Sept. 27, 1927. 1,643,323

J. S. STONE

DIRECTIVE ANTENNA ARRAY

Filed Jan. 4, 1921 4 Sheets-Sheet 1

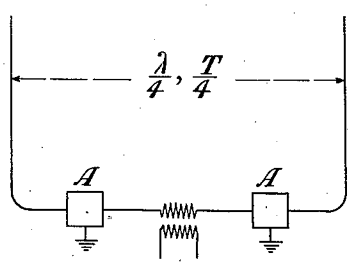

Fig. 1

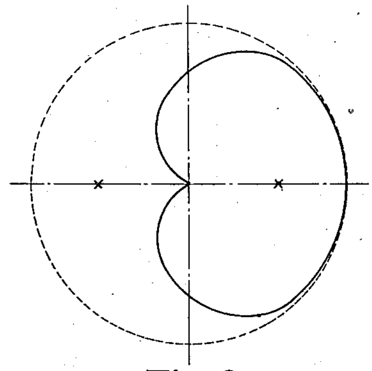

Fig. 2

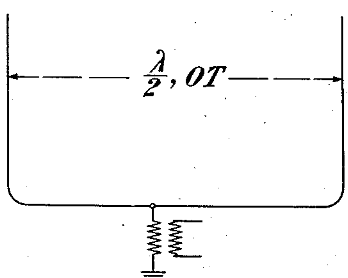

Fig. 3

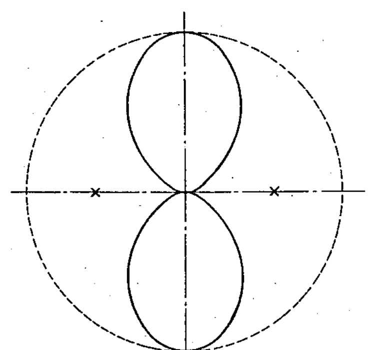

Fig. 4

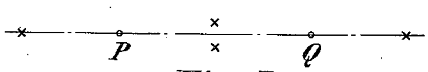

Fig. 5

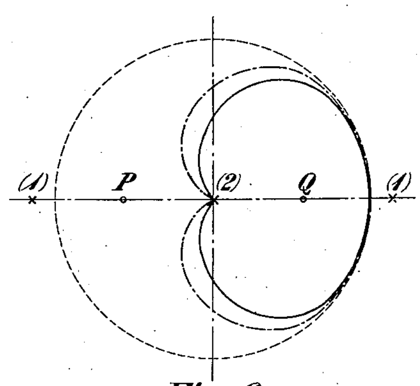

Fig. 6

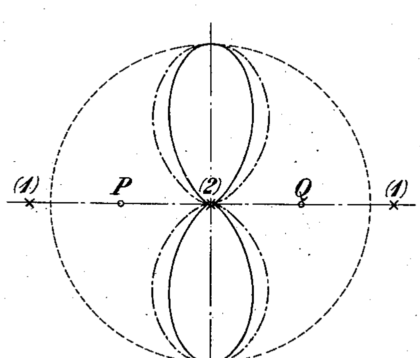

Fig. 7

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DIRECTIVE ANTENNA ARRAY

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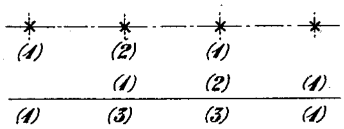

Fig. 8

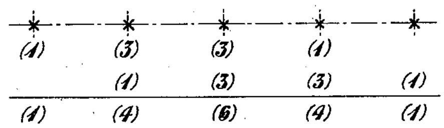

Fig. 9

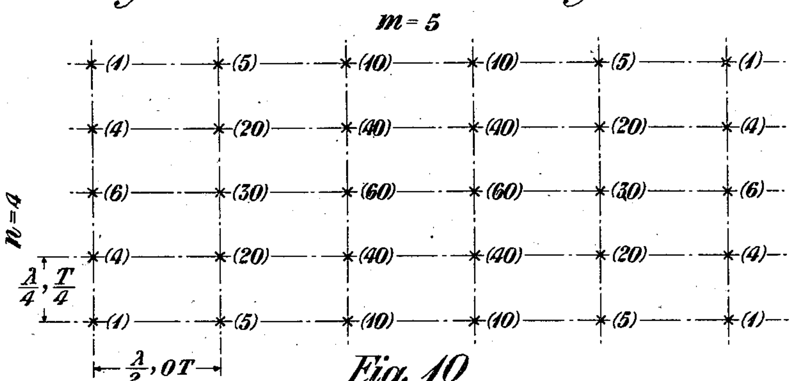

Fig. 10

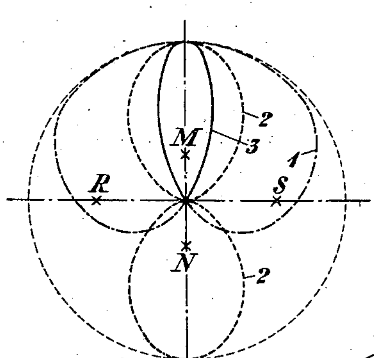

Fig. 11

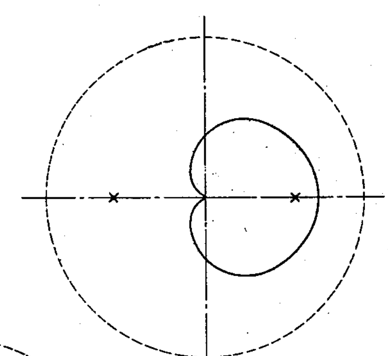

Fig. 12

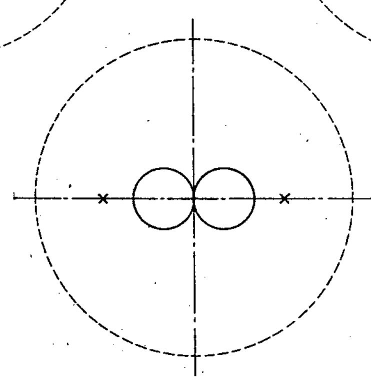

Fig. 13

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DIRECTIVE ANTENNA ARRAY

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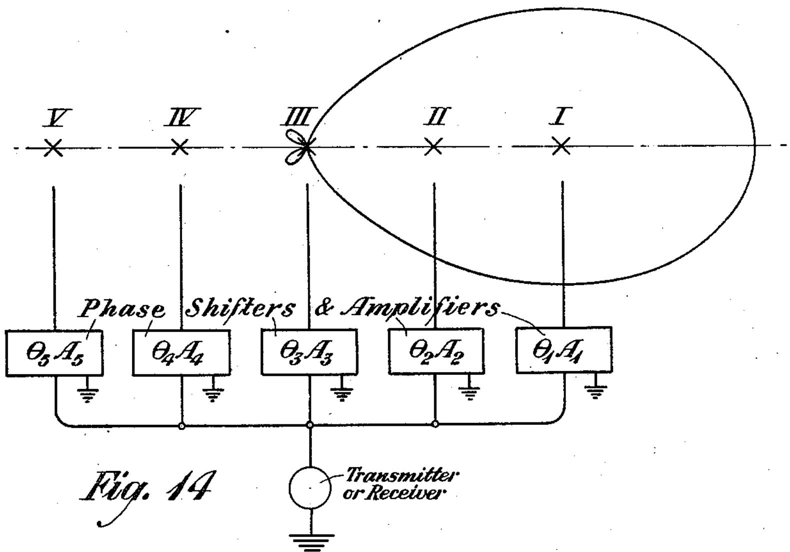

Fig. 14

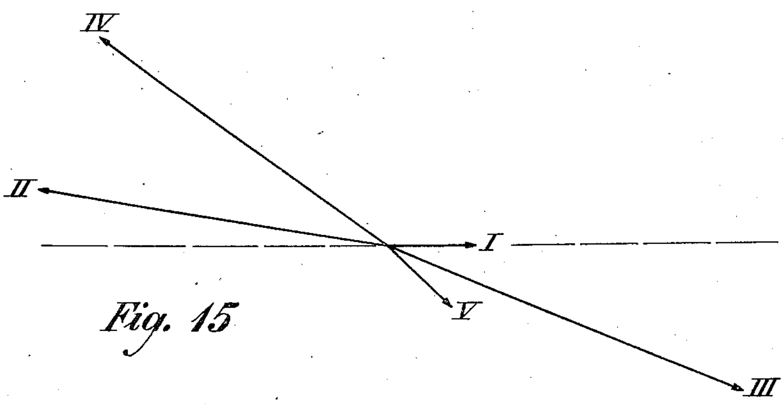

Fig. 15

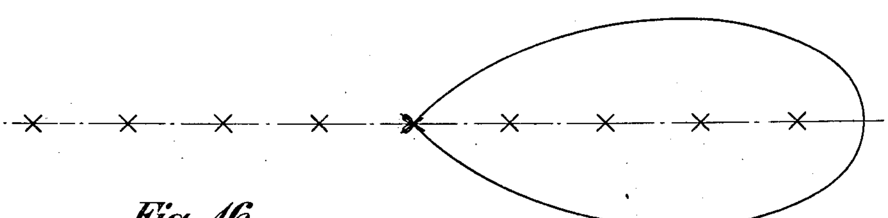

Fig. 16

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DIRECTIVE ANTENNA ARRAY

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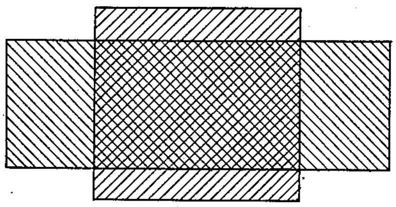

Fig. 19

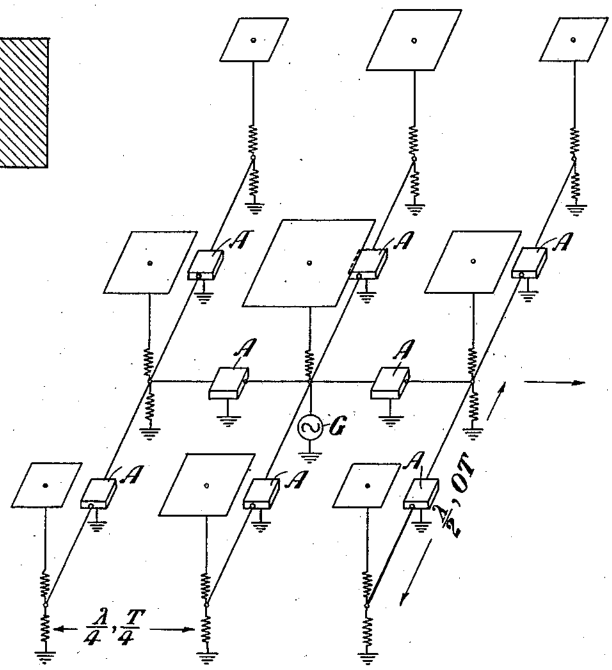

Fig. 17

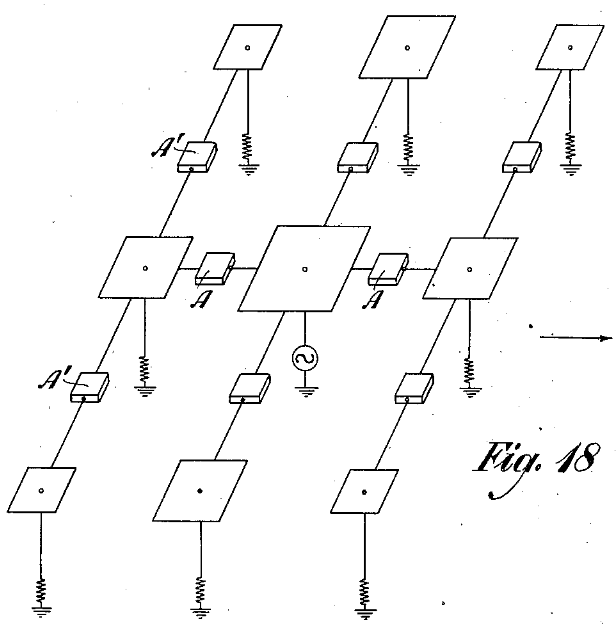

Fig. 18

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Patented Sept. 27, 1927. 1,643,323

UNITED STATES PATENT OFFICE.

JOHN STONE STONE, OF SAN DIEGO, CALIFORNIA, ASSIGNOR TO AMERICAN TELEPHONE AND TELEGRAPH COMPANY, A CORPORATION OF NEW YORK.

DIRECTIVE ANTENNA ARRAY.

Application filed January 4, 1921. Serial No. 434,947.

The principal object of my invention is to provide a new and improved directive radio transmitting or receiving station. Another object of my invention is to provide a radio station with a plurality of interconnected antennæ, so arranged as to transmit or receive effectively in a certain desired direction but not in other directions. Other objects of my invention have to do with such matters as securing a convenient and compact distribution of the antennæ at such a station, exciting them in proper amplitude and phase relation, and getting an angular distribution of intensity for the array, corresponding substantially to a polar diagram of a single loop. A directive antenna array constructed and operated according to my invention and used as a transmitter will radiate power only approximately in the direction in which it is desired to transmit and thus it will give economy of power or, in other words, the available power of the station will be radiated effectively instead of largely in noneffective directions. My directive array, as a transmitter, secures non-interference to stations in other directions than that direction to which it is desired to transmit; and for receiving, it prevents interference from stations lying in any other directions than that direction from which it is desired to receive. In short, my system greatly reduces the annoyance of "cross talk." In the same way that it eliminates interference from other stations for receiving, it also eliminates interference from static to a large extent. Directive systems have been devised which were directive in a plurality of directions, sometimes with the same intensity in each of these different directions, sometimes with different intensities in different directions. I am referring to cases in which polar diagrams of intensity show maximum radii for a plurality of different angular positions. My improved antenna array may be designed to give substantially only one maximum at the particular frequency for which the system is designed as will be made apparent in the following disclosure. These and other objects and advantages of my invention will become apparent on consideration of the disclosure of a few specific embodiments given in the following specification. The invention is defined in the appended claims, and I now proceed to describe the particular forms thereof which I have chosen to disclose by way of illustration:

Referring to the drawings, Figure 1 is a diagram showing an elevation of a pair of antennæ which may be regarded as constituting an elementary component of certain types of my improved antenna arrays. Fig. 2 is a plan diagram showing the angular distribution of intensity of radiation or reception; in other words, this is a polar diagram for the intensity of radiation from or reception by the antenna pair of Fig. 1. Fig. 3 is a diagram showing an elevation of another antenna pair which may enter in a different way in certain types of my improved antenna arrays. Fig. 4 is the polar diagram corresponding to Fig. 3. Fig. 5 is a plan diagram indicating the combination of two pairs, such as shown in Figs. 1 or 3. Fig. 6 is a plan diagram showing this combination of two of the elementary pairs of Fig. 1 with polar diagrams for intensity of radiation or reception. Fig. 7 is a corresponding diagram based on component pairs of the type of Fig. 3. Fig. 8 is a diagram showing the combination of two sets of antennæ, each like those of Fig. 5. Fig. 9 is a diagram showing the combination of two sets like those of Fig. 3. Fig. 10 is a diagram showing a rectangular array built up along one dimension according to the development indicated in connection with Figs. 1, 2, 5, 6, 8 and 9 and along the other dimension as indicated in Figs. 3, 4, 5, 7, 8 and 9. Fig. 11 is a combination of elemental and resultant polar diagrams for Fig. 10. Fig. 12 is a polar diagram for a pair of antennæ separated $\frac{1}{8}$ of a wave length and energized by currents whose phase is $\frac{3}{8}$ of a period apart. Fig. 13 is a polar diagram for a pair of antennæ separated by $\frac{1}{8}$ of a wave length and excited by currents whose phase is $\frac{1}{2}$ period apart. Fig. 14 is a diagram for a certain antenna array based on the systems of Fig. 12 and 13 as components. Fig. 15 is a diagram showing the amplitude and phase relation of the currents in the antennæ of Fig. 14 when they serve for transmitting. Fig. 16 is a diagram for a linear array of nine antennæ, located $\frac{1}{8}$ wave length apart and excited in a phase relation that will be disclosed in the explanation that follows: Figs. 17 and 18 are perspective diagrams showing how the currents may be supplied to the antennæ of one of my arrays in proper phase and intensity, and Fig. 19 is a diagram illustrating an array whose contour is not rectangular.

The two antennæ of Fig. 1 are located a quarter wave length apart and supplied with exciting currents which are in quarter phase relation. This phase displacement is indicated by the insertion of artificial lines at A to secure the desired difference of phase. At considerable distances from these two antennæ, where their respective fields are practically parallel, the resultant intensity will differ according to the direction. Only in the direction of the line joining the two antennæ and from the leading antenna through the lagging antenna will the intensities from both of them add and give a maximum. In other directions the intensity will be less, according to the polar diagram given in Fig. 2.

Thus, it follows that the antenna pair of Fig. 1 has the directive property indicated by the diagram of Fig. 2, and also the energy radiation from the pair is less than twice what it would be from a single antenna, as indicated (not necessarily quantitatively) by the proportion of the cardioid-like curve of Fig. 2 to the dotted circle.

In Fig. 3, I have shown an antenna pair with the members spaced a half wave length apart and excited in the same phase. The angular distribution of intensity of radiation for such a pair is indicated by the polar diagram of Fig. 4.

Comparing Figs. 2 and 4, it will be seen that the antenna pair of Fig. 1 gives a maximum radiation in the direction of the line joining the two antennæ and from the leading one toward the lagging one; on the other hand, the antenna pair of Fig. 3 gives a maximum radiation equally in either direction along the normal to the line joining the two antennæ.

While I have discussed the diagrams of Figs. 1 and 3 as if they represented transmitters, it is true that they act as receivers according to direction, as indicated in the diagrams of Figs. 2 and 4. In other words, the directive properties are the same whether the antenna pairs of Figs. 1 and 3 are employed for transmitting or receiving.

At a great distance from the antenna pair of Fig. 1 or Fig. 3, its effect is equivalent to a single source half way between the two sources, but having a polar diagram like that given in Fig. 2 or Fig. 4, respectively. Thus, I may look upon such an antenna pair as equivalent to a single source and for convenience I call this equivalent source a consequent source of the first order.

If two consequent sources of the first order are placed at P and Q in Fig. 5, a quarter wave length apart and with their axes in the same direction, this will give an arrangement of four antennæ, two of which will be positioned close together, as shown by the adjacent crosses in Fig. 5. Instead of adding the intensities at the intermediate position by placing two antennæ there, it will be more convenient to add these intensities on a single antenna. This gives the arrangement shown schematically in Fig. 6, where the numerals in parentheses indicate relative intensities on the respective antennæ, thus in order (1), (2) and (1). The polar diagram for the combination of the two consequent sources of the first order is shown in a full line and for the purpose of comparison a polar diagram of the same maximum radius, such as given by a single consequent source of the first order, is shown in dotted lines. It will be seen that by combining the two consequent sources of the first order, as in Figs. 5 and 6, I have secured greater directivity. This is shown by the fact that the polar diagram has shorter radii for all directions except the direction of maximum intensity. The combination of the two consequent sources of the first order shown in Figs. 5 and 6 gives what I call a consequent source of the second order.

In like manner, the combination of the two consequent sources of the first order as shown in Figs. 5 and 7 gives a consequent source of the second order. Thus, it will be seen that a source of the second order is more narrowly directive than the first order sources of which it is built, though the general character of the transmission is unchanged, that is, it continues to be uni-directional or duo-directional, as the case may be.

Two second order consequent sources, with their centres a quarter wave length apart and their directions of maximum intensity coinciding, are shown assembled in Fig. 8. The component intensities on the four antennæ are indicated and the addition is shown by which the resultant intensities are obtained. In order, the latter are (1), (3), (3) and (1). The result of the assembly indicated in Fig. 8 is a consequent source of the third order. From the foregoing discussion, it will at once be apparent, with the aid of Fig. 9, how I combined two consequent sources of the third order to obtain a consequent source of the fourth order with five antennæ on which the intensities or amplitudes in order are respectively (1), (4), (6), (4) and (1). Each time that I combine two consequent sources of the nth order to form a consequent source of the $(n+1)$th order, I secure a further narrowing of the polar diagram, just as I explained in detail for the transition of Figs. 6 and 7. The illustration has been carried far enough to show that the law by which the intensities are created in the successive antennæ of the row, is the law of the coefficients in the binomial expansion. In general, the formula for the $(r+1)$th coefficient is

$$\frac{n!}{r!(n-r)!},$$

where n is the order of the expansion. In terms of the present discussion, the intensity of the $(r+1)$th antenna in a consequent source of the nth order is given by this formula. Thus, for Fig. 9, if n is made equal to 4 and r is successively 0, 1, 2, 3 and 4, the results will give the numbers (1), (4), (6), (4) and (1).

Returning now to Figs. 3 and 4 and comparing with Figs. 1 and 2, it will be seen that each loop of the polar diagram in Fig. 4 is decidedly narrower than the diagram of Fig. 2. This is an advantage in directivity but with it comes the disadvantage that radiation in this case is equal in opposite directions. I will now show how the two component types may be combined to join their advantages and eliminate their disadvantages.

Fig. 10 may be looked upon as an assembly of consequent sources of the nth order (each source corresponding to a column of the figure), combined according to the rules for building up a consequent source of the mth order, or vice versa. Hence, I call it a consequent source of the nmth order, or, equally well, it might be called a consequent source of the mnth order. In this particular example, I have made n equal 4 and m equal 5. The numbers along the marginal column, namely (1), (4), (6), (4), (1), give intensities on the respective antennæ for the single consequent source of the fourth order. For the consequent source of the fifth order, the numbers run (1), (5), (10), (10), (5), (1), as given in the upper row of the diagram of Fig. 10. The numbers for the interior positions are obtained by multiplication, as will be readily apparent.

The effect of combining consequent sources in the manner here illustrated in Fig. 11, is to gain the advantage of uni-direction over duo-direction, inherent in the one species, and the advantage of narrower angular distribution of intensity, inherent in the other species. In Fig. 11, curve 1 is the polar diagram for the antenna pair MN. Curve 2 is the polar diagram for the antenna pair RS, and curve 3 is the polar diagram for the combined array of Fig. 10.

Here as elsewhere in this specification, I describe the structure and operation of the antenna array more from the standpoint of transmitting than receiving, but in fact the operation is reciprocal and the polar diagrams apply either way.

In Fig. 12, I have disclosed the polar diagram for another type of antenna pair, comprising two antennæ whose distance apart is ⅛ of a wave length and which are energized for transmitting by currents differing in phase by ⅜ of a complete period. It will be seen that even in the direction of maximum resultant intensity, the intensity is less than the scalar sum of the maximum intensities on the two antennæ. Otherwise, the polar diagram is of the general character shown in Fig. 2. Compared with Fig. 2, the geographical extent of the array of two antennæ is only half as great.

Fig. 13 gives the polar diagram for two antennæ spaced ⅛ of a wave length apart and excited by currents which differ in phase by half a complete period. It will be seen that this polar diagram gives maximum intensities in two opposite directions lying along the line determined by the two antennæ.

The antenna pairs of Figs. 12 and 13 each constitute a consequent source. For convenience I represent Fig. 12 by the formula

$$\left\{\frac{\lambda}{8}, \frac{3}{8}T\right\}$$

where the expression preceding the comma gives the spacing between the two elemental sources in terms of the wave length λ, and the expression following the comma gives the phase difference in terms of the time T for a complete cycle. In the same way, the diagram of Fig. 13 corresponds to the formula

$$\left\{\frac{\lambda}{8}, \frac{1}{2}T\right\}.$$

To arrive at the antenna array whose polar diagram appears in Fig. 14, I first combine two of the consequent sources of Fig. 13 to get a consequent source of the next higher order and again I combine two of these consequent sources to get another consequent source of the next higher order. Each such combination adds one antenna to the array and thus I get a row of four antennæ constituting a consequent source of the third order which I represent by the formula

$$\left\{\frac{\lambda}{8}, \frac{1}{2}T\right\}^3.$$

The general effect is to give a polar diagram like that of Fig. 13 but with narrower and shorter loops. Finally, I take two sources, each represented by the last formula and combine them according to the formula

$$\left\{\frac{\lambda}{8}, \frac{3}{8}T\right\}.$$

This adds one more antenna, making the complete array of five, and substantially converts the double loop of Fig. 13 into a single loop, as shown in Fig. 14. With a larger number of antennæ, the diagram can be narrowed to any extent that is desired. The actual resultant currents on the five antennæ are shown in magnitude and phase relation in the diagram of Fig. 15. In each antenna there is an alternating current which may be represented according to the well known convention by the projection of a rotating vector. Fig. 15 shows the five vectors whose projections as they rotate simultaneously will give the five currents in the respective antennæ. Calling the angle O for the antenna designated I, and the current magnitude on this same antenna being represented by unity, the currents and angles for transmitting are given in the following table:

	$\left(\frac{\lambda}{8}, \frac{1}{2}T\right)^3$ A	$\left(\frac{\lambda}{8}, \frac{3}{8}T\right)$ Θ	
I	1,	0°	
II	3.96	169°	13′
III	4.24	−22°	30′
IV	3.96	−145°	47′
V	1	−45°	

The resultant magnitude of intensity in the direction for a maximum is less than the magnitude on some of the individual antennæ. Comparing the array of Fig. 14 with those of Figs. 1 to 11, it will be seen that the currents in the individual antennæ of Fig. 14 buck one another to a certain extent more than for the earlier figures. On the other hand, the consecutive antennæ are nearer together in Fig. 14 and hence the array is of comparatively less geographical extent. Of course, for substantially the same polar diagrams in the two cases, the energy radiated (in transmission) would be substantially the same, but for the array of Fig. 14 the current magnitudes in the apparatus would be greater and thus, to some extent, the true resistance losses would be greater. This slight disadvantage might be much more than compensated by the gain in having a compact geographical array.

For receiving purposes, the loss of energy in resistance would be immaterial because amplifiers could be employed to magnify the received energy. In receiving, the actual currents excited in the antennæ would not have the phase and magnitude relations that they would have for transmitting, but the phase shifters and amplifiers shown in Fig. 14 would operate to make the current on the receiver correspond to the polar diagram.

In Fig. 16, I have shown an antenna array of nine antennæ in a row, separated by intervals of only $\frac{1}{16}$ of a wave length. The design of this array is reached as follows: I start with a simple consequent source of the first order represented to two antennæ $\frac{1}{16}$ wave length apart and differing in phase by half a complete period and corresponding to the formula

$$\left(\frac{\lambda}{16}, \frac{1}{2}T\right).$$

I build two of these into a consequent source of the next higher order, two of the resultants into a consequent source of one step higher order, and so on until I have seven antennæ in an array represented by the formula

$$\left(\frac{\lambda}{16}, \frac{1}{2}T\right)^6.$$

Then I take two such consequent sources, each represented by the foregoing formula and combine them into a consequent source, in accordance with the formula

$$\left(\frac{\lambda}{8}, \frac{3}{8}T\right).$$

Since the antennæ up to this point were $\frac{1}{16}$ wave length apart and since the two equal consequent sources last mentioned are to be $\frac{1}{8}$ wave length apart, this last operation adds two more antennæ to the array, making the nine shown in the diagram. The details of a further discussion of Fig. 16 would correspond to those for Figs. 14 and 15 and I will merely point out that the polar diagram of Fig. 16 is noticeably narrower than for Fig. 14, although the geographical extent of the array is the same.

Having given the foregoing examples of embodiments of my invention I will now set forth the theory in somewhat greater generality than heretofore.

Consider two simple radiators with relative spatial displacements x, y and relative phase Θ, and of frequency $p/2\pi$. In other words, if two axes at right angles are laid off on the ground with their intersection at one antenna, then x and y are the rectangular coordinates of the other antenna, and the currents in these two antennæ are both of the same frequency $p/2\pi$, but they differ in phase by the angle Θ. At a great distance from such an antenna pair, the intensity will be different in different directions. Assuming polar coordinates, the intensity may be represented by a radius vector with origin near the antenna pair. The expression which gives the value of this radius vector in terms of the angle ϕ is called the interference pattern. In the present case the interference pattern is given by the radius vector whose value as a function of the independent variable angle ϕ is

$$\sin pt+\sin\left[pt-\frac{2\pi}{\lambda}x\cos\phi-\frac{2\pi}{\lambda}y\sin\phi-\Theta\right]$$

which, when referred to the origin

$$\frac{x}{2},\frac{y}{2},\frac{\Theta}{2},$$

may be written as

$$\sin\left[pt+\frac{1}{2}\left(\frac{2\pi}{\lambda}x\cos\phi+\frac{2\pi}{\lambda}y\sin\phi+\Theta\right)\right]$$

$$+\sin\left[pt-\frac{1}{2}\left(\frac{2\pi}{\lambda}x\cos\phi+\frac{2\pi}{\lambda}y\sin\phi+\Theta\right)\right]$$

$$=\sin pt.2\cos\left[\frac{1}{2}\left(\frac{2\pi}{\lambda}x\cos\phi+\frac{2\pi}{\lambda}y\sin\phi+\Theta\right)\right]$$

$$=\sin pt.F(\phi)$$

where

$$F(\phi)=2\cos\left[\frac{x}{\lambda}\pi\cos\phi+\frac{y}{\lambda}\pi\sin\phi+\frac{\Theta}{2}\right]$$

is the resultant interference pattern. It follows at once that the two simple radiators or sources are equivalent to a single compound source, located at

$$\frac{x}{2},\frac{y}{2},\frac{\Theta}{2}$$

and having an interference pattern $F(\phi)$. This equivalent compound radiator or source is what I refer to as a consequent source of the first order.

Now consider two similar and equal consequent sources of the first order having interference pattern $F_1(\phi)$ and relative displacement x_2, y_2, Θ_2. It follows at once that they are equivalent to a single compound source located at

$$\frac{x_2}{2},\frac{y_2}{2},\frac{\Theta_2}{2}$$

and having an interference pattern $F_1(\phi)$ $F_2(\phi)$ where

$$F_2(\phi)=2\cos\left[\frac{x_2}{\lambda}\pi\cos\phi+\frac{y_2}{\lambda}\pi\sin\phi+\frac{\Theta_2}{2}\right]$$

This equivalent source is termed a consequent source of the 2nd order.

This leads to the general law for building up consequent sources and the formula for the resultant interference pattern.

Let $F_1(\phi)$ denote the interference pattern of two single sources with relative displacements x_1, y_1, Θ_1, and let this doublet be referred to as type T_1, or a consequent source of the first order of type T_1. Now let the compound system be built up as follows:

(1) A consequent source of 1st order of type T_1,

(2) Two consequent sources of 1st order of type T_1, displaced in accordance with type T_2, forming a consequent source of 2nd order of type T_1 T_2.

(3) Two consequent sources of 2nd order of type T_1 T_2, displaced in accordance with type T_3 forming a consequent source of 3rd order of type T_1 T_2 T_3.

If this process is continued to build up a consequent source of the nth order of type T_1 T_2—T_n, the resulting interference pattern is $F_1(\phi).F_2(\phi).F_3(\phi)—F_n(\phi)$.

In Fig. 17 I have given a perspective diagram of a simple rectangular array of nine antennæ showing how they may be supplied with currents in proper intensity and phase relation from a common generator G. In this case, the amplitudes or intensities of the currents should be according to the following table:

$$\begin{pmatrix}1\\2\\1\end{pmatrix}\quad\begin{pmatrix}2\\4\\2\end{pmatrix}\quad\begin{pmatrix}1\\2\\1\end{pmatrix}$$

I secure this relation by a proper design of the antennæ, and to indicate this, I have shown the antennæ with their overhead structures of different size, somewhat in accordance with the foregoing table. It will be readily understood that those antennæ that have larger overhead portions, and hence, larger capacity to ground, will take more current when supplied with a given electromotive force, and will radiate more energy.

To secure the desired quarter-phase lead for each transverse row to the rear, relatively to the direction of radiation, I introduce artificial lines or similar devices A, as indicated in the diagram. Of course, it will be understood that to keep all the antennæ in the same transverse row in the same phase, it may be necessary to employ phase restoring devices, which can be introduced into the transverse feeders accordingly.

In Fig. 18 I have shown overhead connections between the antennæ of the array by which certain antennæ are fed through others. The artificial lines or other devices A are intended to secure the proper phase shift for each transverse row to the rear, relatively to the direction of maximum radiation. The devices A′ are intended to secure such an adjustment that all the antennæ of the same transverse row shall oscillate together in the same phase. The design of the several antennæ may be varied to contribute to securing the proper phase relation, as well as the proper amplitude relation.

The disclosure in connection with Figs. 17 and 18 has had reference more particularly to transmission, but the structure and operation for receiving will be evident, in accordance with the principles heretofore discussed.

From the foregoing examples it will be understood how the desired phase and intensity relations may be obtained for other arrays. Loop antennæ may be employed, especially for receiving, with the vertical sides of the same loop corresponding to two consecutive antennæ as shown in the diagrams. Also the antennæ may be energized by respective local sources, controlled by pilot currents from a central station as disclosed in the Buckley Patent No. 1,301,644 of April 22, 1919.

It is not necessary that an array be merely linear or rectagular to realize the principle of my invention. Fig. 19 shows a non-rectangular contour, obtained in this case by superposing one rectagle on another. The intensities on the antennæ common to both rectangles will be the respective sums of the intensities they would have if they belonged to the rectangles apart.

What I claim is:

1. A plurality of antennæ distributed in rectangular array in two dimensions with more than two antennæ along each dimension, a common station conductively connected with said antennæ, and means interposed in the connections to get the currents in progressive orderly phase relation along one direction and in progressive orderly phase relation along the other direction.

2. A plurality of antennæ distributed in rectangular array in two dimensions with more than two antennæ along each dimension, a common station conductively connected with said antennæ, and means interposed in the connections to get the currents in progressive orderly phase relation along one direction and in progressive orderly phase relation along the other direction, said antennæ being spaced a half-wave length along one dimension and a quarter-wave length along the other dimension.

3. The method of securing uni-directional transmission or reception with a rectangular antenna array having more than two antennæ along each dimension, which comprises grading the intensities of excitation along the rows and columns of the array according to the coefficients of the binomial expansion.

4. The method of securing unidirectional transmission with a rectangular antenna array, which consists in grading the intensities of excitation along the rows and colunms of the array according to the coefficients of the binomial expansion and exciting the antennæ a quarter phase ahead for each interval in the direction of maximum intensity and in the same phase across that direction.

In testimony whereof, I have signed my name to this specification this 23rd day of December, 1920.

JOHN STONE STONE.