A WIDE-ANGLED HIGH-XPD NODE STATION ANTENNA FOR LOCAL DISTRIBUTION RADIO SYSTEM

Hajime SEKI* and Mitsuhiro KUSANO

Antenna System Development Department
Microwave & Satellite Communication Division
NEC Corporation
Ikebe-cho Midori-ku Yokohama-shi 226 Japan

ABSTRACT

An antenna with high-XPD over its wide angle coverage is developed as a new nodal antenna for local distribution radio system. The XPD more than 20 dB is achieved almost everywhere in its shaped beam (90° fan in azimuth/cosecant square in elevation) by a longitudinal-shunt slotted waveguide with flares. The design principles and procedures are described besides the experimental results of a prototype antenna.

INTRODUCTION

With the increasing demand for business communications, several point-to-multipoint systems have been proposed [1], among which is NEC's Local Distribution Radio [2]. In order to serve equally any subscriber within a 90° sector zone, it is necessary for a nodal antenna to have such a shaped beam as fan in azimuth/cosecant square in elevation. For this purpose a composite reflector antenna [3] and a shaped reflector one [4] had been developed.

In addition to the pattern requirement identified above, it is desirable that the nodal antenna has high cross polarization discrimination (XPD) characteristics over the full coverage area. This is not only to reduce the interference from adjacent zones but also to allow for frequency reuse in the same zone using polarization quadrature techniques. Reflector type antennas are incapable of achieving such wide-angled high-XPD characteristics due to the inherent cross polarized currents generated by a curved reflector surface.

In this paper the use of array techniques is made to develop a new nodal antenna with desired high-XPD characteristics and the shaped beam. The design principles and procedures are described besides the experimental data of a prototype antenna, which show marked XPD improvement over previous reflector type antennas.

1. DESIGN PRINCIPLES

The radiation pattern of an array antenna is the product of an element pattern and an array factor. It follows therefore that the use of elements free from cross polarization ensures automatically high-XPD characteristics of the array. For this reason a longitudinal-shunt slot in the broad wall of a rectangular waveguide was adopted as a horizontally polarized radiating element.

The residual degree of freedom, i.e. the array factor, can be optimized for beam shaping. However, the synthesis of both azimuth and elevation patterns by the factor requires a two dimensional array, which is costly and bulky. Thus it was decided to shape the elevation pattern (cosecant square) using a slotted array while the azimuth fan beam using appropriate flares.

The resultant configuration is shown schematically in Fig.1. As

*Dr. Seki is now with the Faculty of Science and Engineering, Keio University, Hiyoshi Kohhoku-ku Yokohama-shi 223 Japan.
the flares are still tentative ones, only the design theories of the slotted waveguide are covered below.

2. PATTERN SYNTHESIS

The problem here is to determine the source distribution that will produce the specified cosecant square beam. Our particular case is nonlinear because the excitation phase of the slot depends on its location along the waveguide axis. Nevertheless, the numerical method using linear programming [5] -[6] was employed successfully in the following manner.

An unequally spaced linear array model of a slotted waveguide is shown in Fig. 2. Under the assumption on source distribution

\[ a = a_n, \quad \psi = \psi_n, \quad d = d_n, \quad (1) \]

the array factor becomes real-valued and is given by

\[ A(\theta) = \sum_{n=1}^{N} b_n \cos n\theta + \sum_{n=1}^{N} c_n \sin n\theta, \quad (2) \]

where

\[ b_n = a_n \cos \psi_n, \quad c_n = a_n \sin \psi_n, \quad (3) \]

\[ k_0 = \frac{\lambda_0}{\sin \theta_0}, \quad \lambda_0 \text{ is the wavelength in free space.} \]

Since eq. (2) is linear with respect to \( b_n \) and \( c_n \), the application of LP leads to an optimal distribution \( a_n \) and \( \psi_n \) through eq. (4).

During this process, however, the relation between \( \psi \) and \( d \) is ignored. Hence slots are relocated after the optimization by LP. These processes are repeated until the correction of each slot location becomes small enough.

For a longitudinal-shunt slot the relation is given by

\[ d_n = \frac{\lambda g}{n + (1 + (\lambda g/\lambda_0) \sin \theta_0) + s + \Delta \psi_n/\pi}, \quad (5) \]

where

\[ \Delta \psi = \psi - \psi_0, \quad (6) \]

\[ \psi_0 = k_0 d_n \sin \theta_0, \quad (7) \]

\[ d_n = \frac{\lambda g}{n + (1 + (\lambda g/\lambda_0) \sin \theta_0)} \quad (8) \]

\( \lambda g \) is wavelength in guide; \( \lambda_0 \) : that in free space; \( \theta_0 \) : beam tilt from array normal; \( s = -1 \) \((-\pi < \Delta \psi < -\pi/2)\),

\( 0 \) \((-\pi/2 < \Delta \psi < \pi/2), \) \((-\pi/2 < \Delta \psi < \pi) \). The cophasal excitation for \( \theta = \theta_0 \) and the feed from the right of figure 2 are assumed in eqs. (5)- (8) as the initial conditions for \( \psi_n \) and \( d_n \).

As an example a synthesized pattern with \( N = 20 \) and \( \theta_0 = -5^\circ \) is shown in Fig. 3. The constraints for this case are

(i) \( p(\theta) A(\theta) < q(\theta) A(\theta) \) \((-6^\circ < \theta < -4^\circ)\)

(ii) \( \sin(-4^\circ - \theta_0) / \sin(\theta - \theta_0) = < p(\theta) A(\theta) = R \sin(-4^\circ - \theta_0) / \sin(\theta - \theta_0) \) \((-4^\circ < \theta < 40^\circ \) \text{ with } R = 2 \text{ dB),}

(iii) \( |A(\theta)| = S \) \((-10^\circ < \theta < 45^\circ, 45^\circ < \theta\) ,

Fig. 3 A synthesized cosecant square pattern. (a) After; (b) before the last relocation of slots; dotted lines are the upper/lower limits in pattern synthesis by LP.
where \( p(\theta) \) is the element pattern of a longitudinal slot and is given by
\[
p(\theta) = \frac{\cos((\pi/2)\sin\theta)}{\cos\theta}.
\] (9)
The constrained points are taken every 0.5° in the beam nose (i) and 2° in other regions. The objective function to be minimized is \( S \) in (iii), i.e., the maximum sidelobe level. The pattern in the figure is not \( A(\theta) \) but \( p(\theta)A(\theta) \).

3. SLOTTED WAVEGUIDE DESIGN

The task here is to determine the disposition of the slots so as to realize the source distribution. The well known procedure by Kaminow and Stegen (7) unfortunately confines itself to an equally spaced array. The modified design equations were therefore developed to cover the unequally spaced case.

A conductance-loaded transmission line model of a slotted waveguide section is shown in Fig. 4, where the numbering of slots is in reverse order of figure 2. With \( Y_n^+ \), \( g_n \), and \( V_n \) given, the quantities to be determined are \( \lambda_n \) and \( g_{n-1} \). According to [7] the excitation phase of the nth slot is equal to \( \arg(jV_n) \) when the slot is in resonance. It is therefore required that
\[
\arg(V_{n-1}^+V_n) = \frac{\theta_{n-1} - \theta_n}{2}, \quad (10)
\]
while from the equivalent circuit
\[
V_{n-1}^+V_n = (\cos\theta - b \sin\theta) + jg_n \sin\theta \quad (11)
\]
where \( \theta \) is the electrical length between \( n-1 \) and \( n \)th slots and
\[
Y_n^{-} = q_n^{-} + jb_n^{-} = q_n^{-} + j\tan(h_n^{-}) \quad (12)
\]
Equations (10) and (11) lead to
\[
\theta = \tan^{-1} \left[ \frac{-b_n^{-}\tan(\theta_{n-1} - \theta_n)}{q_n^{-}} \right], \quad (13)
\]
from which the physical length \( \lambda_n \) is determined as
\[
\lambda_n = \frac{(\theta_{n-1} + 2\pi)\lambda}{\beta} (-\pi < \theta < -\pi/2),
\]
\[
= \frac{(\theta + \pi)\lambda}{\beta} (-\pi/2 < \theta < \pi/2),
\]
whence \( 2\pi/\lambda \) and the +/- signs of \( \lambda \) mean to offset the \( n-1 \)st slot in the same/opposite sides of \( n \)th slot, respectively.

With \( p_n^{-} = g_n^{-}|V_n|^2/2 \) and \( \Gamma_n = (1-\Gamma_n^-)/\Gamma_n^- \)
\[
p_n^{-} = p_n^{-} + j\Gamma_n^- V_n^2/2 \sinh(2\lambda_n^-),
\]
\[
p_n^{-} = \frac{\exp(2\alpha_n^{-}) + \Gamma_n^-}{2|\Gamma_n^-|^2} - 1 \quad (15)
\]
Then \( g_{n-1} \) is determined by
\[
g_{n-1} = (p_{n-1}^+/p_n^+)^{-1} \Gamma_n^{-}, \quad (16)
\]
where \( p_{n-1} \) is proportional to \( a_n \)
\[
Y_{n-1}^+ = q_{n-1}^+ + j\Gamma_n^{-} \Gamma_n^{-} V_n^2/2 \quad (17)
\]
The next recurrence may be started with eqs. (16), (18) and
\[
V_{n-1} = V_n \left( \cos(\gamma_n) + j\sin(\gamma_n) \right), \quad (18)
\]
The initial conditions for above algorithm are \( Y_{n=1}^+ = q_n^+ \eta_n^+/p_{n=1} \) and \( V_0 = \sqrt{2}P_L \), where \( P_L \) is the power dissipated in a matched load.

The slot offset \( \alpha_n \) may be determined by using the well known Stevenson's formula [8]
\[
\alpha_n = \frac{a}{2} \theta_n^{-} \sin^{-1} \left( \frac{V_n}{V_0} \right), \quad (19)
\]
where \( a \) and \( b \) are the width and height of waveguide, respectively, and
\[
g_0 = 2.09 \frac{\alpha_n}{b \lambda_0} \cos^2 \left( \frac{\pi a_n}{2\lambda_0} \right), \quad (20)
\]
With \( \alpha_n \) given by eq. (19) the resonant length of slot is determined with the aid of measured data [9].

---

---

---

---

---

---

---

---

---
4. EXPERIMENT

The waveguide used was type WRJ-10, 1000 mm long, and with 41 slots each 2 mm wide and round ended. The tentative configuration of flares is shown in Fig.1 and was arrived at by trial and error to produce the azimuth pattern shown in Fig.5 as (a). The elevation pattern, with the flares attached, is shown in Fig.5 as (b) and very closely follows the theoretical pattern in Fig.3. The measured peak gain was 17.9 dBi.

The most interesting and exciting aspect of this antenna is its wide-angled high-XPD characteristics shown in Fig.6. The coverage of the 20dB-XPD contour has been significantly widened compared with that of a previously developed re- flector antenna (broken lines).

The cross polarization level was about 40 dB below the co-pol beam peak everywhere in Fig.6.

This means that the XPD degraded due to the cosecant squared beam shape and can be further improved by raising up the co-pol level.

CONCLUSION

The wide-angled high-XPD characteristics of the newly developed nodal antenna have been demonstrated. The key features in this development were the adoption of array techniques in place of conventional reflector antennas and the design procedures of a slotted waveguide, a key component of this antenna. Further theoretical investigation into the flare design still needs to be undertaken.

Although this paper has confined its description to the horizontally polarized nodal antenna, a vertically polarized version is now under development in our NEC Yokohama plant in Japan.

ACKNOWLEDGMENT

The authors would like to thank Messrs. S.Yokoyama, H.Shimaya, I.Sato and S.Tamagawa for their encouragement, and Messrs. A.Shiraishi and K.Kurokawa for their assistance in the experiment.

REFERENCES

[9] ibid., p.9-6, Fig.9-7.