Omnidirectional Telemetry Antennas

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Summary. Missiles, rockets, and satellites need as much uniform gain as possible to provide continuous telemetry coverage. The theoretical limit of an ideal antenna would be 0 dB gain with 100 percent coverage of $4\pi$ steradians. It is not practical to attain the theoretical limit in practice on missiles, rockets, and satellites. This paper describes how closely the theoretical limit can be approached.

Introduction. The conformal microstrip antenna provides a unique solution to this problem because:

- It provides the excellent coverage required to maintain continuous telemetry coverage (99+ percent coverage with $G > -8$ dB).
- It provides a low-profile conformal antenna design that has minimum aerodynamic drag and minimum mechanical impact on the structure of the vehicle.
- It is manufactured as a simple, reliable, and easily produced single printed circuit board antenna.
- It is easily wrapped around the missile and bolted or glued in place.

Principle of Operation. The conformal microstrip, antenna is entirely photoetched from the copper on one side of a Teflon fiberglass printed circuit board.

Microstrip, antennas will produce bandwidths (VSWR < 2:1) of 30 MHz to 100 MHz in the L-band and S-band regions with a 1- to 2-dB variation in the roll plane. The microstrip, wraparound antenna consists of two parts: 1) microstrip feed network, and 2) microstrip, radiator.

The microstrip feed network (Fig. 1) is a parallel (corporate) feed network where two-way power splits and equal line lengths result in equal power and equal phase to all of the feed points. The number of power divisions can be 2, 4, 8, 16, etc. The number of feeds and power divisions required is dictated by the microstrip, radiator. The number of feed
points, $N_F$, must exceed the number of wavelengths in the dielectric in the $L$ direction: $N_F > L_D$; $L_D$ is the number of wavelengths in the dielectric = $L(\varepsilon_r)^{\frac{1}{2}}/\lambda_0$; $\varepsilon_r$ is the relative dielectric constant of the board material being used. $\varepsilon_r = 2.45$ is typical, if only the TEM mode is to be excited. This mode will in turn excite only $TM_{OM}$ modes in free space (no roll pattern variation). If $N_F < L_D$, then higher order modes will be excited on the microstrip radiator. These modes will excite $TM_{NM}$ modes in free space ($^1$, p. 276). The excitation of higher order modes on the microstrip radiator will result in breakup of the roll ($\phi$) plane patterns. As an example, the number of feeds required for an S-band 2290 MHz ($\lambda_0 = 12.7$ cm) wraparound for a 25.4-cm missile would be

$$L = \pi D = 79.756 \text{ cm}$$

$$L = L(\varepsilon_r)^{\frac{1}{2}} = \frac{79.756(2.45)^{\frac{1}{2}}}{12.7} = \frac{79.657 \cdot 1.6}{12.7} = 10.05$$

$N_F > 10.05$ and $N_F$ can be 2, 4, 8, 16, 32, 64, etc.

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Thus $N_F$ must be 16.

Two types of feed network are used to accomplish a 2, 4, 8, 16, etc., power split. Most often, tapered lines, Fig. 2(a), are used to transfer a 50-$\Omega$ impedance to 100 $\Omega$, so that it can be combined in parallel with another 100-$\Omega$ line. The same procedure is shown in Fig. 2(b) for a quarter-wave transformer technique. The impedance of the quarter-wave transformer is given by

$$Z_{\text{transformer}} = (Z_{\text{in}} \times Z_{\text{out}})^{1/2} = (100 \times 50)^{1/2} = 70\Omega.$$ 

The number of feed points possible for a very long radiator is limited only by the allowable system losses that can be allocated to the feed network. However, it is desirable to use the minimum $N_F$ satisfying the condition $N_F > L_D$. If 32 feeds were used instead of 16, the preceding example would result in input impedances exceeding 300 $\Omega$ which would be impossible to match efficiently with microstrip feed lines.

![Diagram](image)

**Fig. 2.** (a) Tapered line parallel feed network. (b) Quarter-wave transformer parallel feed network.
**Microstrip Radiator.** Two types of microstrip radiator are generally used: the long microstrip radiator, and the patch radiator. The long microstrip radiator shown in Figs. 2(a) and (b) is shown in top and side view in Figs. 3(a) and (b), respectively. Gap A is an infinitesimal slot (in 0.79-mm microstrip \(a/\lambda = 1/150\) at S-band). The admittance of a slot radiator is given in Harrington (1, p. 183) for small \(ka\) (\(a/\lambda < 0.1\), which is always the case in microstrip antenna practice

\[
G_a \approx \frac{\pi}{\lambda \eta} \left[ 1 - \left( \frac{ka}{24} \right)^2 \right]
\]

\[
B_a \approx \frac{3.135 - 2 \log ka}{\lambda \eta}.
\]

In most microstrip applications, \(ka/24 << 1\) and the conductance simplifies to \(G_a = \pi/\lambda \eta = 1/\lambda(120)\) mho/m or \(R_a = 120\lambda \Omega \cdot m\). The conductance is expressed in per-unit length so that the resistance of the Slot A in Figs. 3(a) and (b) is obtained by dividing \(R_a\) by the length

\[
r_a = \frac{R_a}{L} = \frac{120\lambda}{2\lambda} = 60\Omega.
\]

The dielectric under the microstrip radiator can be treated as a transmission line approximately \(\lambda/2\) long. The problem with the microstrip transmission line is its very low impedance, typically 1 to 10 \(\Omega\). This section of parallel-plate transmission line does transform the Slot A impedance from 60 \(\Omega\) through small impedances near the center and back to 60 \(\Omega\) at Slot B (see Fig. 3(c)). At this point the two impedances combine in parallel to give

\[
\frac{1}{r_{in}} = \frac{1}{r_a} + \frac{1}{r_b} = \frac{1}{60} + \frac{1}{60}
\]

\[
r_{in} = 30\Omega.
\]

In the example shown in Fig. 3(a) this impedance is split between four feed points with each feed theoretically seeing 120 \(\Omega\). In practice, this is the measured impedance. This theory is very accurate in predicting the input impedances for many designs, each with different frequencies, thicknesses, feed point separations, and number of feed points. The previous discussion did not treat the implications of the reactive component of the admittance \(B_a\) because it does not affect the conductance component of admittance \(G_a\).

The effect of the reactance \(B_a\) is to produce a resonance slightly short of a half-wavelength. For example, we can consider the admittance of Slot A to be

\[
Y_A = G_A + B_A.
\]

At a distance of 0.5\(\lambda\) on the parallel-plate transmission line, the admittance has been transformed to \(Y_A = G_A + B_A\), and these admittances combine directly in parallel with \(Y_B\).
Fig. 3. Microstrip radiator.
to produce \( Y_{in} = 2G_A + 2B, \) which is not resonance. At a distance just short (usually 0.49\( \lambda \) to 0.48\( \lambda \)) of a half-wavelength in the parallel-plate transmission line transformer, the transformed admittance of Slot A is
\[
\tilde{Y}_A = G_A - B_A,
\]
and at this length slightly short of a half-wavelength (\( \lambda_0/2(\varepsilon_r)^{1/2} \)), resonance is established with no susceptance
\[
Y_{in} = G_A + G_B = 2G_A
\]
\[
Z_{in} = R_A/2,
\]
and for the example
\[
Z_{in} = R_{in} = 30\Omega \text{ (total resistance)}
\]
\[
R_{in} = 120\ \Omega \text{ (per feed)}.
\]

The bandwidth of a microstrip antenna is dominated by the microstrip parallel-plate transmission line between Slots A and B. Since the transmission line usually has an impedance close to 1 \( \Omega \) and the two slots have impedances close to 100 \( \Omega \), the transformation exists usually for 1-percent bandwidth for VSWR < 2:1. The bandwidth can be easily calculated by adding
\[
Y_{in} = \tilde{Y}_A + Y_B
\]
(where the amount that \( Y_A \) is transformed depends upon frequency), and then evaluating the two frequency points at which the reactances cause the VSWR to equal 2:1.

The major limitation of the microstrip antenna is the bandwidth. To substantially increase the bandwidth of microstrip antennas requires an increase of the thickness of the parallel plate transformer, which increases the characteristic impedance of the transformer. This increase in thickness is undesirable if the antenna is to remain low-profile and conformal. In most applications the advantages of a low-profile antenna outweigh the disadvantage of its narrow bandwidth because present applications require less than 1 percent. Three other methods of increasing the bandwidth are currently being investigated: 1) use of a high (\( \varepsilon_r \)) dielectric constant to decrease the cavity length; 2) increasing the inductance of the microstrip radiator by cutting holes or slots into it. Experiments show increased bandwidth, but at the cost of efficiency; in fact, the same increase could have been attained by using a more lossy substrate; 3) broadbanding by addition of reactive components as discussed in Jasik (2) to reduce VSWR across a limited bandwidth. This technique is very limited, usually to 50 percent of \( \Delta f_0/f_0 \).

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**Microstrip Antenna Pattern Coverage for Omniapplications.** The pattern coverage for the omniantenna shown in Fig. 1 depends on the diameter of the missile. The limiting factor in omnidirectional pattern coverage is a singular hole at the tip and tail of the missile which gets narrower as the diameter of the missile increases. For instance, a 15-in diameter antenna produces a null along the missile axis of radius 1 degree at the -8-dB gain level. The fraction area with gain below -8 dB is given by

\[
F_N = \left( \int_0^{360^\circ} \int_0^{1^\circ} \sin \theta \, d\theta \, d\phi + \int_0^{360^\circ} \int_{179^\circ}^{180^\circ} \sin \theta \, d\theta \, d\phi \right) \\
\int_0^{360^\circ} \int_0^{180^\circ} \sin \theta \, d\theta \, d\phi \approx 0.0002.
\]

Conversely, the fraction of the area with gain above -8 dB is 0.9998, or 99.98 percent coverage with gain greater than -8 dB. The percent coverage increases without limit for larger diameters until a nearly perfect coverage is attained for a single linear polarization.

The percent coverage is only a function of diameter and is independent of antenna thickness. The theoretical and experimental pattern coverages for microstrip antennas on a smooth cylinder are given in Fig. 4 for gain greater than -8 dB.

![Fig. 4. Pattern coverage versus diameter for microstrip wraparound antennas on smooth cylinders.](image-url)
Example of Gain/Coverage for a 22-Inch Diameter Missile. The factors that distract from 100-percent coverage with gain 0 dBi are:

- Roll plane pattern variation - typically ± 1 dB, but sometimes the performance can increase to ± 3 dB.
- Aspect plane (tip to tail) pattern variation - typically ± 4 dB for a large diameter cylindrical missile.
- Microstrip feed losses - typically a function of feedline length, which is proportional to diameter.
- The tip and tail null which are inversely proportional to the diameter of the missile.

The 22-inch diameter conformal microstrip antenna shown in Fig. 5 had the following theoretical deviation from ideal performance:

<table>
<thead>
<tr>
<th>Coverage</th>
<th>Gain</th>
<th>Losses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ideal Performance</td>
<td>100%</td>
<td>0 dB</td>
</tr>
<tr>
<td>Roll Pattern Variation (± 2 dB)</td>
<td>-2 dB</td>
<td></td>
</tr>
<tr>
<td>Aspect Pattern Variation (± 4 dB)</td>
<td>-4 dB</td>
<td></td>
</tr>
<tr>
<td>Microstrip Feedline Loss</td>
<td>-2 dB</td>
<td></td>
</tr>
<tr>
<td>Total Deviations and Losses</td>
<td>-8 dB</td>
<td></td>
</tr>
</tbody>
</table>

Tip and Tail Null Width of 22-Inch Diameter Antenna at -8 dB = ± 1.5 degrees

Percent below -8 dB \[ \frac{2(1.5)^2}{40,000} = \frac{4}{40,000} = 0.01 \text{ percent} \]

Actual Performance (100 - 0.01) = 99.99 percent coverage with gain greater than -8 dB relative to linear isotropic

Conclusion.

- Nearly 100 percent coverage can be attained for near-omnidirectional gain (i.e., ≥ -8 dBi gain.)
- The practical gain/coverage as a function of missile diameter is shown to increase with missile diameter.
• A low-profile, highly reliable printed circuit board method for attaining this omnidirectional coverage is available as a simple printed circuit board antenna.

Fig. 5. 22-inch diameter Aerobee 350 microstrip antenna

Note: This design is covered under U.S. patents and patents pending which are assigned to Ball Brothers Research Corporation, Boulder, Colorado.