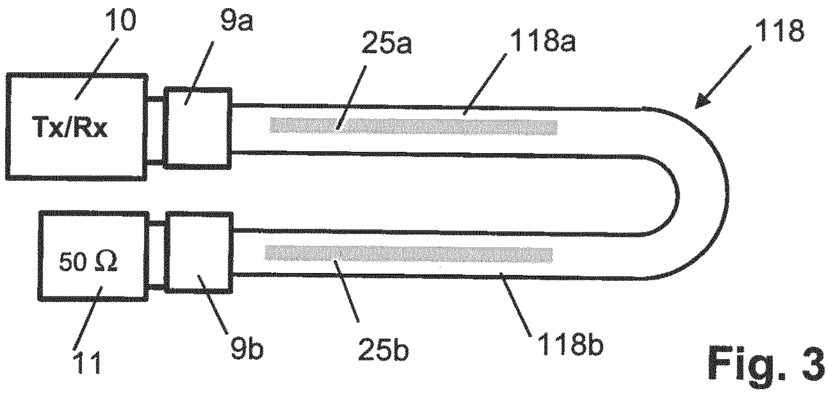


Fig. 33

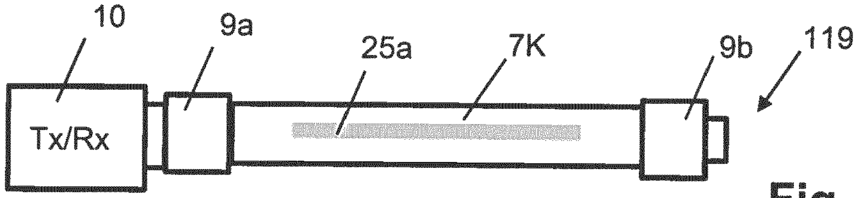


Fig. 34a

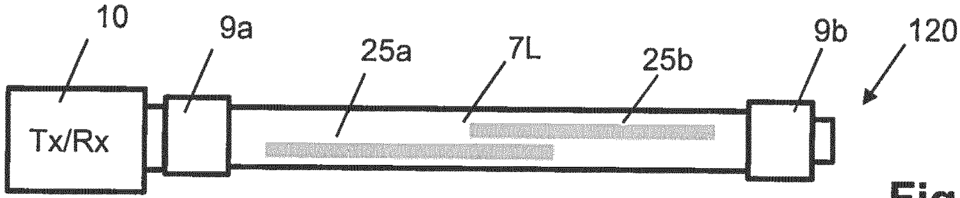
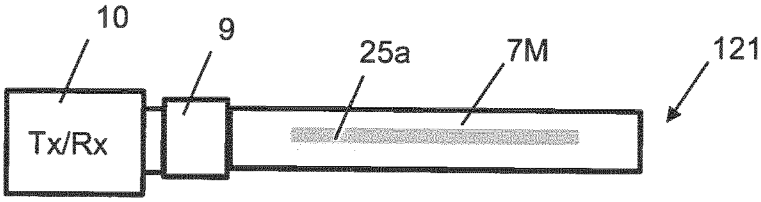


Fig. 34b



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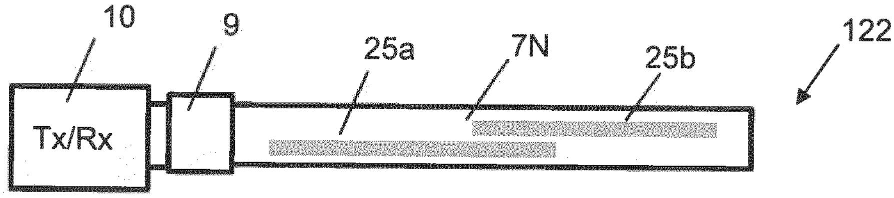

Fig.35b

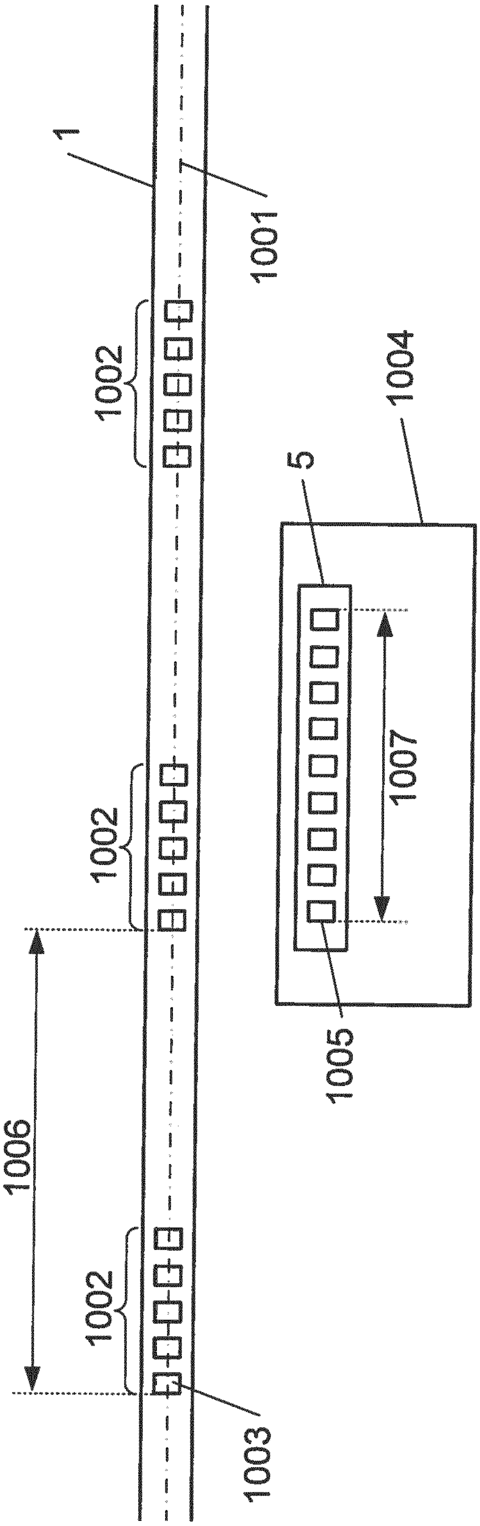

Fig.36

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EUROPEAN SEARCH REPORT

Application Number
EP 17 15 7626

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
A,D	US 6 091 372 A (DIENES GEZA [US]) 18 July 2000 (2000-07-18) * column 3, line 32 - column 7, line 20; figures 1-3 *	1-18	INV. H01Q13/20 H01Q1/32
A	US 2008/029299 A1 (HAKAMADA YOSHIRO [JP]) 7 February 2008 (2008-02-07) * paragraph [0032] - paragraph [0066]; figures 1-6 *	1	
A	US 5 705 967 A (PIRARD WILLY [BE]) 6 January 1998 (1998-01-06) * column 3, line 40 - column 4, line 23; figures 1-3 *	1	
A	EP 1 998 403 A1 (ALSTOM TRANSPORT SA [FR]; INRETS [FR]) 3 December 2008 (2008-12-03) * paragraph [0019] - paragraph [0030]; figures 1-3 *	1	
A	US 3 795 915 A (YOSHIDA K) 5 March 1974 (1974-03-05) * the whole document *	1	TECHNICAL FIELDS SEARCHED (IPC): H01Q

The present search report has been drawn up for all claims

1

Place of search	Date of completion of the search	Examiner
The Hague	29 June 2017	Degraeve, Alexis

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