A Novel Design Method of Loaded Beam Tilting Antenna with Reactive Loads

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1.Introduction

For the base station antenna of cellular mobile telephone systems, a beam tilting antenna is desired[1]. Such a beam tilting is realized easily by a loaded wire antenna. We reported the determination method of the loading impedances for the antenna with 1 or 2 loads from desired tilt angle [2]. In this paper, we describe design method of the loaded beam tilting antenna with more than 3 reactive loads which realize desired tilt angle, high directive gain and low sidelobe level.

From Section 2 to Section 4, the determination method of loading impedances of the antenna with 2 loads is described. In Section 5, design method of the antenna with more than 3 reactive loads is presented. We realized antennas by using the combination of the determination method of loading impedances and determination method of the spaces of the loads we propose this time. In Section 6, examples of the antennas designed by the proposed method are shown.

2.Relation between electric field and loading impedances of antenna

Fig.1 shows a loaded antenna with 2 loads fed by the voltage Vs. The antenna is assumed divided into N equal-length segments. I1, I2, ..., Ii, ..., IN are the currents on the segments. ZL and ZM are loading impedances.

From [3], we have the relation between the electric field at the far zone observation point and the loading impedances as follows. The current is assumed along the z-axis. The current distribution is computed by using the Moment method (Galerkin's method). We used piecewise sinusoidal function as the basis function. By the computing, we obtain

\[ \mathbf{V} = [\mathbf{Z}] \mathbf{I} \]  
(1)

where \( \mathbf{I} \) represents currents on the antenna, \( \mathbf{V} \) incorporates \( V_s, -Z_L I_L \) and \( -Z_M I_M \). \( \mathbf{Z} \) is square matrix which is determined from shape of the antenna.

The electric field at the far zone observation point from the antenna is given by

\[ E(\theta) = jK \sin \theta \int_0^h I(z) \exp(jkz \cos \theta) dz \]  
(2)

where \( K \) is the constant, \( k \) is the free space wave number. \( I(z) \) is current on the antenna and can be represented by

\[ I(z) = \sum_{t=1}^N I_t T_t(z) \]  
(3)

For \( T_t(z) \), we used piecewise sinusoidal function. \( I_t (t=1,2,...,N) \) are the currents on the segments of the antenna.

When the antenna has \( Z_L \) and \( Z_M \), we have from (1), (2) and (3)
\[ E(\theta) \equiv A[ \alpha Z_L Z_M + \beta Z_L + \gamma Z_M + \delta ] \]  
(4)

where

\[ A = jK V_s \sin \theta / [1 + Y_{LL} Z_L + Y_{MM} Z_M + (Y_{LL} Y_{MM} - Y_{LM} Y_{ML}) Z_L Z_M ] \]  
(5)

and

\[ D_t(z) = \int_{Z_{t-1}}^{Z_{t+1}} T_t(z) \exp (j k z \cos \theta) dz \quad (t = 1, 2, \ldots, N) \]  
(6)

\( \alpha, \beta, \gamma \) and \( \delta \) are represented using \( D_t(z) \) and the elements of \([Y]\) which is inverse matrix of \([Z]\) [2].

3. Representation of tilt angle, directive gain and sidelobe

Fig. 2 shows radiation pattern. \( \theta_{TL} \) represents the position of the main lobe maximum, that is, \( \theta_{TL} = \theta + 90^\circ \). From Fig. 2, for the radiation intensity in the \( \theta_{TL} \) direction,

\[ \frac{\partial |E(\theta_{TL})|^2}{\partial \theta} = 0 \]  
(7)

\[ \frac{\partial^2 |E(\theta_{TL})|^2}{\partial \theta^2} < 0 \]  
(8)

are derived.

Next, for the straight wire antenna, directive gain\((G_d)\) in \( \theta_{TL} \) direction is represented using the following equation.

\[ G_d = \frac{2 |E(\theta_{TL})|^2}{\int_0^{\pi} |E(\theta)|^2 \sin \theta d\theta} \]  
(9)

Moreover, we define that radiation to the upper half-plane in Fig. 2 is sidelobe. And, we consider the following equation for representing sidelobe.

\[ \frac{1}{n} \sum_{i=1}^{n} |E(\theta_i)|^2 = b_k |E(\theta_{TL})|^2 \]  
(10)

In this equation, \( b_k \) is the ratio of the average of radiation intensities in \( n \) directions within sidelobe to the radiation intensity in \( \theta_{TL} \) direction. We realize low sidelobe level by making the \( b_k \) small.

4. Determination method of loading impedances to realize desired tilt angle

From (4), (9) and (10), for the antenna with \( Z_L(=R_L+jX_L) \) and \( Z_M(=R_M+jX_M) \), following equations are obtained.

\[ \frac{\partial |E(\theta_{TL})|^2}{\partial \theta} = a_r R_M^2 + ax M^2 + bf R_M + cfx M + df \]  
(11)

\[ \frac{\partial^2 |E(\theta_{TL})|^2}{\partial \theta^2} = asR_M^2 + asX_M^2 + bsR_M + csX_M + ds \]  
(12)

\[ G_d = \frac{2(a_g R_M^2 + agX_M^2 + bg R_M + cg X_M + dg)}{aiR_M^2 + aiX_M^2 + biR_M + ciX_M + di} \]  
(13)

\[ \frac{1}{n} \sum_{i=1}^{n} |E(\theta_i)|^2 = b_l |E(\theta_{TL})|^2 \]  
(14)

where each coefficient is function of \( Z_L \) and derived from (4) and (6). Then, we have the equations which represent circles by assuming (11)=0 and (12)=0.

In Fig.3, determining \( Z_L \), \( C_1 \) is derived from (11) and \( C_2 \) is derived from (12), respectively. When as in (12) > 0, the impedances in the inside area of \( C_2 \) satisfy (8) as shown.
in Fig.2. When as in (12) < 0, the impedances in the outside area of C2 satisfy (8). Therefore, the antennas with the impedances denoted by the arrow realize desired tilt angle. The impedance on X axis represents that the load is reactance. We obtain $G_d$ and $b_k$, by substituting the reactance $X_M$ into (13) and (14), respectively.

For the antenna with reactive loads only, determining $R_L=R_M=0$, $X_L$ and $X_M$ which realize desired tilt angle, higher $G_d$ and smaller $b_k$ are chosen.

5. Design method of the antenna with more than 3 loads

Next, we describe the design method of the beam tilting antenna with more than 3 reactive loads. The model antenna is shown in Fig.4. The antenna has 6 loads. $h$, $L_I$ and $L_E$ are dimensions of the antenna. The loading impedances of the antenna are $Z_F (=R_F+jX_F)$, $Z_L (=R_L+jX_L)$, and $Z_M (=R_M+jX_M)$, that is, a number of $Z_F$ is 4. For the antenna, spaces of the loads are equal. $L_I$ and $L_E$ are determined as following equations.

\[
L_I = \frac{\lambda}{2} + 2D \times i \\
L_E = \frac{\lambda}{2} + D \times i \quad \text{or} \quad \frac{\lambda}{2} + D \times i - 1 \\
(i = 0, 1, 2, \ldots)
\]

where $\omega$ is 1 wavelength and D is length of 1 segment of the antenna. D is $\lambda/24$ for the design. The maximum length of $L_I$ is $\lambda/2$ and that of $L_E$ is $3\lambda/4$. We realize current distribution as shown in Fig.4(a) by $L_I$ and $L_E$ of suitable length and loading impedances of suitable value. Then, the antenna realize current distribution same as dipole array as shown in Fig.4(b).

Determining the dimensions of the antenna and positions of the loads above mentioned method and adding $jX_F$, which is impedance of reactive loads to the corresponding diagonal elements in the matrix $Z$, $X_L$ and $X_M$ are obtained from the same method applied for the antenna with two loads. For $X_F$, several values were used. The beam tilting antenna which realize desired tilt angle, high directive gain and small $b_k$ were designed by using this process.

6. Example of the loaded beam tilting antenna

Table 1 shows example of the dimensions, loading impedances and characteristics of the loaded beam tilting antenna with 6 loads designed by the proposed method. In these antennas, the tilt angles agreed with the desired tilt angles. They realized comparably small $b_k$ and high directive gain. And, their VSWR didn’t exceed 2.0.

7. Conclusion
A novel design method of loaded beam tilting antenna with more than 3 loads to realize desired beam tilting, high directive gain and low sidelobe level was proposed. In this method, a number of loads isn't limited.

References
Table 1. Example of the loaded beam tilting antenna with 6 loads.
(Frequency: 1465MHz, Radius of antenna: 0.015 ∅)

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<th>□T (degree)</th>
<th>gain(dBi)</th>
<th>bk</th>
<th>h (∅)</th>
<th>LE (∅)</th>
<th>LI (∅)</th>
<th>ZF (∅)</th>
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<td>j160</td>
<td>j184</td>
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Fig.1. Loaded antenna with 2 loads.

Fig.2. Expression of beam tilting and sidelobe.

Fig.3. Loading impedance to realize desired tilt angle (when as > 0).

Fig.4. Loaded antenna which realize dipole array.