Analysis of Beamforming in Phased Antenna Arrays

Octavian MANU, Mihai DIMIAN, Adrian GRAUR
Stefan cel Mare University of Suceava
str.Universitatii nr.13, RO-720229 Suceava
octavianm@eed.usv.ro

Abstract — **In this paper the beamforming and radiation pattern of various linear and planar phased antenna arrays configurations are presented. They are intended for use in indoor location estimation and wireless process monitoring applications based on the determining of direction-of-arrival (DOA) of radio signals by measuring the angle-of-arrival (AOA). Beamforming and the steering of antenna's lobes are obtained via a linear phase taper applied between antenna array elements, which provides a relatively simple design. Various antenna array configurations are studied using numerical simulations in order to obtain an optimal beamforming necessary for indoor localization and scanning systems.**

Index Terms — **Antenna arrays, Antenna radiation patterns, Array signal processing, Phased arrays, Indoor localization**

I. INTRODUCTION

The location-based services have received an increasing amount of research interest during the recent years [1, 2]. Ambient Assisted Living is one area aimed at using indoor localization technologies to implement various services such as guidance in unfamiliar buildings, personal security, home based healthcare and the development of innovative interfaces. The new developments in the area of smart sensor network could also benefit from indoor localization in applications like monitoring industrial equipment or warehouse goods management where data recorded from wireless sensors are correlated with their positions. Other promising applications are related to shopping assistance and follow-me services.

While the outdoor localization applications have a general solution based on the Global Position System (GPS) technology, no satisfactory solution has been developed for indoor localization. Several approaches are currently under intense research focus based on infrared, ultrasonic, terahertz and radio technologies. The wireless localization can be realized by using triangulation techniques based on time of arrival (TOA), angle of arrival (AOA) or received signal strength (RSS), multilateration techniques involving time difference of arrival (TDOA), and fingerprint techniques. In the case of TOA, a sphere of presence can be estimated by acquiring the time of flight and multiplying it with the light speed. A necessary requirement of this technique is the synchronization of the clocks of the reference devices. In the case of RSS method, the distance is computed from the power path loss by measuring the received power and comparing it with the transmitted power. The AOA localization method uses the baseline and at least two AOA. Consequently, the position of the user can be obtained from the intersection of three or more spheres of presence, which concludes the trilateration method. By measuring TDOA of a signal from the emitter at two receivers a hyperboloid surface of possible locations is determined, so four or more receivers can uniquely determine the emitter's location as the intersection of three hyperboloids, which constitutes the multilateration method. The last method is based on RSS techniques, but it does not rely on calculating the signal fading in an environment. Instead, this technique relies on a training phase to collect information about the radio signal strength at different locations into a database, known as radio map. In terms of practical implementation, various technologies, such as GPS, radio-frequency identification (RFID), global systems for mobile (GSM) communications, or wireless local area network (W-LAN), have been employed in developing the indoor localization and scanning systems, but no definite solution currently exists [1, 3]. One of the most important issues in this development is the accuracy of location estimation. The possible absence of the line of sight, multi-path diversity along with other wave-related phenomena significantly increase the degree of complexity for the indoor localization and scanning regardless of the technique used and the measurement accuracy [4, 5].

The analysis performed in this paper refers to indoor position estimation and scanning based on an AOA triangulation technique which involves smart antennas for measuring the angle of arrival. The desired radiation pattern of these antennas consists of a main lobe which must be as narrow as possible and significantly greater than the minor sidelobes. Smart antennas have the great advantage of being able to electronically modify its radiation pattern without any moving parts which can be realized by using an array of antenna elements equipped with variable phase shifters or time delays. In addition, signal processing techniques, coined as beamforming, can be used in antenna array for directional signal transmission or reception. An electronically steered array used for localization purposes can be practically realized either as a switched beams array or as an adaptive antenna array. In the case of switched beams array, antenna switches periodically between the predefined beams pattern in order to cover the scanning plane. The adaptive array system can offer optimal gain since it actively identifies and tracks both the desired and the interfering signals.

II. THEORETICAL APPROACH

Let us consider an antenna array with K linear elements oriented along z-axis (see Fig. 1) with a linear phase taper between antenna elements of ψi. The total signal received by the antenna array in the horizontal plane at angle φ with y-axis (normal to the array) can be written as follows [6]:

$$S(\varphi) = S_e(\varphi) \cdot S_a(\varphi) \quad (1)$$

where $S_e(\varphi)$ represents the complex radiation pattern of one individual radiator and $S_a(\varphi)$ is known as the array factor and is explicitly given by the following formula:

$$S_a(\varphi) = \sum_{i=1}^{K} e^{j[k_0 (K-i) d \cdot \sin(\varphi) + \psi_i]} \quad (2)$$

where k_0 represents the free space wavenumber, while d is the spacing between antenna elements.

In order to form a beam in the desired direction φ_0 let us choose a linear phase taper of the following form:

$$\psi i = -k0(K-i)d \cdot \sin(\varphi 0) \quad \text{for } i = 1, 2, \ldots, K \quad (3)$$

The maximum of the corresponding array factor is attained for: $\sin(\varphi) - \sin(\varphi_0) = 0$, or, provided that $-90° \leq \varphi$, $\varphi_0 \leq 90°$, for $\varphi = \varphi_0$. Thus, by choosing a desired beam-pointing direction φ_0 and subsequently phasing the linear antenna array elements according to $\psi_i = -k_0(K-i)d \sin(\varphi_0)$, the array factor will reach its maximum at the desired angle $\varphi = \varphi_0$. This property can be used to design the phased antenna array for indoor scanning and localization.

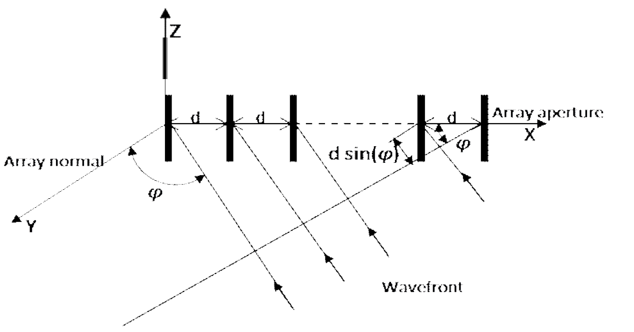


Fig. 1. Schematic representation of the linear antenna array and the coordinate axes.

However, the previous theoretical analysis has not taken into consideration the mutual coupling between antenna elements nor the interaction between the radiation and the indoor environment. Parts of these issues are addressed in section III.

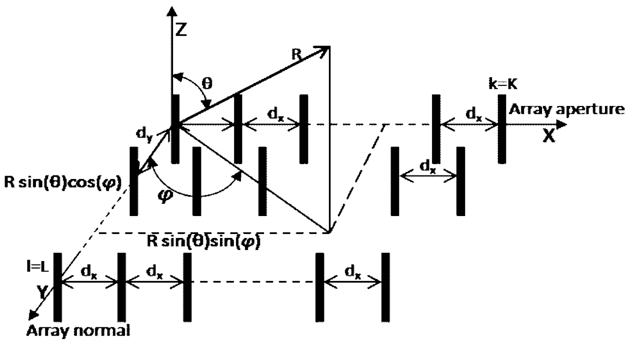


Fig. 2. Schematic representation of the planar antenna array consisting of *K* X *L* elements and the coordinate axes.

Next, let us consider a planar antenna array with K x L elements arranged in a rectangular lattice, grouped in a configuration of L rows, having an inter-element distance dy between the rows and K columns with an inter-elements distance dx between columns as shown in Figure 2. This antenna array can be regarded, for example, as a linear antenna array directed along the x-axis, having linear arrays as elements, directed along the y-axis.

The natural occurring phase difference ψkl of element (k,l) relative to the element (1,1) chosen as reference, is given by:

$$\psi kl = k0(k-1)dx \cdot \sin(\theta)\sin(\varphi) + k0(l-1)dy \cdot \sin(\theta)\cos(\varphi) \quad (4)$$

where k0 represents the free space wavenumber, dx dy represent the spacing between elements across X and Y axis.

The resulting planar array radiation pattern S(θ,φ) is given by the following formula:

$$S(\theta,\varphi) = S_e(\theta,\varphi) \cdot S_a(\theta,\varphi) \quad (5)$$

where Se(θ, φ) represents the element radiation pattern.

The array factor Sa(θ, φ) of a rectangular planar phased antenna array becomes:

$$S_a(\theta,\varphi) = \sum_{k=1}^{K} \sum_{l=1}^{L} e^{j(\psi_{kl} + \Psi'_{kl})} \quad (6)$$

In order to steer the beam in the desired direction we must chose a phase taper that satisfies the following relation:

$$\Psi' kl = -k0(k-1)dx\sin(\theta 0)\sin(\varphi 0) + k0(l-1)dy\sin(\theta 0)\cos(\varphi 0) \quad (7)$$

where (θ_0, φ_0) indicates the direction for the desired beam. It is apparent from eqs. (5)-(7) that the maximum of the array radiation will occur for $(\theta, \varphi) = (\theta_0, \varphi_0)$. Compared to the beam of the linear antenna array which can be steered only in one plane, the beam of the planar antenna array can be steered in any direction (θ, φ). However in our study we analyze the steering of the planar array's beam only in the *xy* plane, as needed for an indoor localization system. Thus, the value of θ_0 will be 90°. For φ_0 equals to 0°, the planar array is viewed as a linear array of K elements along the x axis, and for φ_0 equals to 90° scanning angle, the planar array is viewed as a linear array of L elements along the y axis. This theoretical analysis, as in case of linear antenna arrays, has not taken into account the mutual coupling between antenna elements. Due to more compact nature of planar antenna array where a relative large number of elements are close together, the effects of mutual coupling between planar antenna array's elements are greater than the effects of mutual coupling between the elements of the linear antenna array.

III. MULTI ELEMENTS LINEAR ANTENNA ARRAY

Antenna array elements are typically made of yagi-antennas, helix-antennas, printed dipoles, patch antenna, and slotted waveguides. Antenna array simulations were performed by using 4NEC2 software which is a freeware software package based on Numerical Electromagnetic Code version 2 (NEC2) developed at Lawrence Livermore National Laboratories by G. J. Burke and A. J. Poggio. NEC2 computes the numerical solution of integral equations for induced currents and simulates the electromagnetic response of antennas and metallic structures by using Method of Moments.

In the first part of our analysis, numerous numerical simulations have been performed for various geometrical configurations of antenna array and different phase shift applied between elements and the results were compared with the corresponding analytical calculations based on Eqs. 2 & 3. The array elements are made of half wavelength dipoles. Since 4NEC2 software takes into account the mutual coupling between antennas elements neglected in the derivation of Eq. 2, this comparison provides a clear account of the electromagnetic coupling influence on the array radiation pattern.

The results for the normalized array factor pattern of a 2 elements linear antenna array with half wavelength spacing are presented in Fig.3 for phase shift corresponding to steering angle φ_0 equal to 0°, 45° and 90°. It is apparent that the mutual coupling effect on the radiation pattern is negligible for broad-side (φ_0=0°) and end-fire (φ_0=90°) configurations, but it is significant for intermediate phase shifts.

In Fig 3 (a) it is visible that it is possible to obtain a directional radiation pattern with two major lobs oriented along y-axis for 0 phase shift. The radiation pattern can be rotated with 90o, though the two-lobes are also enlarged, by , by applying an 180o phase shift between the two elements.

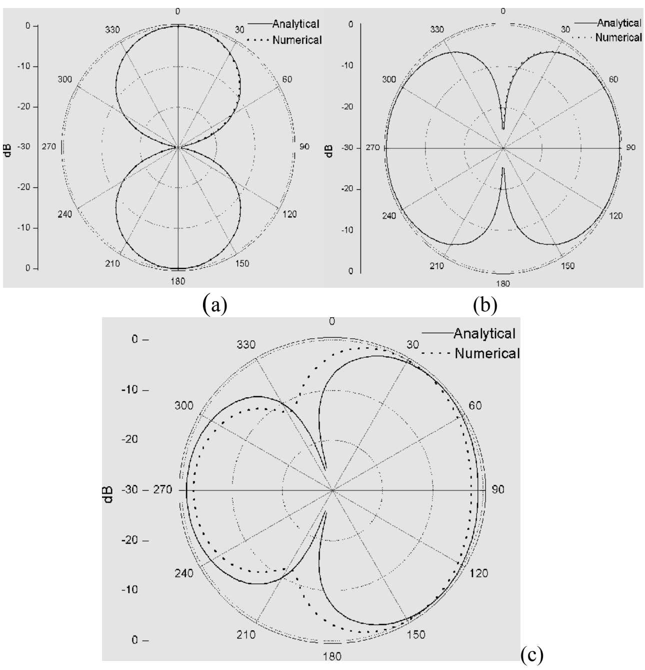


Fig. 3. Analytical and numerical radiation pattern of a 2 elements array with φ_0 equal to (a) 0°, (b) 90°, (c) 45°.

Unfortunately, the intermediate phase shifts do not lead to a coherent rotation of this directional radiation pattern in the scanning plane, as one can see in the snapshot presented in Fig. 3 (c). In order to obtain narrower lobes and coherent lobe rotation, phased antenna arrays with higher number of elements are next addressed.

In the following study, numerous linear antenna arrays consisting of 6, 8 and 12 antenna elements with various phase tapers between antenna elements have been simulated and analyzed.

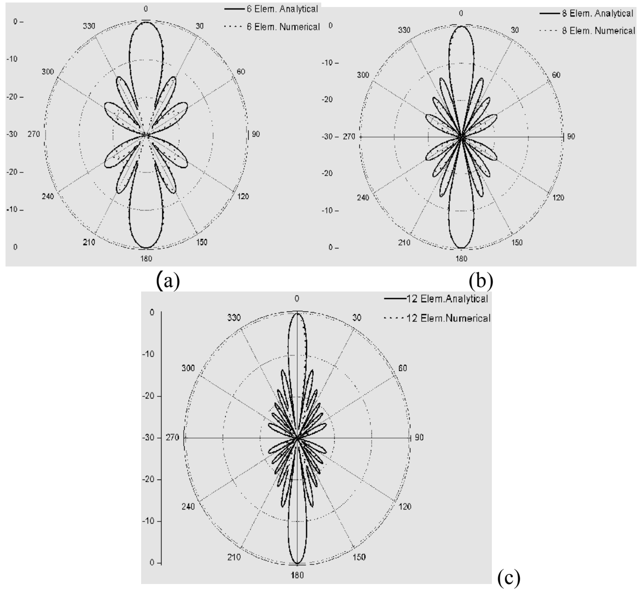


Fig. 4. Radiations pattern of a (a) 6, (b) 8 and (c) 12 elements antenna array with φ_0 equal to 0°.

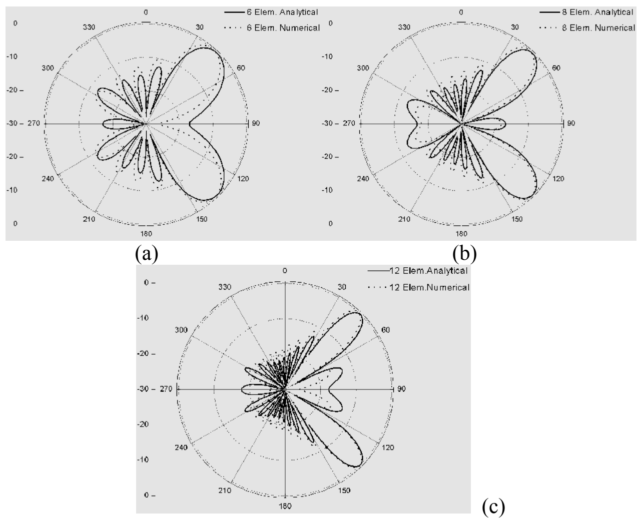


Fig. 5. Radiation pattern of a (a) 6, (b), 8, and (c) 12 elements antenna array with φ_0 equal to 45°.

It has been observed that the beamwidth of the major lobes is decreasing with the increase of the number of antenna elements and also is widening with the increase of scanning angle. The minimum beamwidth is obtained in broadside array configuration while the maximum beamwidth is achieved in an end-fire array configuration.

These conclusions are apparent from the sample results for the corresponding radiation patterns presented in Figures 4, 5 and 6 (simulation results using 4NEC2 are plotted by dotted lines and the analytical results obtained by neglecting the antenna element coupling are plotted by continuous lines). In broadband array configuration presented in Figure 4, the beamwidth of the major lobes is 16° for 6-elements antenna, 12° for the 8-elements antenna, and 8° for 12 elements antenna, while the other two figures show a significant increase of the major lobe beamwidth with the scanning angle.

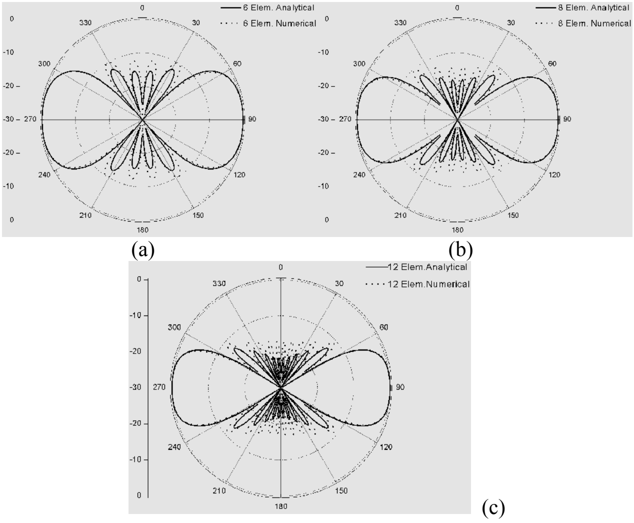


Fig. 6. Analytical and numerical radiation pattern of a (a) 6, (b) 8, and (c) 12 elements antenna array with φ_0 equal to 90°.

IV. PLANAR ANTENNA ARRAY

Planar antenna arrays consisting of 2x2, 4x4 and 6x6 antenna elements with various phase tapers between antenna elements have been simulated and analyzed. The numerical simulations have a great importance due to the fact that they take into account the mutual coupling between antenna elements, which have a significant influence in the case of planar antenna array. For scanning angles of 0° and 90° the shape and the beamwidth of the planar antenna array with an equal number of elements along x and y axis, are the same, the only difference being the 90 degree rotation of the lobes.

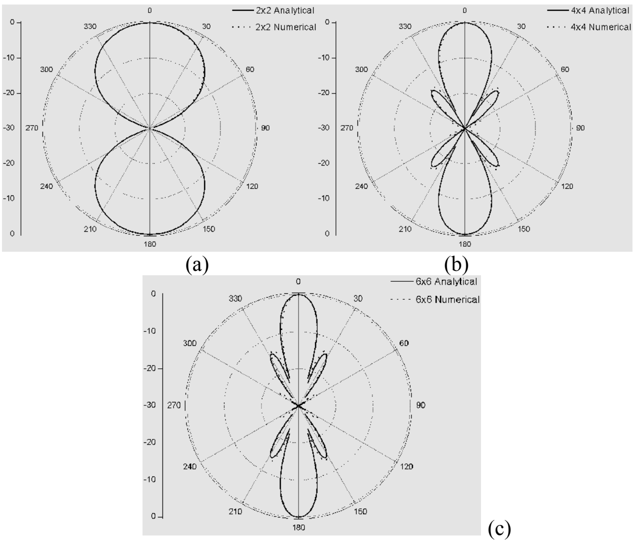


Fig. 7. Radiation pattern of a of a (a) 2x2, (b) 4x4, and (c) 6x6 elements planar antenna array with φ_0 equal to 0°.

In Figure 7 the beamwidth of the two major lobes is 58° for 2x2 - elements antenna, 26° for the 4x4 - elements antenna, and 16° for 6x6 elements antenna.

At a 45° scanning angle, the planar array exhibits a single main lobe, two adjacent lobes and a small number of sidelobes as is visible in Figure 8. The beamwidth of the major lobes is 60° for 2x2 - elements antenna, 24° for the 4x4 - elements antenna, and 16° for 6x6 – elements antenna array.

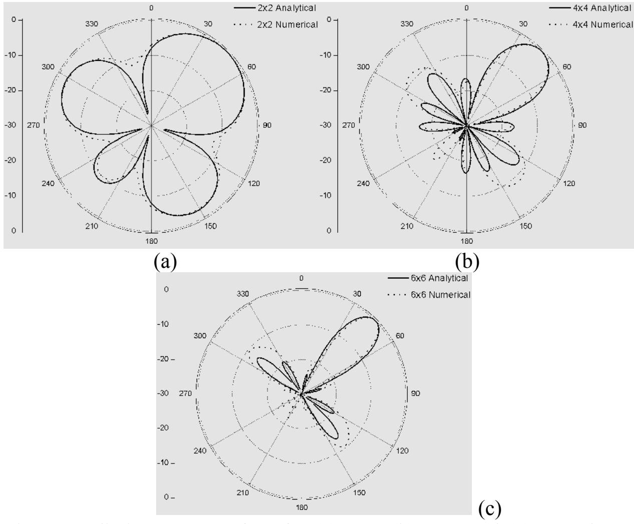


Fig. 8. Radiation pattern of a of a (a) 2x2, (b) 4x4, and (c) 6x6 elements planar antenna array with φ_0 equal to 45°.

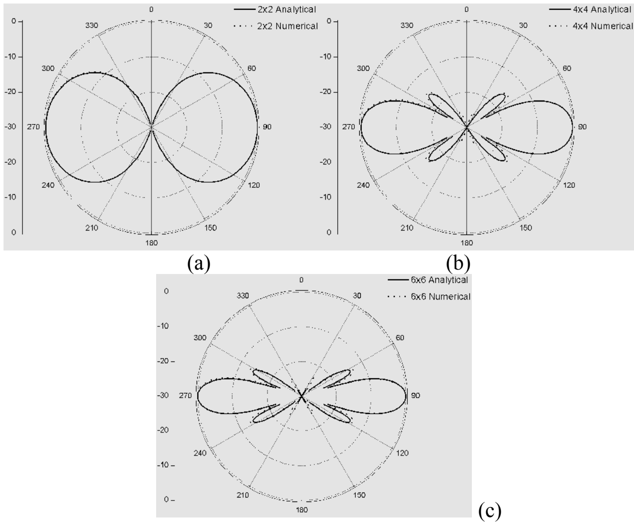


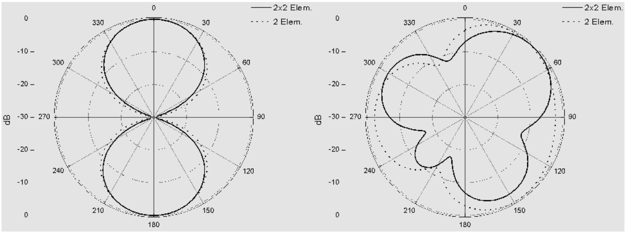
Fig. 9. Radiation pattern of a of a (a) 2x2, (b) 4x4, and (c) 6x6 elements planar antenna array with φ_0 equal to 90°.

For a 90° scanning angle the beamwidth of the planar antenna array is the same as in the 0° scanning angle.

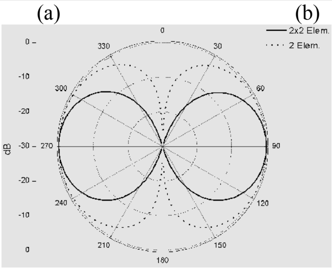
In figure 10 a comparison between radiation pattern of a linear antenna array with 2 elements and a planar antenna array with 2x2 elements is presented. In figure 11 the same comparison is done between linear array with 4 elements and planar array with 4x4 elements.

The advantages of the planar antenna array consist in the relatively constant beamwidth of the main lobe, a major benefit in the implementation of location estimation and monitoring application. The small number of sidelobes, compared to linear antenna array is another advantage of planar antenna array. The planar arrays are more efficient in endfire configuration than linear array as it is observed in Figure 10 and Figure 11.

The main disadvantage of the planar antenna array is the large number of antenna elements necessary in antenna's implementation. If the same numbers of antenna elements are used to build a linear antenna array and a planar antenna array as seen in Figure 12, the planar antenna array has a constant beamwidth of the major lobe, a great endfire array radiation pattern; meanwhile the linear antenna array exhibits a significantly narrowed beamwidth of the major lobes in broadside configuration.

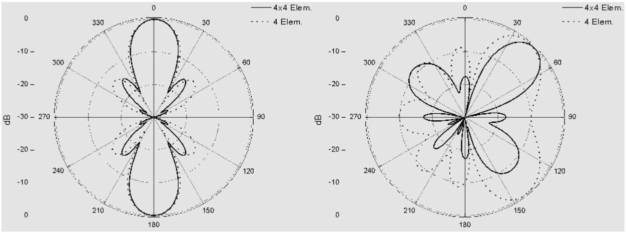


(a) (b)

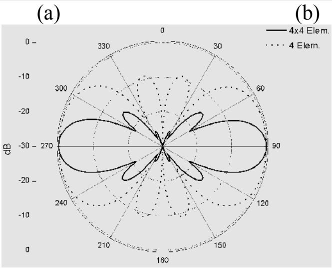


(c)

Fig. 10. Radiation pattern of a 2 elements antenna array and a 2x2 elements planar antenna array for (a) 0°, (b), 45°, and (c) 90° degree scanning angle

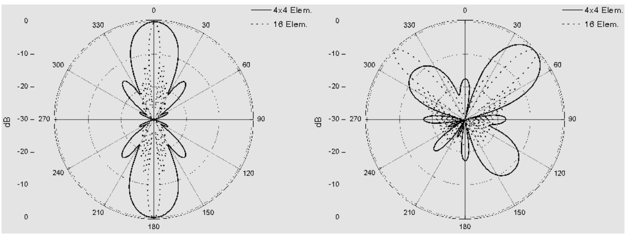


(a) (b)

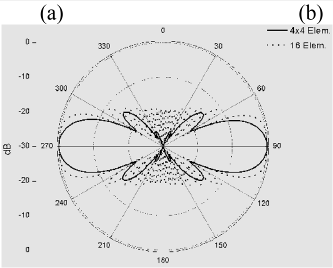


(c)

Fig. 11. Radiation pattern of a 4 elements antenna array and a 4x4 elements planar antenna array for (a) 0°, (b), 45°, and (c) 90° degree scanning angle



(a) (b)



(c)

Fig. 12. Radiation pattern of a 16 elements antenna array and a 4x4 elements planar antenna array for (a) 0°, (b), 45°, and (c) 90° degree scanning angle

V. CONCLUSION

Due to their complexity active antenna arrays have been usually used in military applications, and only recently where deployed in commercial applications. Despite of many potential advantages, the application of beamforming in consumer electronics is scarce due to the relatively high cost of the current implementations. The presented simulations have shown that it is possible to implement beamforming in antenna array by using phase taper only and maintaining the number of antenna elements to a reasonable number. A possible phase taper only location estimation method based on AOA measurements could be used for triangulation localization in wireless sensor network (WSN) where there are clear limitations for power consumption, fabrication cost and device complexity. Different antenna array configurations were analyzed in trying to determine the best antenna array setup.

The beamwidth of the major lobes decreases with the increase of antenna array elements, providing the possibility to do a more precise localization and an approximate coherent rotation of the major lobes is observed by changing the phase shift. However, a special attention should be paid to the side lobes whose number increases with the number of antenna elements. In linear antenna array special attention must be paid to endfire scenario where the beamwidth of the major lob increases significantly. Using planar array this problem can be avoided, but the beamwidth of the major lobes will be greater for the same number of elements. It is recommended to have the scanning area covered by at least two antenna arrays in order to prevent any ambiguity that can arise from the side lobes interferences.

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