Experimental Investigations of Adaptive Reactance Parasitic Antenna Dipole Array

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Abstract—This work describes a simple, low-cost electrically steerable antenna system suitable for long-distance point-to-point links based on WiFi technology. The antenna consists of a tunable mirror, assembled as an array of closely spaced passive dipoles (scatterers) illuminated by one driven element. The scatterers are arranged in multiple layers that contribute overlapping ranges of phase shift. While collectively providing full 360 degrees of phase range, this approach enables individual scatterers to provide greater amplitude response across narrower phase bands. Smoothness of phase composition is guaranteed by the small spacing between layers (< 0.15λ). Results show that with careful design given the amplitude-phase characteristics of the scatterers, both individually and in aggregates, the antenna can form highly directional beam patterns that are controllable in azimuth and elevation. Experiments demonstrate that an antenna with 500 scatterers, with a 100 cm × 65 cm aperture, achieves 19–22 dBi of gain across 120 degrees of azimuth and 20 degrees of elevation.

1. INTRODUCTION

Many contemporary information and communication technology (ICT) activities around the world are using low-cost, off-the-shelf radios with directional antennas for long-distance point-to-point wireless links. The antennas provide additional gain that compensate for the low powers (< 1 W) of the typically unlicensed radios. The use of directional antennas with narrow beams requires that antennas at each endpoint of a link be precisely aligned during installation. Moreover, because some antennas drift out of alignment over time, performance may gradually suffer until a complete outage requires costly and time-consuming on-site maintenance visits. Simple, low-cost electrically steerable antennas have the potential to simplify and reduce the costs of these networks.

High antenna gain can be achieved by using electrically large parabolic reflector, but steering the pattern of such an antenna is non trivial. One possible solution is to move the whole antenna mechanically, but this has disadvantages. Large mechanically steerable antennas require significant hardware power, and they are difficult to adjust either quickly or precisely. Ruze [1] demonstrated that the principal beam direction can be changed slightly by moving the feed position in the focal plane. Such a movement, however, substantially degrades the antenna gain, as the feed point is no longer at the focus. Winter [2] proposed an electrically steerable antenna consisting of a tunable reflective surface illuminated by an active element. This work received its continuation when Durnan [3] used a switched parasitic antenna located at the focus as the feed. Two parasitic elements are displaced vertically from the driven element and have a diode switch located at their center. The vertical polar pattern is controlled electronically by changing the impedance state of the diode. The technique of beam steering by shifting bias voltages has been used in various antennas [4] and reflectarrays [5, 6].

The main idea of the antenna system presented in [7] is shown in Figure 1. It uses discrete passive dipoles as an element of the mirror excited by the active RF element. The distance between scatterers in each layer is chosen to be much less than the wavelength in order to minimize power losses due to energy leaking though the layers (the mirror) while providing a wide range of steerability. Another significant feature of its construction is the use of a multi-layered structure. Many efforts focus on extending the phase deviation range of the reemitted or radiated field, and in this regard, are archiving up to 360 degrees range or more, but at the same time there can be significant amplitude deviations, e.g., as in [8] which corresponded to the resonant properties of the elements. The key points with large phase offsets may also have small reemitted/radiated field amplitudes.
The layering of the antenna structure allows operation within other bands of the phase-amplitude response of a scatterer. If one layer antenna assembled of scatterers has the possibility to vary phase of the reemitted field in the range of $360\,\text{deg}$ divided by $N$ (where $N$ is the number of layers), then there’s a solution to use the same layers located in space by $D$ further from the RF element, it will produce shifting of phase range by doubled $D$ divided by wavelength and multiplied by 360 degrees. Collectively, the $N$ layers provide full (360 degrees) phase range. This construction allows scatterers to have near uniform reemitted field amplitude characteristic, because they use portions of the amplitude and phase characteristics from the resonant point at each layer.

Discrete passive dipoles, which are mounted orthogonally to the face of the array, additionally help the layered construction because of each layer is RF-transparent at some points where reemitted amplitude of custom layer can be set to minimum, and there are no other obstacles to propagation like ground substrates [9].

The work is dedicated to explain experimental analysis and optimization of the work presented in [7]. There are five stages of the investigation: Section 2 presents the scatterers amplitude-phase characteristics précising. Section 3 presents the multilayer structure and construction. Section 4 presents a bandwidth investigation. Section 5 presents the pattern diagrams and optimization. And Section 6 concludes with preliminary field tests.

2. SCATTERER CHARACTERISTICS ANALISIS

The scatterers (Figure 2) were modeled as dipoles printed on the surface of common printed circuit board material (FR4) loaded with varactor diodes through impedance transformers (slot lines). The dipole and slot line geometries (length and width of the dipole, and the gap, length and width of the slot line) were determined from models optimized with HFSS, FEKO and Microwave Office, given the FR4 board thickness (1.57 mm), dielectric permittivity (4.9), and dissipation factor (0.018). The models were based on the voltage-capacitance response of the MA4ST-1240 diodes supplied by the vendor, and were then optimized given the experimentally measured characteristics of the diode, as well as the amplitude and phase of reemitted field by actual prototype scatterers.

The amplitude and phase characteristics of the varactors were in the antenna chamber using the following approach. A circular assembly of scatterers was made (Figure 3, $R = 300\,\text{mm}$) with an active dipole in the center for transmitting and receiving. The signal from center propagated the same distance ($R$) to each scatterer along the circumference, and the reflections arrived back at the center. By uniformly changing the capacitances of all diodes in unison, the reflections arrived back at the center in phase, and it was possible to obtain the amplitude and phase characteristics of the reemitted field, which take into account the now uniform mutual coupling and interactions among the scatterers as a first approximation. It is also possible to vary the radius of the assembly, which allows the strengths of those interactions to be examined. The numerically predicted and experimentally measured characteristics are shown in Figure 4, showing the close match of phases and amplitudes.
3. MULTILAYER STRUCTURES INVESTIGATION

Each row of scatterers in the antenna has a controller consisting of an FPGA (Field Programmable Gate Array), which provided 100 channels with operational amplifiers. The controller produces diode bias voltages in the range of 0 V to 15 V. Up to five controllers can be interfaced by a high speed serial bus to host computer that carries out multivariate optimization processes, e.g., genetic algorithms. The optimization process searches for the best distribution of bias voltages (equivalently diode capacitances or elemental phase shifts) in term of forming the necessary phase front for specific wave propagation situation and in terms of forming maxima or minima of antenna directivity diagram. The active receiving/transmitting element from a 24 dBi parabolic grid antenna was reused for this work. This exciter was placed as the same focal distance in front of the array as for the dish. Experiments were carried out in the antenna chamber of the N.I. Lobachevsky State University of Nizhni Novgorod. Images of the antenna in the antenna chamber and experimental plant are presented in Figure 5. Agilent Network Analyzers were used to measure the $S_{12}$ characteristics.

Within this framework, several additional experiments were carried out to refine the multilayer structure. The first step was to determine the optimal horizontal spacing between scatterers in a layer in order to maximize gain. For this, a subset of the complete antenna array assembly was used, which consisted of one row and one layer. An adjustable mechanism for holding the individual elements was made, and spacing was varied from 1 cm to 12 cm in 1 cm increments (note the operational wavelength was 12.5 cm). The 3 cm spacing corresponded to a maximum achievable gain of the subassembly of 10.5 dBi. The second step was to determine the optimal spacing between layers also in order to maximize gain. For this, a different subset of the complete antenna array
assembly was used, which consisted of one row with two layers with the 3 cm spacing between the scatterers in each layer. Another adjustable mechanism for holding the individual elements was made, and spacing between layers was varied from 15 mm up to 59 mm in 2 mm increments. The 27 mm spacing corresponded to a maximum achievable gain for the subassembly of 13.5 dBi. Subsequently, a 3 layer subassembly was produced, distances were varied, the optimal spacing was 21 mm, and the optimal gain for the sub-assembly was found to be 14 dBi. The final step was the assembly of multiple rows. The maximum achievable gain depends on the array aperture, which is turn depends on the length of a row and the number of rows stacked one on top of another: 2 rows achieved 16.2 dBi, 3 rows achieved 18.9 dBi, 4 rows achieved 20 dBi, and 5 rows achieved 21.2 dBi.

The final array assembly has five rows of 100 elements. The aperture was 100 cm by 60 cm, which is the same as for 24 dBi parabolic grid antennas. Each row had three offset layers of scatterers with a horizontal spacing of 3 cm and a separation between layers of 21 mm. The vertical separation between rows was found experimentally with the ideal separation of 96% of the wavelength, in this case 120 mm.

4. ANTENNA BANDWIDTH INVESTIGATION

An important consideration for the antenna system was that it should be possible to produce beam patterns with sufficient bandwidth for transmitting WiFi signals, which are nominally 22 MHz wide. While it would be desirable for a given pattern to exhibit constant or minimal variation in bandwidth, e.g., of 1 dB or less, across the entire frequency band used by 802.11b/g signals, optimizing channel-specific patterns remains viable.

Figure 6 shows the bandwidth characteristics of the antenna. The top (orange) curve shows the gain for a pattern optimized for a center frequency of 2.415 GHz to the direction (azimuth = 0 deg, elevation = 0 deg). The bandwidth is 47 MHz wide defined by the $-1$ dB level. The green curve (bottom) shows the gain for a pattern optimized for a center frequency of 2.415 GHz to the direction (azimuth = 30 deg, elevation = 0 deg). The band is 45 MHz wide. Significant variation in gain is observed for frequencies out of 50 MHz band, where maximum distortion for the first direction (0/0) is $-3.5$ dB, and for the second direction (30/0) is $-4.5$ dB. (We believe that a modified pattern optimization process that simultaneously optimizes the pattern gain at multiple frequencies with the 802.11b, for example, could find alternative vectors of varactor bias voltage that would correspond to highly directive patterns with correspondingly wider bandwidths.)
5. DIRECTIVITY DIAGRAM FORMING

The next step of adaptive antenna investigation is to create a table of bias voltages distributions for different beam orientations. These patterns form a lookup table that can be used to retrieve the bias voltage vectors associated with a particular pattern. Experiments were provided in antenna chamber by rotating the antenna in azimuth and elevation planes, and then executing external optimization algorithms to maximize the gain. Figure 7 shows several directivity diagrams for patterns with different orientations in azimuth and elevation.

Figure 8 shows graphs of the maximum gains across a range of beam orientations. They show the experimental results (blue) and predicted diminution (red) of the effective antenna aperture (COS-diminution). In general, the experiments track predictions well. An experimental artifact of the antenna chamber, specifically imperfections around the access door, is believed to be responsible for the divergence approaching the $-60$ degree angle. The maximum gain was $22.5$ dB, when using a genetic algorithm for optimizing the varactor loads.

Figure 7: Azimuth (right) and elevation (left) planes customizability (rectangular coordinate system: ordinate — gain [dBi], abscissa — direction [deg]; polar coordinate system: radial — gain [times]).

Figure 8: Maximum reachable gain (left — elevation $+10$ deg; center — elevation $0$ deg; right — elevation $-10$ deg).

Figure 9: Scheme of the field tests.
6. OUTDOOR FIELD TESTS

Preliminary field trials were done as shown in Figure 9. The antenna was placed on the 9th floor of one office building approximately 30 meters above ground level. A standard parabolic dish antenna with 18 dBi of gain was placed on the 6th floor of a second office building approximately 20 meters above ground level. The distance between the two antennas was approximately 1200 meters.

Each antenna was connected to a Gateworks Avila Network Processing System (GW2348-4) with one 600 mW Ubiquity XR2 802.11bg network adaptor. The systems utilized a wireless stack with TDMA MAC extensions. A single 802.11b point to point link was established between the systems. The sustained performance of TCP transfers of 10 MB files was observed to range from 6.17–7.53 Mbps, which corresponds to similar measurements reported in [10] but with the possibility of beam steering.

7. CONCLUSIONS

This work demonstrates the potential of using multi-layer structures of passive tunable scatterers in highly directional antenna arrays with near uniform gain across a wide range of steerability. The careful optimization of the amplitude-phase characteristics of the scatterers, in isolation and in multilayer structures, is essential given the strong mutual coupling of the elements and the desire to maximize gain and steerability simultaneously. Investigations show the array had sufficient bandwidth to accommodate WiFi channels. Pattern measurements show well formed, high gain patterns that are controllable in azimuth and elevation. Preliminary outdoor experiments demonstrate these antennas in operation in point-to-point links based on WiFi technologies.

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REFERENCES