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REDUCING FM BROADCAST ENERGY CONSUMPTION USING DIRECTIONAL RADIATION PATTERN

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ABSTRACT

Much energy is saved in the daily operation of FM broadcast stations if the transmitting antenna system employed transmits RF signal only in directions where the signal is wanted. Most FM broadcasters employ antenna systems that radiate equally in all directions or having an omnidirectional pattern on the horizontal plane. In most cities where broadcast stations operate, the target population is located only in some directions from the antenna location and definitely not around it. The use of correct radiation patterns in FM broadcasting is very important to assure that every RF energy emitted by the transmitter is received only within the target areas and not to be wasted in directions where the signal is not needed. This paper presents a method of producing directional patterns that are suitable for FM broadcast applications with simple implementation. These patterns are shaped by varying the physical distance and the phase relationship of two basic antennas called bays in uniform linear array. The bay used in the array is the shunt-fed, slanted dipole commonly used in FM broadcasting. Computer simulations show that the patterns presented in this paper have sufficient gains in certain directions, greater beamwidth and sidelobe-free. Though only two control factors are used in shaping the radiation pattern of the array, several patterns can still be produced that find practical applications in FM broadcasting.

Keywords: FM broadcast, directional pattern, array factor, bay, sidelobe-free pattern, uniform linear array, slanted shunt-fed dipole.

INTRODUCTION

Most FM broadcast antenna systems used by broadcast stations in the Philippines, the United States of America and in other parts of the world are made up of several identical antenna elements called bays. Commonly, bays are stacked and side-mounted on metal towers and are connected electrically in parallel and unsymmetrically through transmission lines (Williams, 2007). Identical bays are stacked to produce higher gains. The bays are developed over the years to exhibit an omnidirectional azimuth pattern. Broadcasters usually employ four (4) bays in their antenna system spaced approximately one wavelength apart all on one side of the tower. This makes the bays effectively connected in parallel with each bay radiating the same intensity and the phase difference between adjacent elements is constant. The antenna system is end fed, i.e. it is fed from one common point on the lower end of the array using rigid coaxial cable. The axis of the bays is vertical as shown in Figure-1. In effect, the antenna system used by FM broadcasters is a collinear array having a radiation pattern that is omnidirectional on the horizontal plane. Whether the station is located along the seashore where the target area is only in one direction or in a valley where the population is in two opposite directions, broadcasters today still employ antenna systems with omnidirectional patterns. Transmitting RF signal towards the sea where there are no would-be listeners or directly towards the mountains is a waste of RF power. Much energy is saved if the radiation pattern of the antenna system follows a contour similar to a shape based on the population locations within the station's service area.

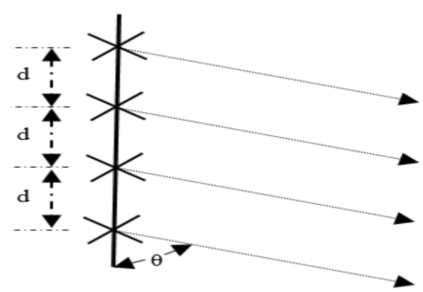

Figure-1. The Bays on the vertical axis.

One of the most popular antennas employed as bay in FM broadcasting in the Philippines and other parts of the world is the Onnigian antenna, technically called the shunt-fed slanted dipole. It was patented in the name of Peter K. Onnigian in the patent office of the United States of America in 1970. Technically, it is circularly polarized and consists of two shunt-fed slanted half-wave dipoles offset by 90^0, separated by a ¼ wavelength (λ) boom. Both dipoles are rotated 22.5^0 from the horizontal plane. The two dipoles are fed in phase through gamma match. Figure 2 illustrates the original Onnigian shunt-fed slanted dipole. It is now being fabricated by majority of the antenna manufacturers and used by most FM broadcast stations. The dimensions and other physical specifications of the original antenna are shown in Table-1.

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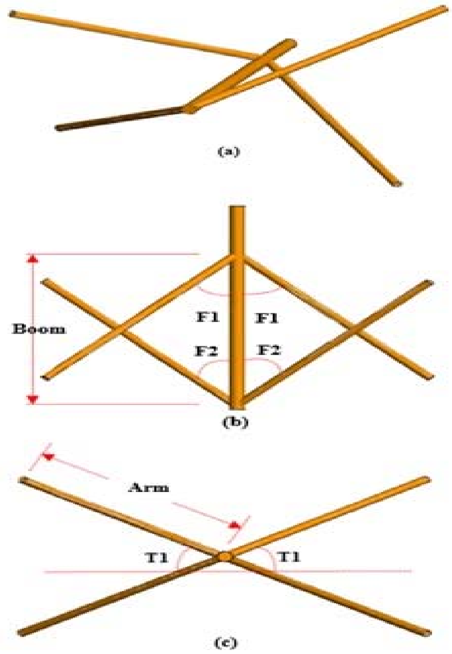

Figure-2. The shunt-fed, slanted dipole, (a). isometric view, (b) top view, (c) front view.

Table-1. Dimensions and physical specifications of the shunt-fed, slanted dipole.

Dimension/Physical Specification	alue
Boom Length	λ
Arm Length	λ
F1 (Arm offset angle of Dipole	5^0
F2 (Arm offset angle of dipole	5^0
T1(Skew angle)	2.5^0

BASIC THEORY

If the bays in the collinear array illustrated in Figure-1 are point sources, theoretical analysis indicates that the total radiation pattern of the antenna system has an omnidirectional pattern on the horizontal plane the same as the pattern of the individual bays but with higher gain. However, increasing the gain by stacking several bays causes the beamwidth to decrease and creates sidelobes.

If the bays in the collinear array are shunt-fed slanted dipoles or any practical antenna element, the total radiation pattern is derived using the principle of pattern multiplication (Crutchfield, 1985 and Balanis, 2005). Equation 1 is a general equation for the total electric field pattern of an array of bays arranged in linear array as in Figure-1. $E_B(\theta,\Phi)$ is the electric field pattern of each identical bay. In this paper, it is the electric field pattern of one shunt-fed slanted dipole element. $AF(\theta,\Phi)$ is the array factor of isotropic point sources that are arranged to form a uniform linear array.

$$E_T(\theta,\Phi) = E_B(\theta,\Phi) \bullet AF(\theta,\Phi) \quad (1)$$

As mentioned earlier, the shunt-fed slanted dipole was developed to exhibit an omnidirectional pattern on the horizontal plane ($\theta=90^0$). This makes the normalized value of $E_B(\theta,\Phi)$ in equation 1 similar to the electric field pattern of a point source on the horizontal plane. The normalized total electric field pattern of the shunt-fed slanted dipole array then becomes the same as the array pattern.

The array factor (Balanis, 2005) of a uniform linear array along the z-axis is

$$AF = \sum_{n=1}^{N} e^{j(n-1)(kd\cos\theta+\beta)} \quad (2)$$

where N is the number of identical elements or bays, $k = \frac{2\pi}{\lambda}$, d is the distance between elements in the array and β is the constant phase shift applied to each bay.

The radiation pattern on the vertical plane is determined by varying the value of θ in equation 2 on the y-z plane. The array factor in equation 2 is further simplified by having β=0 since all bays are basically connected in parallel making all bay currents to be in phase. With these assumptions and setting the number of bays to 2, leads to equation 3.

$$AF = \left[\frac{\sin 2(kd\cos\theta)}{4\sin((kd\cos\theta)/2)}\right] \quad (3)$$

Equation 3 is the normalized array factor with the phase reference at the array center. The maximum gain of the array is equal to 4 or equal to the number of identical elements and occurs at $\theta=90^0$.

Analyzing equation (3), minor lobes occur at several values of θ and is given in equation 4 where S=0, 1, 2, 3…

$$\theta = \cos^{-1}\left[\left[\frac{\lambda}{2\pi d}\left(\pm\frac{2S+1}{4}\right)\pi\right]\right] \quad (4)$$

Figure-3 is the polar plot of equation 3 showing the pattern nulls and the minor lobes. The number of minor lobes is proportional to the number of identical elements.

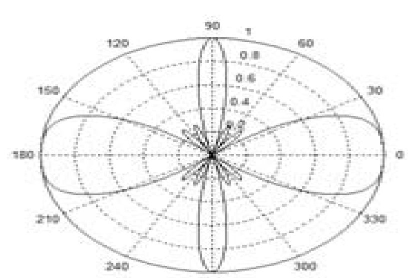

Figure-3. Plot of the array factor of uniform linear array on the vertical plane for N=4 spaced d=λ apart along the z-axis.

The above presentation just shows that when identical antenna elements form a linear array, several

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sidelobes and pattern nulls are produced and the beamwidth of the main lobe is reduced.

INDUSTRY PRACTICES

In attaining higher gains, the usual practice of stacking 4 or more bays "spaced approximately one wavelength apart and fed unsymmetrically (Crutchfield, 1985)" became very common. However, the corresponding increase in the gain of the antenna system produces sidelobes and pattern nulls and reduces the beamwidth of the main lobe (Balanis, 2005). The presence of minor lobes in the radiation pattern causes blanketing near the antenna tower, poses danger to the general public due to excessive radiation (Mappatao, 2010) and produces source-induced multipath distortion at the receiver. The pattern nulls between lobes also cause signal outage at some distances away from the antenna. Additionally, due to the reduced beamwidth, much of the power radiated is above the horizon and misses the service area, especially for high antenna heights above average terrain. To solve the effects of pattern nulls, broadcast operators use relatively complicated methods like beam tilting and null fill. These methods practically alter the gain, power dissipated by each bay and overall radiation pattern.

In the design of antenna systems to exhibit directional patterns on the horizontal plane, some companies use trial-and-error method in realizing directional pattern. They usually use parasitic elements [Circularly Polarized Directional FM Antenna www.jampro.com] to achieve a desired directional pattern.

METHODOLOGY

The proposed method of shaping the antenna radiation patterns in this paper for FM broadcast uses two bays (indicated as 1 and 2) in uniform linear array as shown in Figure-4. For two bays along the x-axis separated d away from each other forming a uniform linear array, the normalized array factor (Blake, 2009) is

$$AF = \left[\frac{\sin\psi}{2\sin\left(\frac{\psi}{2}\right)}\right] \tag{5}$$

where $\psi = kd\cos\phi + \beta$.β is the phase difference between the two bays and d is the physical distance between the bays. Several patterns are produced for different values of d and β. Generally, there are five possible control factors that are used to control the radiation pattern of an array (Balanis, 2005 and Blake, *et al.* 2009) including distance and phase variation. The three other factors require more elaborate process and equipment that are not common in an ordinary broadcast station, so possible implementation of patterns produced using these factors are difficult.

Further improvements for a pattern to resemble more closely the desired pattern can be achieved by making small adjustments on the value of d and/or β or by using the optimization techniques suggested in (Mappatao, *et al.* 2011,1(3) and Mappatao, *et al*. 2011, 1(5)).

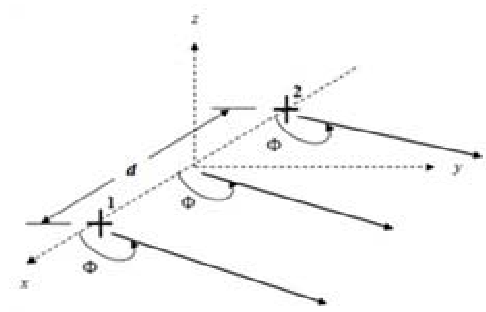

Figure-4. Uniform linear array formed by two bays on the horizontal plane along the x-axis.

More pattern shapes are realizable if more control factors are considered othern then just the distance and phase considerations. The use of more control factors allows pattern optimization to resemble a specific desired radiation pattern as well as the use of the methods described in (Shang, 2010 and Diaz, *et al.* 2003). However, as described somewhere in this paper, some control factors are difficult to implement.

RESULTS

A pair of shunt-fed slanted dipoles is used in this paper in shaping a particular pattern illustrated in the set-up shown in Figure-5. In all succeeding pattern results presented, the dimensions and other physical specifications of each bay are the figures presented in Table-1.

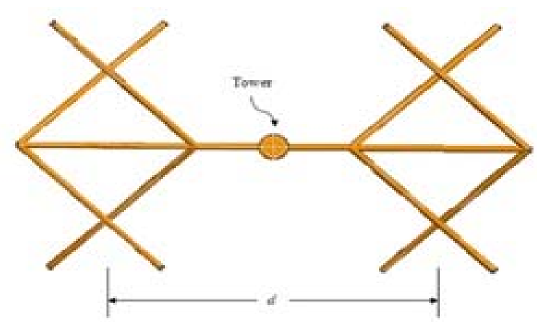

Figure-5. The shunt-fed, slanted dipoles in a uniform linear array.

Each pattern in this paper is approximated by numerical simulation by a hybrid of numerical methods like the Method of Moments, Multi-level Fast Multipole Method and Finite Element Method. A detailed discussion on the Method of Moments and other similar methods is presented in (Delgado, C., *et al.* 2015). The specific software used in this paper is the more advance Feko Antenna Simulation software version 6.3. The frequency used is 97.5 MHz (center of the FM band in the Philippines and the U.S.). All frequency-related values are therefore referred to this frequency. Also, the value of d is the bay center-to-bay center as illustrated in Figure-5.

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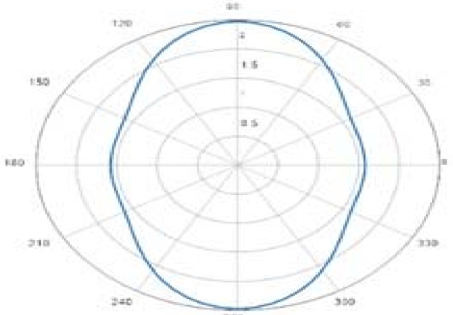
Bi-directional pattern

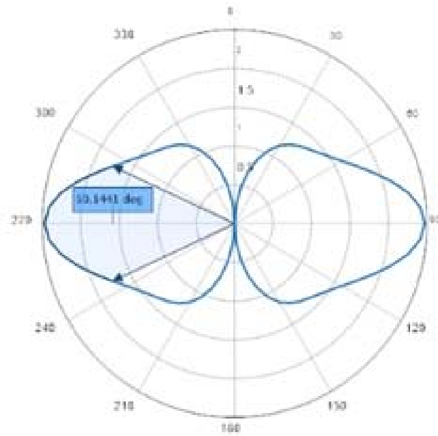
This pattern is useful in broadcast locations where the target areas are just in two broad and opposite directions. In the Philippines, one particular application is in the Cagayan Valley Region in Northern Philippines as shown in Figure-6. The location is a valley between the Cordillera Mountain range to the west and the Sierra Mountain range to the east. There are at least four (4) centers of commerce in the region where FM broadcast stations operate. The pattern is generated by having the ***d*** equal to 0.3λ and the bays are fed in-phase (***β*** = 0) in the uniform linear array.

Figure-6. Bi-directional pattern fitted for use in the Cagayan Valley Region in northern Philippines.

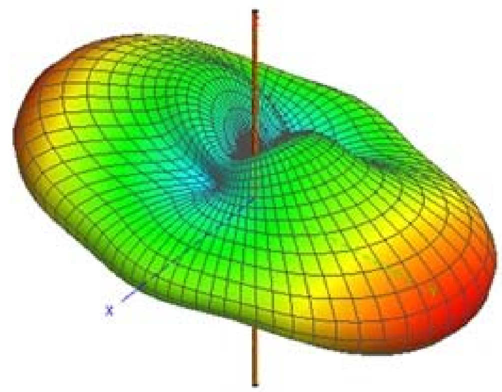
The FEKO antenna simulation software rendition of the total electric field intensity of the bi-directional pattern is shown in Figure-6. All patterns illustrated in this paper are the total electric field patterns (H-pol and V-pol). Figure-7(a) shows the azimuth radiation pattern with a maximum gain of 5.452 dB_i(5.452 dB referred to an isotropic antenna) in both the 90^0 and 270^0 directions. The minimum gain is in the 0^0 and 180^0 directions with a value of 1.546 dB_i. All gains indicated in this paper are referred to an isotropic antenna. The vertical field pattern is also shown in Figure-7(b) where maximum gains occur (azimuth angle equal to 90^0 and 270^0). The beamwidth is about 50^0. Lastly, Figure-7(c) shows the rendition of the computer simulation software used in the calculations of the electric field pattern in three-dimensional coordinates.



(a)



(b)



(c)

Figure-7. Electric field pattern of with *d*=0.3λ and *β*=0 on thehorizontal plane, (b) vertical plane and (c) 3D coordinates.

To practically produce this radiation pattern, the bay center distance between the two bays must be 0.3λ. λ is the wavelength in free-space. To assure that the two bays are in-phase, the length of the transmission line connecting each bay to the main transmission line must always be the same or the difference in length must be one wavelength or multiples of it. The wavelength in the transmission line is equal to the wavelength in free-space multiplied by the velocity factor of the transmission line used. Slight deviation from the illustrated shape of the pattern is achieved by varying slightly the values of d and β.

Using the commercial 2-bay Jampro JMPC omnidirectional antenna as reference with a gain of 1.64 (2.148 dBi) as claimed by the manufacturer, the array has a gain of 2.14 (3.304 dB). If this is translated to transmitted power, the 2-bay commercial antenna needs a power of 100 watts while the array needs only 46.729 watts to produce the same amount of signal level at the same point in the far-field, especially in the 90^0 and 270^0 directions. This relates to an RF power reduction of 53.271%. In simple terms, the reason for the big energy

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saving is the ability of the antenna array to concentrate its radiation only to two directions with lesser radiation to other directions.

Fan-shaped pattern

This pattern allows maximum transmission of signal in one side and with limited radiation on the other side. In the Philippines, this pattern is suited for Tuguegarao City in Cagayan Valley region, Northern Philippines as shown in Figure-8. The location is near the foot of the Sierra Madre mountain range. There is a need to transmit more power in the northern, southern and western directions only. This pattern also finds applications in broadcast locations along sea shores. The pattern is derived with d equal to 0.3λ and the bays are out-of-phase by 90^0 ($\beta = 90^0$) in the uniform linear array. Figure-9 shows the rendition of the computer program used in the calculations of the electric field pattern. Figure-9(a) shows the polar azimuth radiation pattern. The maximum gain is determined to be 4.984 dBi occurring at 65^0 and 295^0 while the gain at 0^0 is 4.202 dBi. Figure-9(b) shows the polar radiation pattern on the vertical plane at an azimuth angle of 65^0 where maximum gain occurs on the horizontal plane. At this azimuth angle, the gain is maximum and the beamwidth is about 49^0. To practically implement this radiation pattern, the bay center distance needs to be 0.3λ at the operating frequency. The difference in the length of the transmission line connected to each bay referred to the main transmission line is 90 electrical degrees or λ/4. λ is equal to ($3x10^8$/frequency) x vl. vl is the velocity factor of the transmission line.

Figure-8. The Fan-shaped pattern fitted for use over Tuguegarao City in northern Philippines.

Again, using the commercial 2-bay Jampro JMPC omnidirectional antenna as reference, the gain of the array in the 65^0 and 295^0 directions is 1.921 (2.836 dB). This means, if 100 watts is applied to the reference antenna, it will take only about 52 watts for the array to produce the same signal level in those two directions. This is equivalent to a power saving of 47.944%.

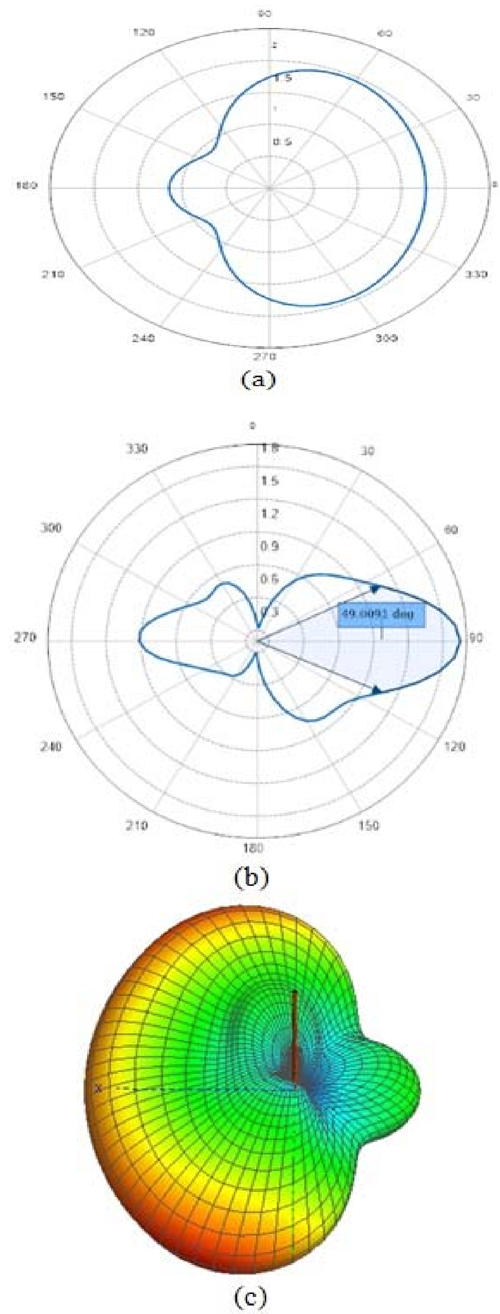

Figure-9. Electric field patterns of with d=0.3λ and $\beta=90^0$ on the(a) horizontal plane in polar plot, (b) vertical plane in polar plot and(c) 3D Coordinates.

Other patterns of interest

Other patterns that can be realized with the proper combination of the physical distance and the phase difference between the two bays in linear array. Table-2 shows some of these patterns with the corresponding values of d and β that find applications in some specific areas of operation of FM broadcast stations.

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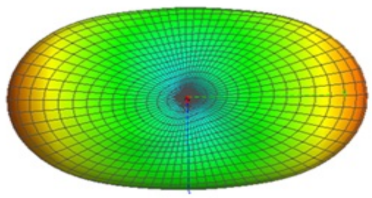
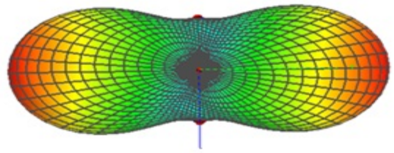
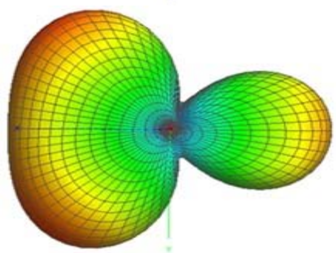
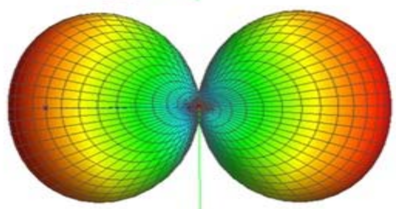
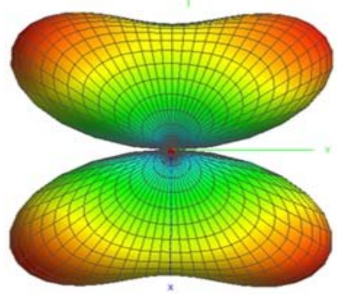
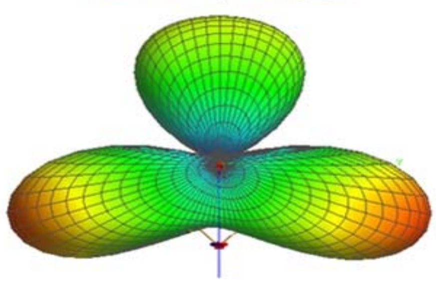
Table-2. Other Patterns produced with the corresponding values of d and β.

d	β	Pattern
0.375λ	0^0	
0.5λ	0^0	
0.5λ	135^0	
0.5λ	180^0	
0.75λ	180^0	
0.75λ	90^0	

CONCLUSIONS

This paper described a simple method of shaping and controlling the azimuth radiation pattern for the eventual purpose of reducing the energy consumption on the daily operation of FM broadcast stations. The method is capable of producing directional patterns for FM broadcast applications using a uniform linear antenna array of two shunt-fed, slanted dipoles as bays. The method is simpler than the tedious trial-and-error method of adding parasitic elements to produce a certain radiation pattern as practiced by antenna manufacturers. Even though the method uses only two control factors (d and β variation), it was shown that it is possible to produce directional patterns that find practical applications in FM broadcasting. In the radiation patterns presented, there are no sidelobes and pattern nulls produced that pose adverse effects on the reception of the signal and to the health of people living around the transmitting antenna. The radiation patterns exhibit high gains but with higher beamwidths that improve the coverage within the service area of the broadcast station. With higher gains and beamwidths, lower transmitter power is utilized in the operation of a broadcast station to cover the same target areas. Employing the correct directional pattern and with power savings reaching about 50%, much energy is really saved in the daily operation of a broadcast station as compared to the use of omnidirectional pattern.

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