Focusing Principle of Phased Array Antennas for Localization Applications

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Abstract: This work concerns the localization of wireless communication systems. The use of focusing principle in order to localize radiation at a given space point is considered. The later is obtained by application of Huygens principle.

Keywords: Localization, Focusing, Radiation source, RF Lens, Interference.

1. INTRODUCTION

Since the 50's, The Radio Frequency (RF) systems have never stopped to become more and more sophisticated. Today, they are used in most of applications as for example: telecommunications, like Wifi or Ultra Wide Band systems, medicine, like scanner or MRI and recently, traceability with the Radio Frequency Identification (RFID) [1]. In all these applications, the antenna takes an important place. A lot of behaviors have been developed around this component. In MIMO systems multiple antennas are used to improve the communication by using the spatial and/or polarization diversity. In radar, scanning beam or conformal beam were developed with RF Lens [2], phased arrays [3] and more recently metamaterial antenna [4].

With the growing interest of the RFID in both industry, and everyday life, new applications like tag localization were needed. This could be done with triangulation systems. This system is based on three different antennas to find the position of the tag. To be efficient, a powerful post processing have to be done in order to calculate the position of the tag as a function of the three signals. Another solution is the use of focusing systems like in optics with the spherical lens. In [5], a square array is used to focus at 12 GHz for sensor applications like the characterization of substrate. This system allows a focal point at 126 mm with 16 antennas but its design is tedious due to a complicated feeding network. Indeed, each antenna has to be feed with a particular phase.

In this paper, we propose to use a circular phase antenna array to realize a focusing system. First, the principle of this system is introduced. In the second part, theoretical and simulation results are presented. Finally, the last section concludes the paper

2. FOCUSING BEAM SYSTEM PRINCIPLE

In optics, a common way to focus a light beam is to use a spherical lens (Fig.1 (a)). A lens can be seen as a phase transformer. An incident plane wave is transformed into a spherical wave that will be focused at the focal point by undergo a phase shift function of r, radius of the lens, to the incident wave front. The light wave propagation can be explained with the Huygens-Fresnel principle [6]. It states that each point of a wave front is a secondary light source that emits a spherical wavelet whose complex amplitude is proportional to the complex amplitude of the incident wave. The wave fronts are found by interfering, at each point, all the wavelets produces by the secondary sources. Following this, a convergent wave front can be emulated in the RF domain with a circular phase array (Fig. 1 (b)). Each radiator will generate a spherical wave with a phase shift ϕ_{ij} given by the equation (1).

$$\phi_{ij} = k\left(\sqrt{f^2 + \left(x_i^2 + y_j^2\right)} - f\right) \tag{1}$$

with x_i, y_j, the coordinate of the antenna, k the wave number and f the focus length. The Electrical (E) field is then calculated by summing each spherical wave following equation (2).

$$E\left(xf, yf\right) = \sum_{i=1}^{n}\sum_{j=1}^{n} A\frac{e^{jkR_{ij}}}{R_{ij}}e^{-j\phi_{ij}}\ , \tag{2}$$

with:

$$R_{ij} = \sqrt{\left(x_i - x_f\right)^2 + \left(y_i - y_f\right)^2 + f}\ , \tag{3}$$

where x_i, y_j are the coordinates in the thin lens plane, x_f, y_f are the coordinates in the focal plan, A is the amplitude of the field and k is the wave number.

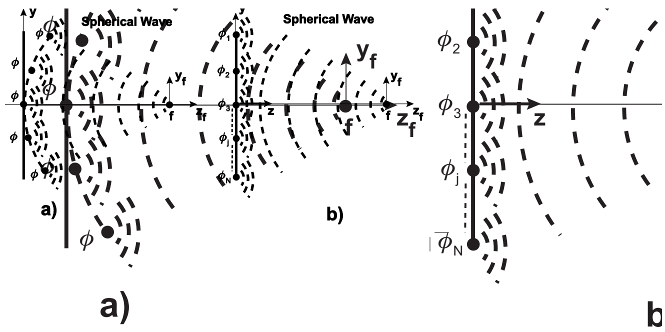


Fig. 1. Equivalent Systems of a) thin spherical lens b) of the RF focusing system.

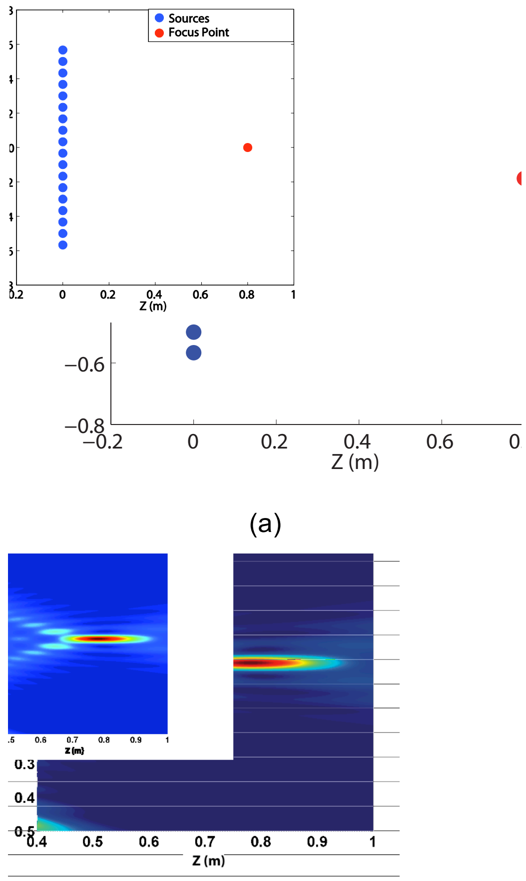
The figure 2 (a) shows an example of focusing phased array antennas composed of 18 isotropic sources. The phase distribution was calculated with equation (1) to have a focus point at 800 mm. The total length of the array is 1200 mm. We can clearly see the focalization point on the figure 2 (b). The full width at half maximum of the beam is 200 mm x 40 mm. Our simulations have clearly shown that the size of the spot is inversely proportional to the size of the array. The width of the spot is also limited by the wavelength of the used signal. The size of the waist is not influenced by the number of sources. The figure 3 shows the variation of the electric field along the Z axis for an array of 1 m diameter of 60 isotropic antennas and a second one of the same dimension but with only 6 antennas, the focal point being fixed at 780 mm. The amplitude's variation is the same in both cases. The only difference is the apparition of periodic secondary lobes in the focal point along the *x* and *y* axes due to the increase of the sampling frequency.

We can see the apparition of side lobes around the focal point on the figure 2 (b). This is due to the finite size of the array. The electrical field emitted by the array is computed with the equation (2). This equation can be seen as a discrete Fourier transform of a window signal with a width equal to the length of the array. The result will be a signal with a shape of cardinal sinus.

In practice, an isotropic antenna does not exist. For example, a short dipole has an omni-directional radiation pattern. The E field E_θ of a dipole along x in far field is:

$$E_\theta(r,\theta) = \frac{j k I_0 l e^{-jkr}}{8\pi r}\sin\theta = jA\frac{e^{-jkr}}{8\pi r}\sin\theta, \qquad (4)$$

with k, the wave number, I_0, the current along the dipole and l, the length of the dipole. The r and θ parameters are the usual spherical coordinates with respect to the (x,y,z) axes of the figure 1. The main difference between the equation (4) and the E field of an isotropic source is the term $\sin\theta$ that will modify the E field following the azimuth angle. Its influence will be maximum near the antenna and negligible when θ will be closed to 0°. This particularity can be used to minimize the parasitic sidelobes near the array.



(a)

(b)

Fig. 2. a) Phased array antennas of 18 isotropic sources with a focus point at 800 mm b) Average power emitted by the array

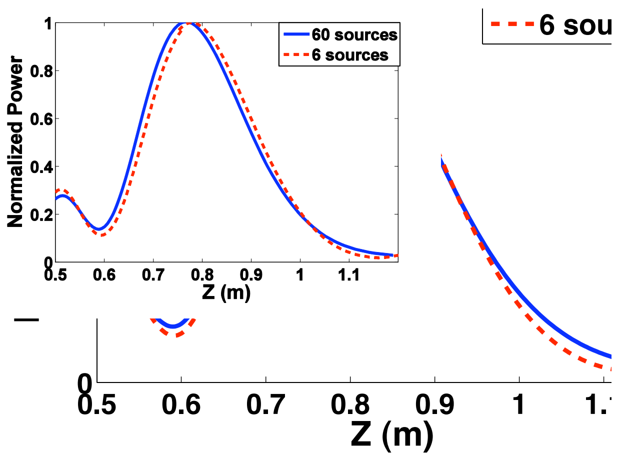


Fig. 3. Normalized Power along Z axis for an array of 1 meter of diameter with 6 rows and 60 rows of antennas.

The figure 4 shows the E field along the z axis of an array of 6 dipoles oriented along x and y. The phase distribution was computed to provide a focus point at z = 1000 mm. The E field for the array oriented following y-axes has less parasitic fluctuations for z less than 500 mm. As the field radiate by the dipole is function of sin θ, its magnitude will decrease when we are near the array. We can see that the magnitude at the focus point is the same in both cases. When z > 500 mm, the field $|E_\theta|$ can be approximate by:

$$E_\theta(r,\theta) \approx \frac{j k I_0 l e^{-jkr}}{8\pi r}. \tag{5}$$

In this case, the E field becomes equal to the one with the isotropic sources. For this reason, we choose to use this orientation for the experimental realization.

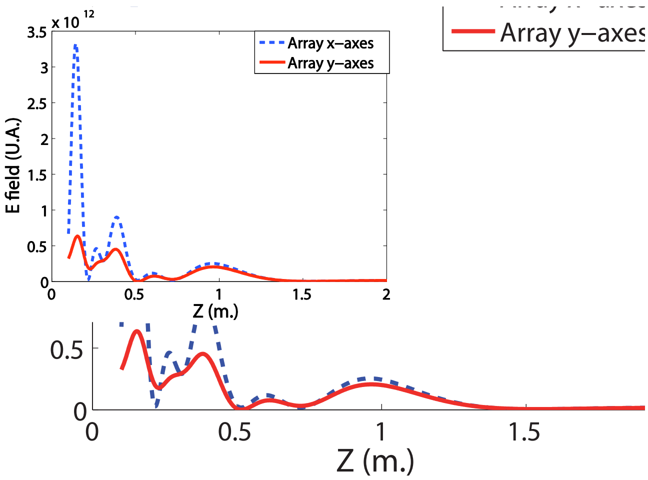


Fig. 4. $|E_\theta|$ for an array of 6 dipoles following the x and y direction for a focus length of 1000 mm. The length of the array is 1000 mm.

3. FOCUSING SYSTEM IMPLEMENTATION

The figure 5 shows the scheme of the chosen array with its feeding network. We designed a circular array of dipole antenna in the RFID frequency band of 5.8 Ghz. This frequency was chosen to have a small focal waist: the size of the spot is inversely proportional to the frequency. The array is made of three rows of 8 antennas. In this configuration, only two phase shifts are needed to control the focus length. This is done with commercial phase shifters. The feeding network and the dipole antennas were made on Arlon 25N substrate (60 mils thick, εr = 3.38, tanδ = 0.0025). The magnitude of the electric field of the array was measured with a HP8720D vectorial network analyzer in an anechoic chamber. A dipole antenna was used as a probe.

4. THEORETICAL AND MEASUREMENTS RESULTS

The figure 6 shows the comparison between the developed theory, full wave simulations and experimental measurements of the power along Z-axis of the circular array composed of three rows with radius of 100 mm, 300 mm and 500 mm respectively. The phase shift distribution was computed to provide a focal plane at 850 mm. We see a good agreement between simulations and measurement. The measured focal spot is located at a distance of 850 mm as expected. The full width at half maximum is equal to 230 mm along Z and 60 mm along X axes. The figure 7 shows the power variation along X axisfor a second focal length of 1000 mm obtained with the same array. The size of the spot is 260 mm along z and 100 mm along x axis. As expected, the size increases when the focal length increases for a constant array's diameter.

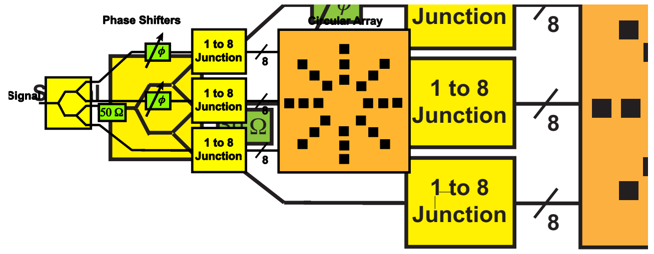


Fig. 5. Scheme of the chosen array with its feeding network.

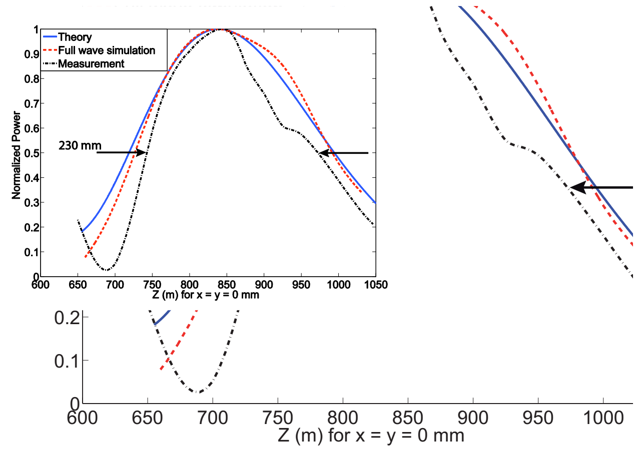


Fig. 6. Theoretical, Full Wave simulation and measured normalized power along z axes of a 3 rows array with radius of 100 mm, 300 mm and 500 mm respectively. Focus length is 850 mm.

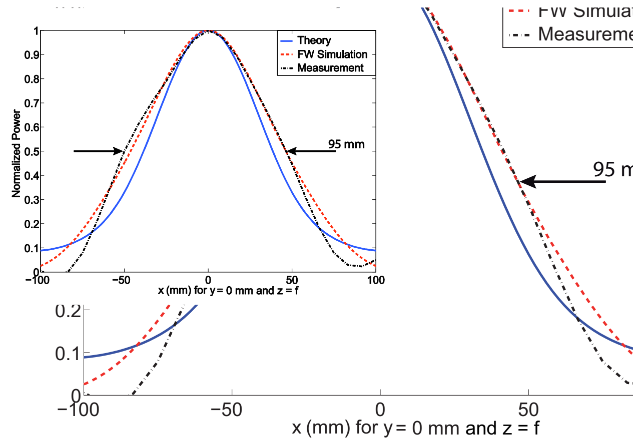


Fig. 7. Theoretical, Full Wave simulation and measured normalized power along z axes of a 3 rows array with radius of 100 mm, 300 mm and 500 mm respectively. Focus length is 1000 mm.

4. CONCLUSION

A circular microstrip array with focused beam for RFID applications was presented. An analogy with the optical lens and optical diffraction was made to describe the behavior of this system. A theoretical analysis shows that the critical parameter of this type of structure is the global size of the array. The number of sources has low influence on the size of the focal point. The use of dipole antenna as sources in the array was analyzed theoretically. An example of focusing array in the 5.8 Ghz RFID band was presented. A comparison between theoretical predictions, full wave simulations and measurements for two focus lengths was presented with good agreement. This solution could be used to develop RFID devices for the localization solution.

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