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UTILIZATION OF A YAGI ANTENNA DIRECTOR ARRAY TO SYNTHESIZE A SHAPED RADIATION PATTERN FOR OPTIMUM COVERAGE IN WIRELESS COMMUNICATIONS

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Abstract—A novel application of shaped radiation patterns in wireless communications is described to improve coverage planning which occurs potential problems when conventional base-station antennas are used. In particular, a simple antenna design arisen from the implementation of a Yagi antenna is developed to produce the required shaped beams in a cost and implementation effective fashion. Numerical examples, validated by experimental measurements, are presented to demonstrate the proposed concepts.

1. INTRODUCTION

Good electromagnetic (EM) field's coverage of wireless communications [1] in urban and suburban areas has been challenging due to the existence of many EM scatters, such as building and other structures. The difficulty arises from the design and utilization of conventional base-station antennas in the cell planning [2], where standard and relatively identical sectors [3] with horizontally and relatively omnidirectional radiation patterns are used for the reason of easy implementation and low cost of mass productions. These antennas, consisted of vertically co-linear elements, rely on an element's radiation pattern in the horizontal plane to determine the coverage, which used to result in large overlap regions between adjacent cells and caused cochannel interference and ping-ponging handovers between cell base stations. Multi-path interferences are also very apparent in these cases.

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To improve the communication quality, typical approaches proposed to use smart antenna system [4], which uses phased arrays of antenna elements and is implemented by switching pre-determined radiation beams or dynamically forming directional beams with nulls in the multi-path directions. The beams were formed by imposing proper phases on the array elements. In a practical implementation, the smart antenna system utilizes an array of antenna elements in the horizontal dimension, and may dramatically increase the beam-forming circuit complexity to produce proper phases for antenna elements and, as a result, the antenna manufacture costs, which has limited its actual values of implementation in commercial services.

To simplify the implementation and reduce costs, [5] proposed to use a shaped reflector antenna to produce a contoured beam, which was widely used in the satellite communications and may be used to optimize the EM field distribution in the coverage. The multi-path interferences can be also reduced since the wave blockages of large structures can be taken into account in the synthesis of contoured patterns. Also the pattern may also have a very sharp taper at the edge of coverage if the size of reflector is very large. This contour pattern may also be created by using a phased array of antenna elements. Because the contour patterns need to be synthesized according to the geometrical features in coverage areas, both approaches do not appear to be cost effective in a realistic implementation, in which the phased array antenna tends to have a large complexity of beam forming circuits, and the shaped reflector antennas cannot be mass produced and repeatedly used. They are very cost expensive even though the implementation concept is relative simple.

Cost effectiveness is a primary consideration in a commercial implementation of antennas. This paper presents an antenna design that is simple in structure while, in the mean time, retaining low cost in manufacture and implementation, which arises from the design concepts of a Yagi-type antenna [6], and utilizes parasitic directors to enhance the radiation directivity of a driven dipole placed beyond a reflector. It was shown that the number and separation distances of co-linearly located directors may affect the directivity in its end-fire direction. Thus if more than 2 sets of co-lineared directors are used, then the directivities in these end-fire directions will be different. A shaped pattern in the horizontal plane can be therefore formed if the parameters associated with the directors' separation are optimized. These optimized Yagi antenna elements may also be used to form a sector antenna in a similar fashion to conventional sector antennas. The advantages of this concept can be immediately observed by considering its simple design and implementation.

This paper is formatted in the following order. Section 2 describes the fundamental design concepts as well as an optimization tool developed by integrating Genetic Algorithm (GA) [7] with HFSS [8]. Section 3 presents numerical examples to demonstrate the shaped radiation patterns. Finally a short discussion is presented in Section 4 as a conclusion of this work.

2. YAGI ANTENNA DESIGN WITH AN 3-D ARRAY OF DIRECTORS

2.1. Characteristics of Yagi Antennas and Proposed Structures

A Yagi-type antenna, in comparison to a simple wire dipole, may increase radiation directivities by using a reflector and parasitic directors. A conventional design co-linearly orients the driven dipole, and its reflector and directors in an 1-D fashion as illustrated in Figure 1(a), and results in a directional radiation toward its end-fire direction, whose directivity generally increases with the increase of the number of parasitic directors until a maximum value is reached.

While a conventional design uses 1-D directors, the proposed work relaxes the linearity of parasitic directors' positions, and allows them distributed in a 3-D fashion as illustrated in Figure 1(b), which is exampled by placing several sets of directors in various angular locations for simplicity. In general, each set may have a different number of directors or different separations between them. Thus they effectively result in various weightings for directivities in angular directions, and will form a shaped radiation pattern if the orientation of parasitic directors is properly designed.

As illustrated in Figure 1(b), in our work the elements of a driven dipole, and its reflector and parasitic directors are printed on dielectric substrates for simplicity of prototyping, which also assist to reduce the sizes of antenna elements. The reflector is a ground plane and is placed approximately at a distance of $\lambda/4$ below the driven dipole, where λ is the wavelength of a free space, such that the fields reflected from the ground will propagate in-phase with that directly radiated from the dipoles in the broadside direction of the antenna.

2.2. Parameter Optimization for Directors in Radiation Synthesis via Genetic Algorithm

In a practical implementation of the proposed work in Part 2.1, a predetermined shape of targeted directivity is employed as a criterion to narrow the difference between antenna radiation and it by adjusting the

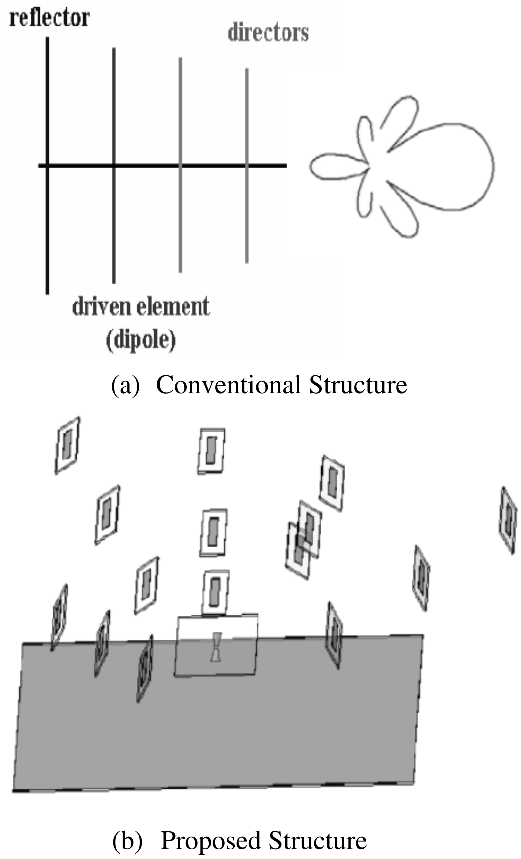


Figure 1. A Yagi-type antenna structure.

parameters associated with the directors' locations. It would be more effective to perform a numerical optimization procedure. In this work, a simulation tool integrating GA [7] with HFSS [8] as a computational engine was developed [9] to optimize the radiation patterns of the Yagi-type antenna. This GA based optimization procedure is illustrated in Figure 2. In the design, the driven dipole is first adjusted to operate in the desired frequency band. The parameters of the directors as labeled in Figure 3 are used as optimization variables and are consequently adjusted in the GA optimization procedure until the computed pattern has met the requirements of directivity within an allowable margin.

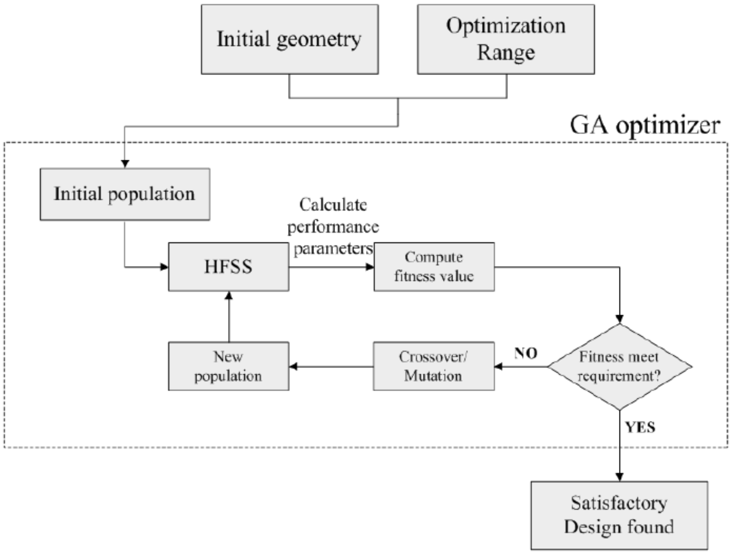


Figure 2. Structure of an EM optimization procedure.

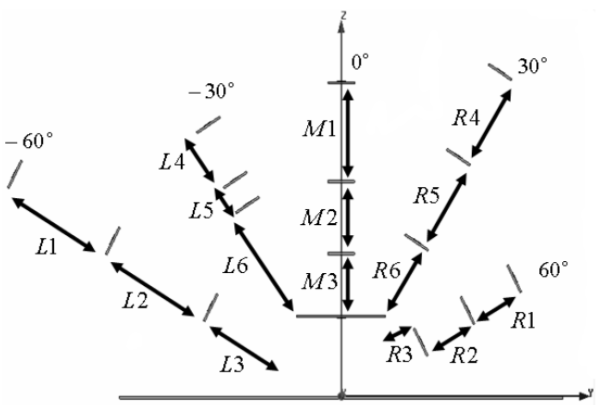


Figure 3. Parameters of Yagi directors for the pattern optimization.

The cost function is defined by

$$F = \frac{1}{1 + \sum_{n=1}^{N} |G_n - G_n^d|} \tag{1}$$

where G_n and G_n^d are the computed and desired directivities at nth of N observation angles. The design goal is to maximize (1), where the largest value locates at $F = 1$. In the example shown in Figure 3, five sets of directors, in which each has three directors, are considered, where their angular separations remain fixed at 30 degrees. These separations are found sufficient not to affect the return loss of the driven dipole.

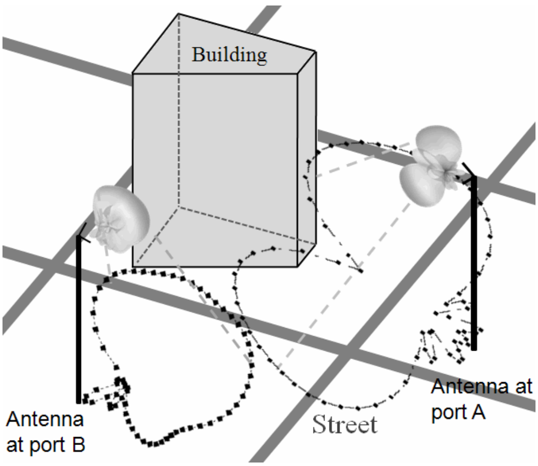


Figure 4. Illustration of coverage planning in wireless communications.

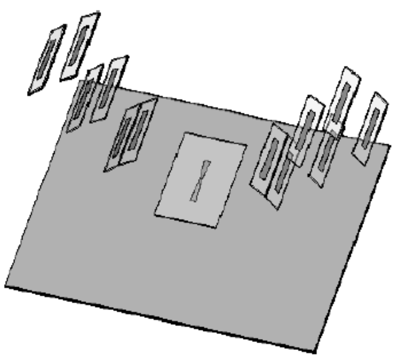
3. DEMONSTRATION EXAMPLES

Typical examples in the applications of WLAN operating in 5 GHz band of IEEE 802.11a specifications are presented to demonstrate the proposed ideas, which are designed to provide an outdoor coverage within 100 m as illustrated in Figure 4, where it is assumed that a tall building is located inside a coverage area. Two base stations, located at pole A and B, utilize the proposed antenna structure to provide proper coverage.

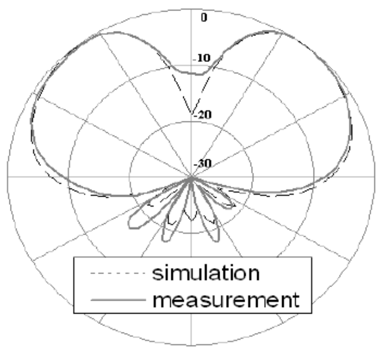
3.1. Increase of Directivity with Respect to Parasitic Directors

One first examines a regular Yagi antenna where only a set of parasitic directors is used. In this case, the focus is placed on the increase of directivity with respect to the number of directors. The results

Figure 5. The increase of directivity with respect to number of directors when only a set of directors is used.



(a) Antenna Structure



(b) Horizontal Radiation Pattern

Figure 6. Low broadside directivity design and its radiation patterns.

are shown in Figure 5, where it is observed that the directivity increases rapidly for small numbers. The slope decreases as the number increases. It is thus selected three directors in the following examinations, which shows a largest slope.

3.2. 3-D Unequal Distribution of Parasitic Directors

This case is illustrated in Figure 4 as the antenna is placed on pole A, where the building locates at the broadside of the antenna and may cause multi-path interferences since it blocks the radiation of the antenna at the angles with strongest radiation strengths. Thus the design philosophy decreases the radiation directivities and thus its gains in this angular region, which in turn reduces the strengths of the multi-path signals. To achieve this, it is desired to produce a butterfly-like pattern with a low directivity at the antenna broadside direction, which can be achieved by placing parasitic directors as illustrated in Figure 6(a). Thus each side uses two set of directors with equal separation distances to produce higher directivities. The radiation pattern is shown in Figure 6(b), where measured and simulated patterns are shown. It is observed that the broadside has a gain 12 dB below the peak. The peak gain is found to be 8.45 dBi and 9.44 dBi (roughly 1 dB larger than that obtained by measurement) obtained by measurement and simulation, respectively.

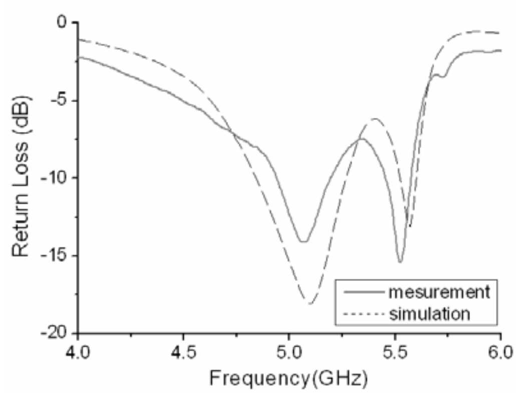
3.3. Shaped Pattern Optimization

This case is also illustrated in Figure 4 as the antenna is placed on pole B, where the building is also located at the broadside of the antenna. In this case, pole B is located at the left-hand side that faces a large area of the building that blocks the radiation. The distances between the antenna and blockages vary with respect to observing angles. In particular, wider angles on the right-hand side appear to be larger than that at the left-hand side. A shaped pattern is thus required to optimize the coverage in this area. The antenna structure in Figure 1(b) is used. The parameters in Figure 3 are optimized using GA described in the previous section to achieve the contour constraint shown in Figure 7(b). The optimized values of parameters are shown in Table 1 with initial values of 18.6 mm for all parameters. The design gives results shown in Figures 7(a)$\sim$(c) for the return loss and radiation patterns. The return loss in Figure 7(a) shows that this antenna operates at 5 GHz band. The radiation patterns, shown in Figure 7(b), exhibit the assumed shape, simulated and measured patterns. They show good agreements, and indicate good fulfillment of the design goal. The pattern on the E-plane is also shown in Figure 7(c).

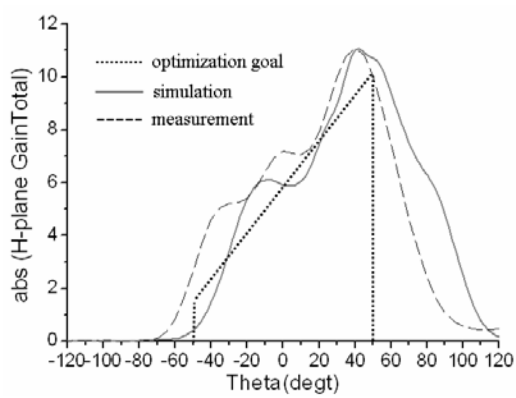
In the above discussion, both simulation and measurement results of prototypes show good agreements and also consistent with the design

Table 1. Optimized values for Figure 7's antenna design. (unit: mm)

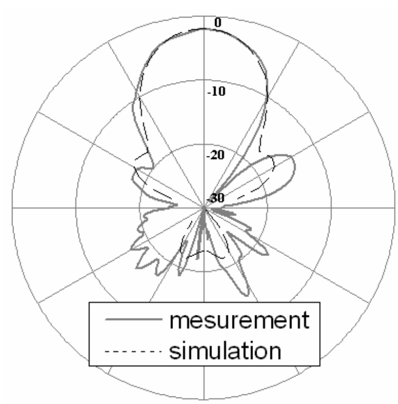
Parameter	L1	L2	L3	L4	L5	L6	M1	M2
Opt. Value	24.4	23.7	21.5	11.6	5.3	29.2	18	12.6
Parameter	M3	R1	R2	R3	R4	R5	R6	
Opt. Value	15.5	11.3	10.6	9.9	18.3	17.7	21.5	



(a) Return Loss

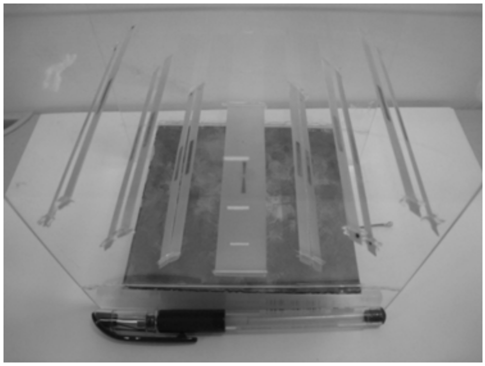


(b) Horizontal *H*-plane Pattern

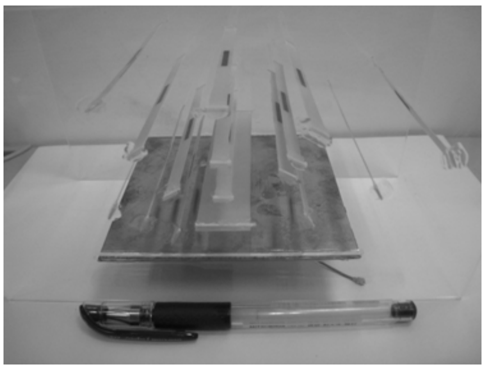


(c) Vertical *E*-plane Pattern

Figure 7. Shaped beam synthesis for optimum coverage using Yagi antenna structures.



(a) Case of Figure 6



(b) Case of Figure 7

Figure 8. Pictures of antenna prototypes for the cases in Figures 6 and 7.

goals. Finally the pictures of the prototypes are shown in Figure 8 for a reference, which exhibits simple in design and manufacture as one has described in the introduction of this work.

4. CONCLUSION

A Yagi-type antenna is presented for the shaped radiation pattern synthesis, which will become very useful in the applications of wireless communications. The shaped pattern is formed by properly allocating the directors to weight the directivities in a various directions since the uses of directors have been shown to increase the directivity of a Yagi antenna radiation. Both numerical and experimental examinations have validated the current approach to be very effective in both applications and cost.

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