# Intelligent beamforming and control circuits research applied to the electric power distribution for the last 10 years in Brazil


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*Abstract*— **This paper presents the design of a smart directive antenna array used to concentrate and point the radiation beam toward a desired direction. The design is especially aimed at supervision systems of electric power distribution switches with the objective to replace the vertical arrays of electric dipoles commonly used by electric power distribution companies. Simulation and experimental results have demonstrated the proposed four Yagi-Uda antenna array performs well when compared to an array of four vertical folded dipoles.**



***Keywords—antennas Yagi-Uda; linear array; PSO; smart antennas; UHF.***


## I. INTRODUCTION

An electric power distribution company, being an essential public service, needs to have a real-time supervision system that is reliable and fast. Aiming at this objective, radio base stations are commonly installed to establish communication links between the Electricity Company's Integrated Operation Center (IOC), where the supervision system is located, and the remote electrical switches. These links set channels for an ongoing dialogue between the IOC and the switches in order to collect information on the status of the current switches and for the IOC to apply potential interventions.

At the repeater stations, referred to as base stations (BS), high power radios and radiofrequency antenna arrays are used in order to ensure reliable RF links with the outstations. However, it is well known that several factors, such as distance, terrain topology and civil constructions between the electric switches and the BS, may reduce the quality of the link. Hence, distant switches may not be covered. In order to overcome these difficulties, there are two possible approaches, e.g., install new BSs in areas closer to these shadow regions, or increase the power of the signal transmitted at the existing BSs, which is not recommended.

Common BSs of energy distribution substations use vertical collinear folded dipoles antenna arrays. Each of these arrays are able to generate an almost omnidirectional radiation pattern with a gain which depends on the number of dipoles employed [1]. In order to improve the communicational efficiency between the BSs and the outstations, a switched smart directive antenna array is here proposed. By using this, it is possible to increase the gain by concentrating the radiation beam, pointing it toward a desired direction. This study has been developed by the Microwaves Research Group in the Department of Electronics and Systems at the Universidade Federal de Pernambuco (UFPE), Brazil [1,2,7,8].

In [1,2,7], the authors used arrays of four seven-element Yagi-Uda antenna to implement part of the radiating communication system. The phase shift and relative weights between the feeding signals of the antennas were determined by electromagnetic simulations. In [1,2], however, no optimization method was used in the formation of the beam. In these studies, the amplitude of the antenna inputs were kept constant and the same, whereas the phase shifts between them were determined by trial-and-error procedures.

In [7], the antenna array was composed of a symmetrical circular set of 3 identical antenna arrays with amplitude and phase control of each antenna. Each array was responsible for covering 120° on the azimuthal plane. In order to obtain viable combinations of phase shifts and amplitudes of each antenna input, so as to point the radiation beam toward a desired direction, the Particle Swarm Optimization (PSO) method was used [4,5,6].

In this study, the antennas that formed each array were the Yagi-Uda type, with seven elements, including a reflecting rectangular grid as the reflector, as depicted in Fig.1. The smart antenna radiation system consisted of two identical such antenna arrays positioned in a back-to-back configuration (Fig. 2). The antennas at the end of each array were tilted at a 70° angle, so that considerable gain could be achieved near the 0° and 180° angles. In order to point the radiation beam in any desired direction, the PSO method was used to find the appropriate feed, magnitude and phase of each antenna. The software used to perform the simulations was the Ansys HFSS. Measurements were carried out with the proposed array of 4 directive antennas, together with a vertical array of four folded dipoles, typical of a current BS radiating system used by electricity distribution companies. The results were then reported for comparison.

## II. The Yagi-uda Array

### A. *Single Yagi-Uda Array*

The antenna array used in this project is composed of 4 identical Yagi-Uda antennas. Each antenna has seven elements, including a rectangular reflecting grid of 52.7 cm x 34 cm as the reflector element and a boom length of 120 cm. The other dimensions are shown in Figure 1. It is able to operate from 440 up to 470 MHz with a VSWR of less than 1,5:1. It has a nominal gain of 11.8 dBi, a front-to-back ratio of 24 dB and -3 dB beamwidths of 46° and 58° on the E and H planes respectively at 455 MHz.

The outer antennas of the array are tilted at $\xi$ = 70° away from the two central parallel antennas. Rotation is achieved with respect to the axis at the beginning of their own booms and starting with a distance of $d_g$ = 2 cm from the neighboring antenna. Thus, the boom distance between the central antennas is $d$ = 53 cm.

### B. *The Complete Radiation System*

The complete radiation system is composed of two identical antenna arrays (Fig. 1) in a back-to-back arrangement, according to Fig. 2. Optimized main lobes occur for 0° <$\varphi$< 180° when Array 1 is fed by a certain vector $A_i$ (magnitude), $\beta_i$ (phase) and for 180° <$\varphi$< 360° when Array 2 is fed by the same sets of feed. In order to find these sets of feeds, the Particle Swarm Optimization method is used with the Ansys HFSS software. For a given direction, a feed set is found from optimization and used at the antenna input of the array so that the main beam points in that direction. In order to accomplish the task, a beamforming circuit with 4 branches is conceived. Through each branch, an RF signal flows, the individual amplitude and phase of which is adjusted by a digitally controlled circuit. To connect the output of each branch to the antennas of either array 1 or array 2, a set of four SPDT switches are employed, as depicted in Fig. 3. With these switches, it is possible to digitally select which array will be fed at a time, depending on the direction of the remote device to be contacted.

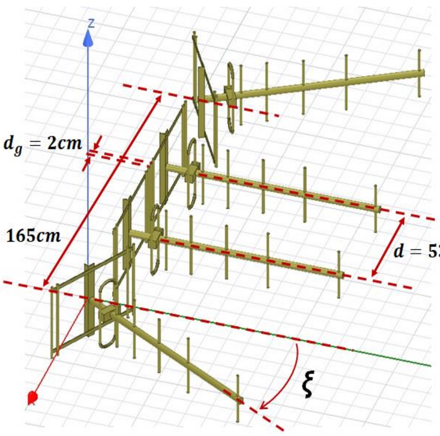



Fig. 1. Physical characteristics of the Yagi-Uda antenna array.

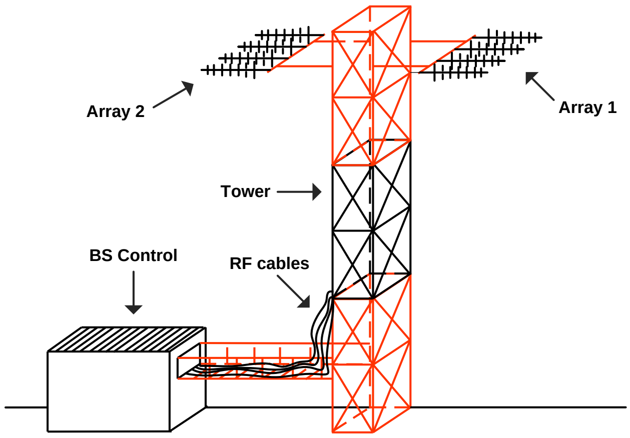



Fig.2. Sketch of the radiation system and BS control.

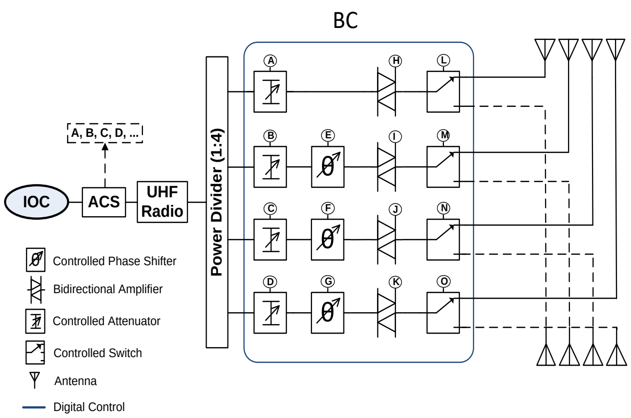



Fig.3. Diagram of the complete smart antenna system

## III. Description of the Smart Antenna System

A brief description of the smart system is given in this section and it is depicted in Fig. 3. The BS is composed of a beamforming circuit (BC), a radio, two Yagi-Uda antenna arrays, and an antenna control system (ACS). The BC is formed by one power divider, four digital controlled attenuators, three digital controlled phase shifters, two bidirectional amplifiers and 60 m long coaxial cables. Figs. 4, 5 and 6 show the circuit diagram in details.

The antenna control system(ACS) is a software that, running in an embedded computer (device *U5* in Fig. 4), is responsible for all dynamic antenna array adjustments. It receives TCP/IP messages sent by the IOC over a standard ethernet network connection (*Eth0* port in device *U5* in Fig. 4), locate the geographic position of message destination addresses, dynamically adjusts the antenna array parameters to the best ERP (effective radiated power) in the desired direction/azimuth, and transmits the messages via digital radio (device *Ra0* in Fig. 4). To achieve the best ERP parameters for each direction/azimuth, the ACS dynamically controls three types of antenna array parameters: the amplitude and phase at each antenna branch and the antenna switching (Fig. 4 and Fig. 5). The system uses fixed-gain RF bidirectional amplifiers (device *U0* in Fig. 5), and system amplitude control is then performed by programmable attenuators (device *Att0* in Fig. 5). And phase control is performed by digital phase shifters (device Ph1 in Fig. 5). The bidirectional amplifiers are composed of two unidirectional amplifiers that work alternately, one for transmitting and one for receiving signals. Therefore, the system needs to know when radio *Ra0* is in transmit or receive mode. Thus, to solve this problem, a carrier detector circuit was created to detect in advance when the radio *Ra0* initiates a transmission by identifying the existence or not of a carrier signal at the radio output. The presence of a strong carrier at the radio output indicates a start of transmission by the radio *Ra0*. And the absence of a strong carrier signal indicates that the radio *Ra0* is in receive mode. The carrier detector circuit is shown in Fig. 6, the output of this circuit is digital and controls the operation mode of the bidirectional amplifiers. To cover 360 degrees, the system has four branches each one capable of switching between the respective antenna array 1 and 2, see Figs. 4 and 5. To perform the switching between these arrays, the ACS uses SPDTs digital control switches (device U4 in Fig. 5). From the perspective of the system topology, the system lies in a TCP/IP connection between a base station (or IOC) and an outstation, in a typical network configuration known as "man-in-the-middle". The system is proposed for use in a network with a star topology. The ACS needs to configure the array and transmit TCP/IPs packets via radio in real time, so there is no way to perform very complex operations or simulations when the system is running. So, the array adjustment parameters are precomputed in electromagnetic simulation software, as described in section 3, subsection A. For each angular position and network address of the outstations a set of parameters is pre-calculated to maximize the system ERP. The association between network address and best parameters is performed through a lookup table (LUT). The connection of the base station with the outstations works in a manner similar to an RF multiplexer. Through the beamforming circuit it is possible to change the effective radiated power of the system on demand without changing the RF power of the transceiver. Thus, to establish communication with distant outstations, one can increase the ERP and decrease it for closer

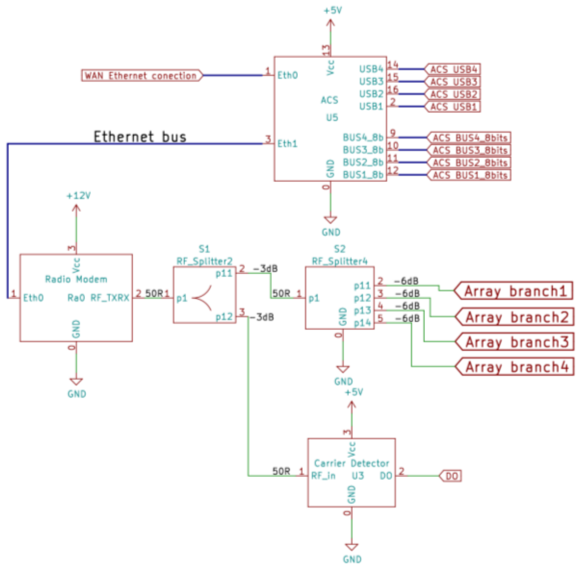



Fig.4. Circuit diagram connecting the ACS, radio, carrier detector circuits, and branches of the beamforming system.

outstations. As the IOC tries to communicate with one of the outstations, it sends a message with the proper address to ACS which controls the phase shifters, the bidirectional amplifiers and the digital attenuators of each branch of the beamforming circuit in such way as to provide the right feeds for the antennas of the array. If the outstation to be monitored is in the opposite side, the SPDT (Controlled switch) must be activated so that the other array must be used. Fig.3 shows the diagram of the complete smart system and Fig.7 brings the photo of the beamforming circuit.

*A. Computer Simulation Results*

The PSO optimization method is applied to the antenna array designed in the Ansys HFSS to obtain an optimized azimuth radiation pattern by pointing its main lobe toward the desired direction. The method also forces the minimization of secondary lobes to generate a concentrated radiation beam toward the target switch.

The inputs at the antennas, were used as the optimization variables. Thus, each antenna has an input amplitude value which lies in the range [0, 1] watts and an input phase in the range [0, $2\pi$] rd. Once PSO is applied, the output is a vector containing an optimized set of inputs.

Only one array was used in the simulations (array 1, which covers the 0° - 180° range in Fig.1). Since arrays 1 and 2 are identical, an optimal configuration achieved for array 1 may also be applied to array 2, so that the beam points in its supplementary direction.

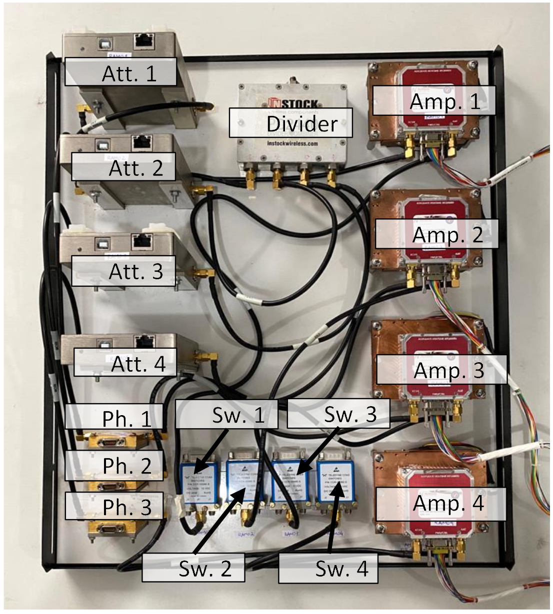



Fig. 7. Photo of the beamforming circuit (BC).

Four parallel antennas were initially arranged, physically pointing to 90° (direction in Fig. 2). After observing the limitation of this arrangement in attempts to point its radiation beam to 30° or to lower angles by the PSO, the extreme antennas were tilted sideways under selected angles, and the optimization was then reapplied for the same target direction. Figure 4(e) presents the optimization outputs when trying to point the radiation beam in the direction of $\varphi$ = 30° for some different tilt

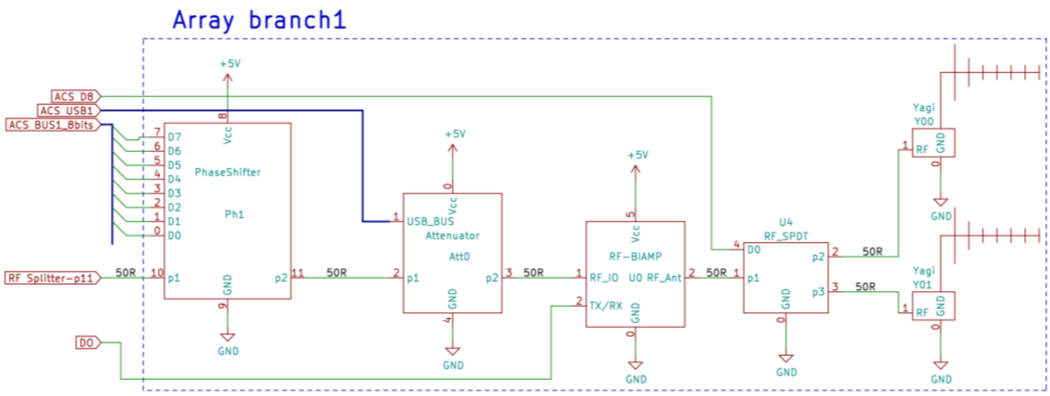



Fig.5. Circuit diagram of the branch 1 of beamforming circuit. Branches 2, 3 and 4 are identical to this one.

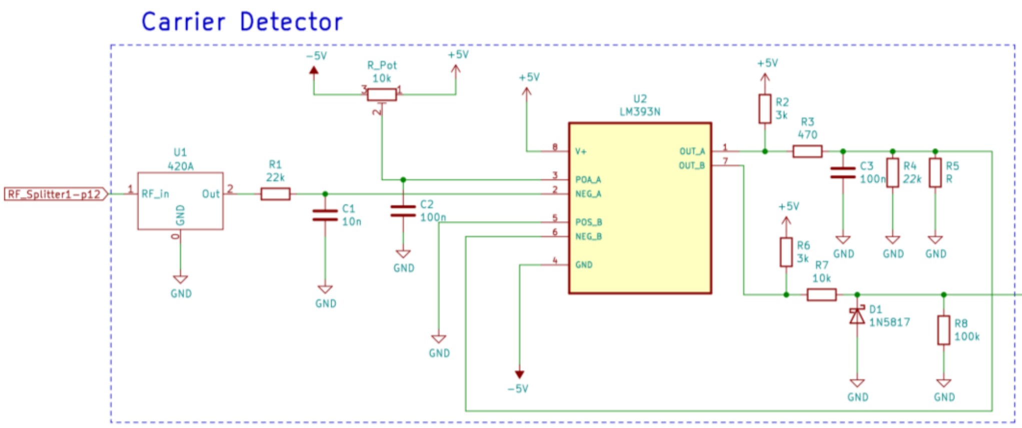



Fig.6. Circuit diagram of carrier detector. It essentially works by monitoring the signal strength levels of a carrier at the radio output. High carrier power levels indicate that the radio is in transmit mode. The carrier power level that characterizes a transmission can be adjusted by the resistor *R_pot*.

angles $\xi$ described in Fig. 1. The antenna array with $\xi$ = 70° was selected as the final array arrangement. The radiation patterns resulting from the application of PSO to this mathematical model of the antenna array are presented in Fig. 9 for target positions $\varphi$ equal to 90°, 75°, 50°, 45°, 30°, 20°, 15° and 0°. For the weights of 1 and 0.33 in the first and second components, the optimization yielded the pattern in dashed line. Thus, by modifying the weights to 1 and 0.25, the optimization produced the pattern in the solid line, which increased the gain by 2.49 dBi in the target direction.

Figure 9(c) demonstrates that optimization yields a set of inputs that results in a more suitable radiation pattern depending on the weights used in the two objective function components.

Due to the array symmetry, results for angles within $[90°, 180°]$ may be reproduced (Fig. 9) by applying in reverse order the optimization excitation results obtained within $[0°, 90°]$. Fig. 9(d) and Fig. 9(g) exemplify this by plotting the radiation pattern for $\varphi$=135° (dashed line) from the optimization result for $\varphi$=45° (solid line) and the radiation pattern for $\varphi$=165° (dashed line) from the optimization result for $\varphi$=15° (solid line) respectively.

## IV. COMMUNICATION BETWEEN THE INTEGRATED OPERATION CENTER (IOC) AND THE REMOTE STATIONS

In the electricity distribution supervisory system, each BS monitors a certain number of electrical switches that are installed in the surrounding area. The BSs work as repeater units and produce radio links to enable communication between the IOC and the switches. The communication architecture, however, works by pooling, so that the BS sets communication with one of its switches at a time, in a shift circular manner. At master/slave mode, the remote unit reports to its BS only if requested.

As previously stated, existing radio links with the BS commonly use a vertical collinear array of folded dipoles, which radiates in an almost omnidirectional pattern on the horizontal plane, as illustrated in Fig. 9. If a smart antenna array of directive elements replaces the commonly used array, a more directive radiation behavior with higher gain may be achieved. Thus, more distant switches may also be monitored without having to build a new BS [7].

The very nature of the current communication architecture creates this directivity methodology by switched beam concentration in an applicable approach without compromising the existing characteristics of the supervisory system. To implement it, it is only necessary to synchronize the array beamforming excitation controller and then send the data packets to the desired electrical switches.

In the systems described in [1,2], the main lobe points, on the horizontal plane, toward the direction of switches located in the region for which 0° <$\varphi$< 180°. Figure 2 demonstrates the proposed scenario for extending the angular region to 0° <$\varphi$< 360°: Two arrays of 4 antennas with 7 elements in a back-to-back arrangement, where $d_a$ = 2 cm and $d_b$ = 53 cm (Fig. 1). The extreme antennas of each array are horizontally tilted to $\xi$ = 70° in relation to its two central parallel antennas.

The PSO method is used here to maximize the gain. Optimized main lobes occur for 0° <$\varphi$< 180° when array 1 is fed

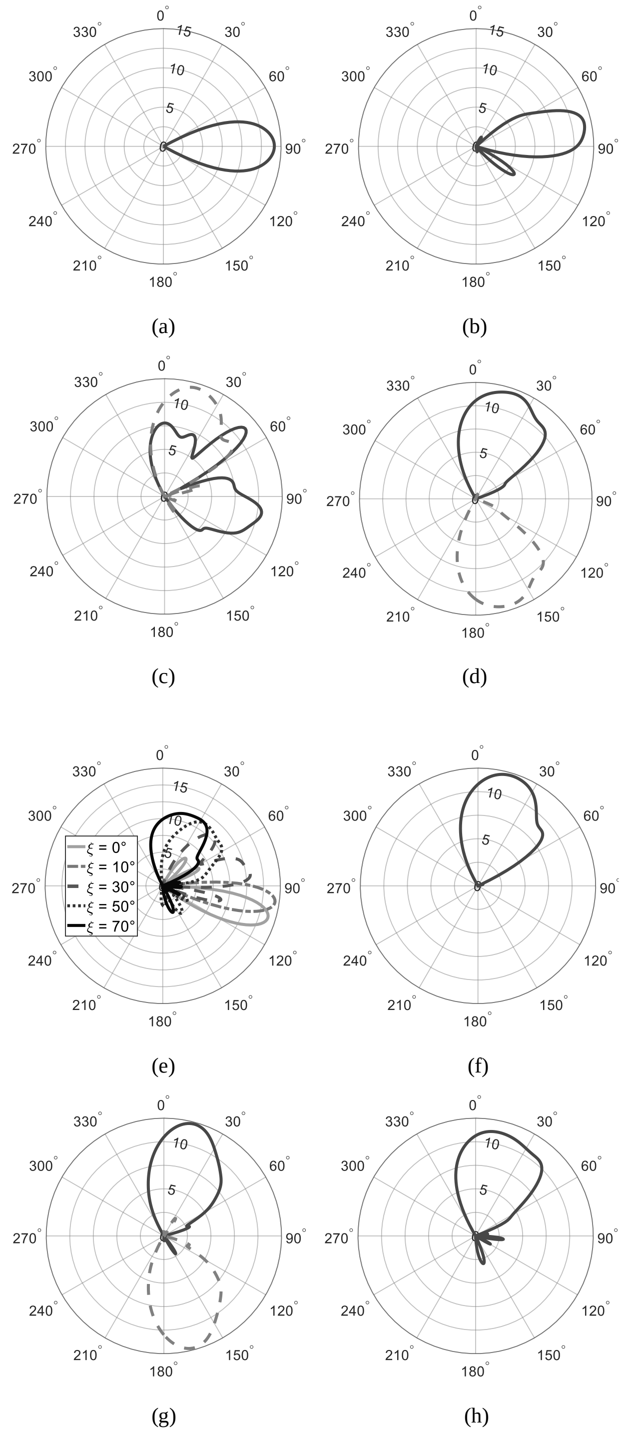



Fig. 9. Directivity optimization with the main lobe maximized at 469.3875 MHz for: (a) $\varphi = 90°$ - 14.15 dBi, (b) $\varphi = 75°$ - 13.95 dBi, (c) $\varphi = 50°$ in the first (dashed line) trial - 8.71 dBi, and second (solid line) trial - 11.20dBi, (d) $\varphi = 45°$ - 10.45 dBi (solid line) and $\varphi = 135°$ - 10.19 dBi (dashed line), (e) $\varphi = 30°$ for some different applied tilt angles $\xi$ (for $\xi = 70°$ - 11.33 dBi), (f) $\varphi = 20°$ - 12.18 dBi, (g) $\varphi = 15°$ - 12.30 dBi (solid line) and $\varphi = 165°$ - 12.31 dBi (dashed line), (h) $\varphi = 0°$ - 10.64. dBi.

by a certain vector $A_i$ (magnitude), $\beta_i$ (phase) and for 180° <$\varphi$< 360° when array 2 is excited with the same feed.

## V. EXPERIMENTAL RESULTS

In order to demonstrate the improvement provided by using the proposed Yagi-Uda array in an electricity distribution supervisory system instead of a folded dipole array antenna, communications tests were conducted between a BS and two units (named here CAC and CCEN), which simulated electrical remote switches. They were installed in the campus of the Universidade Federal de Pernambuco, and their locations are presented in Fig. 8.

CAC is at an angle of 18° and 400 m from the BS, whereas CCEN is 200 m away, at an angle of 135°. These locations were chosen so that the system could be tested for positions around the worst angular regions ([0°,30°] and [150°,180°]) for the PSO method.

Table I presents the best PSO parameters defined for the beam pointing to CAC (20°) and to CCEN (135°). These parameters, normalized for the BC, provide 5 dBm to the antennas. For this, the output radio power is 20 dBm and the minimum BC attenuation is 15 dB.

The BS radio transmission and reception frequencies are 469.3875 MHz and 459.3875 MHz, respectively. These are frequencies allowed by Brazilian National Telecommunications Regulatory Agency (ANATEL) radio frequency communication for remote sensing [7].

A 2-port network analyzer was used on each branch of the BC to equalize the signal that feeds the antennas, according to Table I. To equalize the beamforming circuit signifies setting the attenuators, phase shifters and the bidirectional amplifiers, by using the ACS, so that the relative amplitude and phases between the antennas inputs are equal to the values produced by the PSO. The attenuator and phase switch are digitally controlled by the ACS in steps of 0.25 dB and the phase switch, in steps of 1.4°, providing very precise parameter control. To simulate the remote electric switches, the Yagi-Uda antennas and a metallic box containing a digital radio and a Raspberry Pi were installed on electric poles.

The communications tests consisted of capturing the received signal strength indication (RSSI) at the CAC and the CCEN when the BC was connected to the Yagi-Uda array for the beam pointing toward 20° (CAC) and 135° (CCEN), and

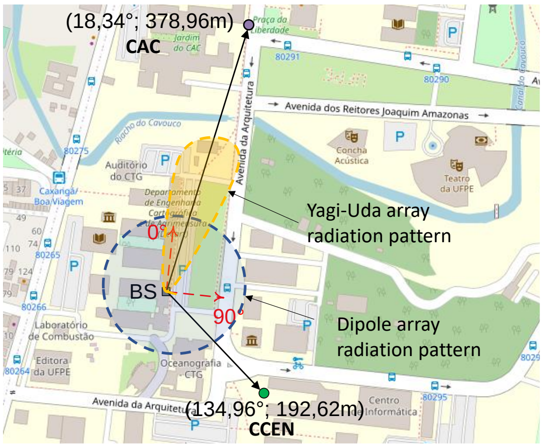



Fig. 8. The BS and the electrical remote switches (here called the CAC and CCEN) locations, and the illustrations of a horizontal radiation pattern of a vertical dipole array and an optimized Yagi-Uda array.

TABLE I
PSO PARAMETERS TO CONFIGURE THE BC

| Objective Angle (°) | 20 | *135* |
|---|---|---|
| $A_1$ (dB) | -15.00 | -36.57 |
| $\beta_1$ (°) | 52.76 | 53.15 |
| $A_2$ (dB) | -80.00 | -36.57 |
| $\beta_2$ (°) | - | 53.15 |
| $A_3$ (dB) | -35.94 | -36.57 |
| $\beta_3$ (°) | 58.91 | 159.48 |
| $A_4$ (dB) | -35.94 | -15.00 |
| $\beta_4$ (°) | -109.56 | -103.30 |

TABLE II
CAC AND CCEN RSSI MEASUREMENT RESULTS WHEN THE YAGI-UDA AND FOLDED DIPOLE ARRAY IS FED BY THE SAME POWER

| | Electrical remote switches | CAC (20°) | CCEN (135°) |
|---|---|---|---|
| Yagi-Uda Array Objective angle 20° | Mean (dBm) | -60.34 | -63.02 |
| | Standard deviation (dBm) | 0.23 | 0.15 |
| Yagi-Uda Array Objective angle 135° | Mean (dBm) | -73.74 | -51.37 |
| | Standard deviation (dBm) | 1.00 | 0.47 |
| Folded Dipole Array | Mean (dBm) | -66.65 | -61.41 |
| | Standard deviation (dBm) | 0.48 | 0.50 |

comparing them with the RSSI when a radio was directly connected to a folded dipole array delivering the same power to the antennas (5dBm).

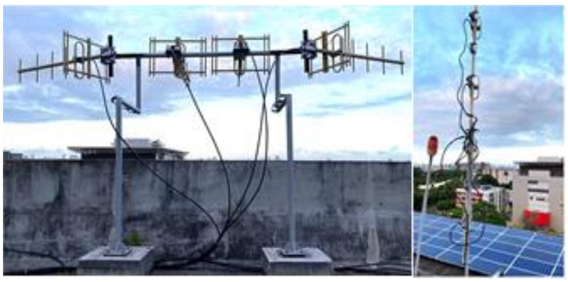
The Yagi-Uda and the folded dipole arrays were installed on masters that were placed on the roof of the Geoscience and Technology Center at UFPE, as presented in Fig. 10. The building is 40 m tall.

The mean value and the standard deviation of the RSSI and the Yagi and Dipole arrays were fed by the power of 5dBm.

It may be observed in Table II that the RSSI at the CAC and the CCEN, when the communications have been established, using the dipole array, is -66.65 dBm and -61.41 dBm, respectively. These values are different from one another due to the distance between the BS and the electrical switches. When communication is established using the proposed Yagi-Uda array pointing toward the electrical switches, it may be observed that the RSSI is 6.31 dB and 10.04 dB bigger with the dipole array at the CAC and the CCEN, respectively. Moreover, the Yagi-Uda array presents a high power attenuation in the electrical switch to which the beams are not directed. This attenuation is approximately 12.5 dB.

## VI. CONCLUSIONS

In this paper, the PSO method was used to find the feeds of an array of four Yagi-Uda antennas, each of seven elements, to



a) b)

Fig.10. Photograph of the a) Yagi – Uda array and b) folded dipole installedat the BS (on the roof of the Geoscience and Technology Center).

maximize the main beam of the radiation pattern in a given direction, and also to minimize the secondary lobes. This paper has described and analyzed the new topology of a four Yagi-Uda antenna linear array, which exhibits the outer antennas tilted 70° sideways in relation to those that are parallel.

The results from the PSO method in all cases proved to be efficient in directing the main lobe, and also succeeded in minimizing the secondary lobes. The lowest gain value obtained in the target direction of the optimized patterns was 10.19 dBi, which is 4.19 dB larger than the gain of the collinear vertical array of folded dipoles. As previously mentioned, due to the symmetry of the array, it is only necessary to perform the optimization for one quadrant, since its results may be applied to the quadrant directly below. The configuration may be applied in a BS with the purpose of communicating with electrical remote switches located in the full range from 0° to 360°, with high gain, considering two identical antenna arrays in a back-to-back arrangement.

Finally, to simulate a supervisory control system and validate the good performance achieved by the proposed Yagi-Uda array, a BS and two units (CAC and CCEN) simulating remote electric switches, were installed on the UFPE campus. RSSI measurements at the CAC and the CCEN comparing the Yagi and the dipole array fed with the same power were carried out. These results have indicated that the set of parameters provided by the PSO yielded considerable gains in these objective directions, while in the others there was a reduced gain.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