MONOPOLE ANTENNAS

This article describes the concepts underlying monopole antennas and their many applications, such as for broadcasting, car radios, and more recently for cellular telephones. In its simplest form, the monopole antenna above an infinite ground plane shown in Fig. 1(a) can be considered as one-half of a corresponding double-length center-fed linear dipole shown for comparison in Fig. 1(b). The current distribution for a vertical monopole antenna of height h is assumed to be a standing wave of the following form, in terms of the feed point current $I(0)$:

$$I(z') = \frac{I(0)}{\sin(kh)} \sin k(h - z') \tag{1}$$

for $0 \leq z' \leq h$. This occurs because the perfect ground plane creates an image of the monopole with a current distribution identical to that for the lower arm of the dipole. Together with this image, the monopole antenna appears to be a center-fed dipole for the upper half-space. There is negligible penetration of fields into a high conductivity ground for a monopole antenna, and all that radiation is directed into the upper half-space creating a power density for any angle θ (see Fig. 1) that is twice as high as that for a dipole radiating the same amount of power. This gives a directivity or gain of the monopole antenna that is twice that for the double-length dipole. Many of the other properties of a monopole antenna above

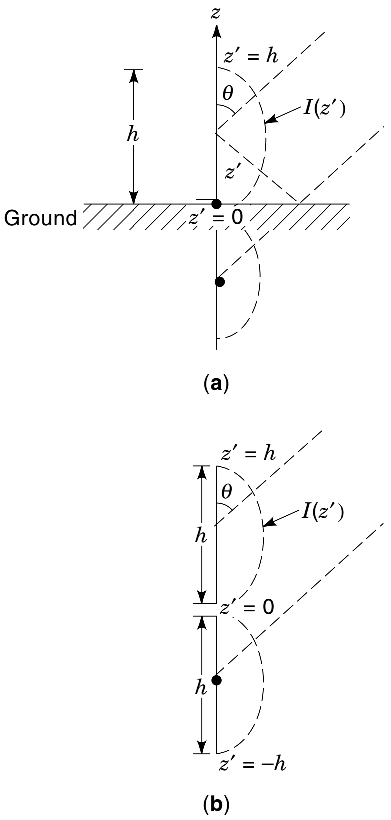

Figure 1. A vertical monopole antenna above ground (a) and the corresponding center-fed dipole (b). Shown also are the current variations $I(z')$ over the lengths of both the monopole and the corresponding dipole.

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Table 1. Relationships Between Monopole and Dipole Antennas

	Monopole Above Ground Length = h	Corresponding Dipole of Twice Length $L = 2h$
Radiation pattern	Same as that for the dipole but only for angle $0 \le \theta \le 90°$	
Feed-point resistance R_a	$R_a \big\vert_{\text{monopole}} = \frac{1}{2}R_{a,d}(2h)$	$R_{a,d}$: function of length $L = 2h$ (see Fig. 2)
Feed-point reactance X_a	$X_a \big\vert_{\text{monopole}} = \frac{1}{2}X_{a,d}(2h)$	$X_{a,d}$: function of length $L = 2h$ (see Fig. 2)
Directivity D_a	$D_a \big\vert_{\text{monopole}} = 2D_{a,d}(2h)$	$D_{a,d}$: function of length $L = 2h$

ground are also related to those for the corresponding double-length dipole in a fairly simple manner.

We give in Table 1 the relationships between a monopole antenna of length h above ground and the corresponding dipole antenna of length $L = 2h$. A graph of the variation of the feed-point resistance and reactance of the monopole antenna above ground is given in Fig. 2 as a function of length h/λ, where λ is the free-space wavelength at the radiation frequency (1). Note that the reactance X_a depends on the conductor radius a, whereas the feed-point resistance R_a is relatively independent of conductor radius a for thin antennas ($a/\lambda \ll 1$). The radiation patterns of a few typical monopole antennas are given in Fig. 3. Because a monopole antenna is symmetric with respect to angle ϕ in the azimuthal plane (xy plane), these patterns are independent of angle ϕ and depend only on angle θ (see Fig. 1). The following relationship is given for power density $S(\theta)$:

$$S(\theta) = \frac{30}{\pi r^2}\frac{W}{R_a}\frac{P^2(\theta)}{\sin^2(kh)} \tag{2}$$

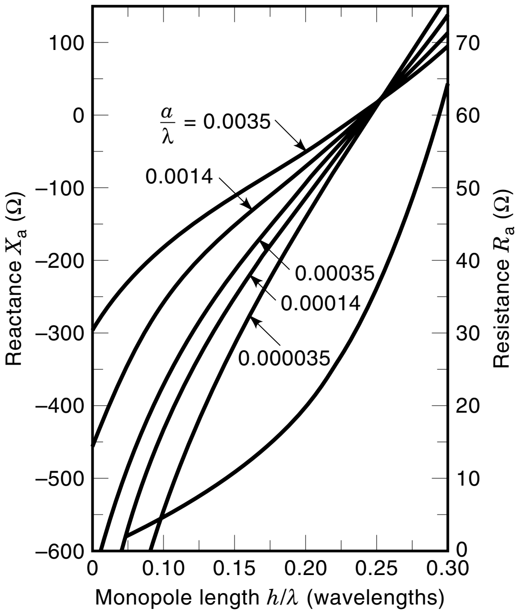


Figure 2. Variation of feed-point resistance R_a and reactance X_a for an end-fed monopole above ground as a function of height h/λ [source: E. C. Jordan and K. G. Balmain (1)].

where W is the radiated power, r is the distance to the field point, $k = 2\pi/\lambda$ is the propagation constant, and $P^2(\theta)$ is the pattern factor given by

$$P^2(\theta) = \left[\frac{\cos(kh\cos\theta) - \cos(kh)}{\sin\theta}\right]^2 \tag{3}$$

Because monopole antennas help reduce the length of the needed dipole by a factor of two and result in directivities that

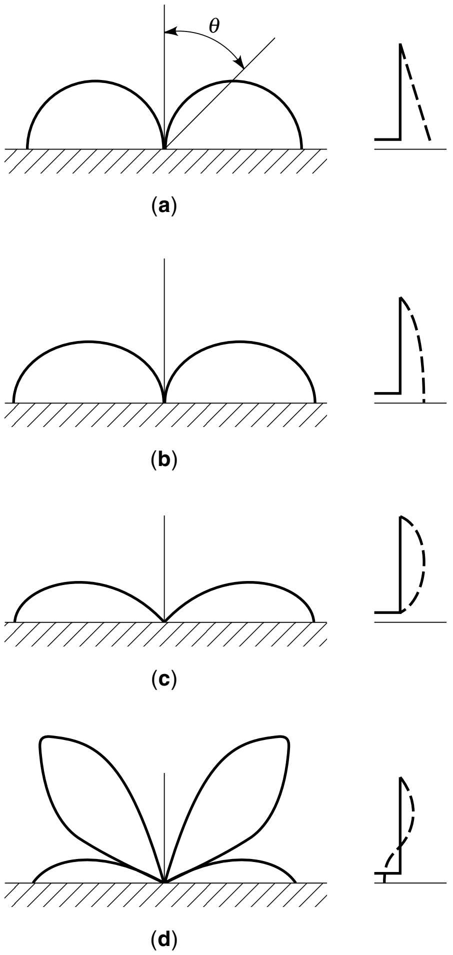


Figure 3. Radiation patterns for some typical end-fed vertical monopoles above infinite ground: (a) $h/\lambda l = 0.05$ (short monopole), (b) $h/\lambda = 0.25$ (quarter-wave monopole), (c) $h/\lambda = 0.5$ (half-wave monopole), and (d) $h/\lambda = 0.75$ ($\frac{3}{4}\lambda$ monopole) [adapted from E. C. Jordan and K. G. Balmain (1)].

are twice as large, vertical monopole antennas above ground are extensively used for amplitude modulated (AM) broadcasting in the frequency range 535–1605 kHz. For this application, the wavelengths are long on the order of 200–600 m, and the monopole antennas are immensely helpful in reducing the required height. It is necessary, of course, to create a good conductivity ground, which for dry or rocky soil conditions is often obtained by burying a conducting screen made of radially spread metal wires with angular separations of 2–3° that extend to a radius at least equal to the height of the antenna, but preferably 20 to 50% larger than this minimal requirement. This screen, called a counterpoise, is often buried a few inches below the surface of the natural ground but may also be left slightly above ground for rocky or otherwise difficult terrain.

EFFECT OF FINITE CONDUCTIVITY GROUND AND CURVATURE OF THE EARTH

Equation (2) gives the power density radiated from a monopole antenna for a ground of infinite conductivity and for flat earth. For finite conductivity ground, the power density at the surface of the earth diminishes more rapidly than the square of the distance r from the antenna (2). Furthermore, the rate at which the power density at the surface of the ground diminishes with distance is steeper at higher frequencies. The rate of reduction of the radiated power density as compared to Eq. (2) is also higher for lower conductivity soil such as sandy or rocky lands, cities, etc., rather than propagation over seawater, marshy, or pastoral lands, etc.

For distances in excess of about 1000 miles, there is a precipitous drop in the surface power density at all frequencies due to the increased effect of the curvature of the earth (2).

Monopole antennas are also the antennas of choice for very low frequency (VLF) (3 to 30 kHz) and low frequency (LF) (30 to 300 kHz) communication systems. For these applications, the height h of the antenna is generally a small fraction of the wavelength. From Fig. 2, for small values of h/λ, the feed-point resistance R_a is very small, on the order of a few ohms, and the ohmic losses resulting from the surface resistance of the antenna can be significant by comparison. This results in reduced antenna radiation efficiency η_r given by the following equation:

$$\eta_r = \frac{R_a}{R_a + R_o} \tag{4}$$

where R_o is the effective ohmic resistance of the antenna.

Top loading of the monopole antenna illustrated in Fig. 4 is often used to improve the feed-point or antenna-equivalent resistance R_a. Because the top set of wires acts as a capacitance to ground rather than the open end of the antenna, the current at the top of the antenna ($z' = h$) no longer needs to go to zero as it does for an open-ended monopole [from Eq. (1), $I = 0$ at $z' = h$]. The upper region of the antenna can, therefore, support a substantial radio frequency (RF) current, resulting in improved radiation efficiency. The antenna-equivalent resistance $R_a = 395\ h^2/\lambda^2$ for open-ended short monopoles may be improved by a factor of 2 to 3 by use of top loading, resulting in higher radiation efficiency.

It should be mentioned that the various concepts discussed here are also usable at higher frequencies. Open-ended monopole antennas are, in fact, used up to ultrahigh frequency (UHF) and microwave frequencies where metallic conducting sheets, either solid or in the form of a screen, may be used in lieu of the ground to create the image antenna. A variety of top-loading "hats" illustrated in Fig. 5 may also be used at these higher frequencies.

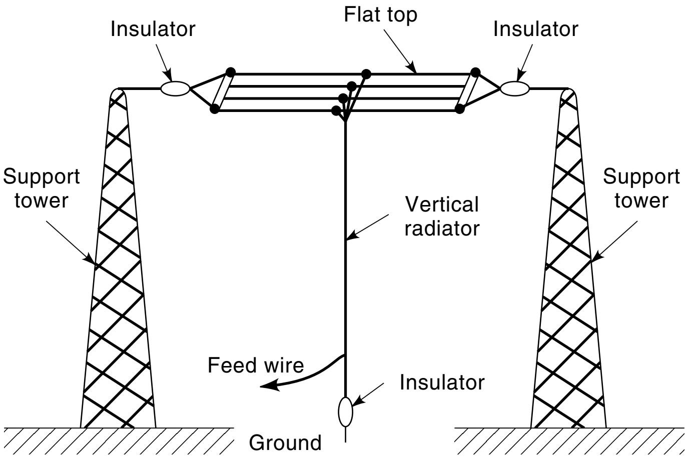


Figure 4. A top-loaded short-monopole antenna typical of VLF/LF communication systems.

Because a monopole antenna above ground or similar reflector acts as a dipole antenna, several of the concepts that are useful for dipole antennas are also used for the monopole antenna. Some of these concepts that are often used in practice are discussed next.

Folded Monopoles. A folded monopole antenna is illustrated in Fig. 6(a) where the feed point is connected to arm 1, and arm 2 is grounded at the bottom end. For dipoles, this

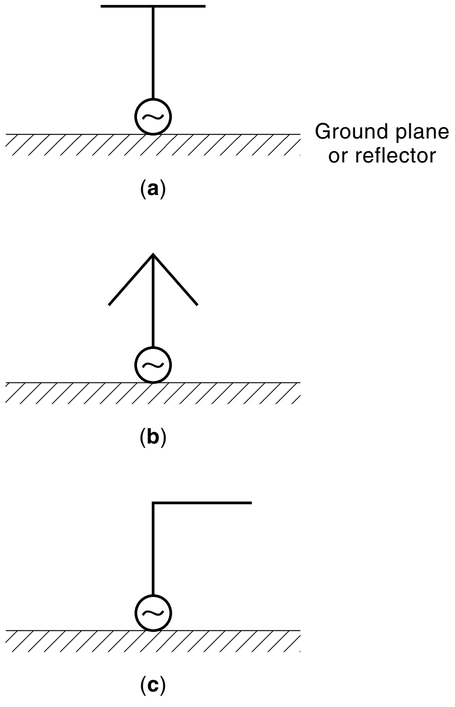


Figure 5. Some typical geometries used for top-loaded monopole antennas: (a) plate, (b) umbrella of wires, and (c) inverted L monopole.

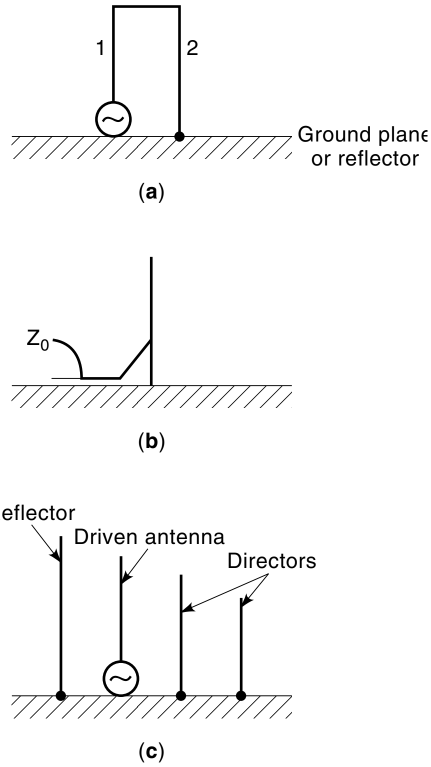


Figure 6. Some special adaptations of monopole antennas: (a) folded monopole antenna, (b) shunt-fed grounded monopole, and (c) four-element Yagi-Uda array of monopoles.

provides a method of increasing the feed-point impedance given in the following relationship (3):

$$Z_{\mathrm{i}} = (1+c)^2(R_{\mathrm{a}} + jX_{\mathrm{a}}) \tag{5}$$

where R_{a} and X_{a} plotted in Fig. 2 are the resistance and reactance of the single arm (not-folded) monopole antenna, and the factor c is given approximately by

$$c \approx \frac{\ln(d/a_1)}{\ln(d/a_2)} \tag{6}$$

In Eq. (6), a_1 and a_2 are radii of wires or rods used for arms 1 and 2, respectively, and d is the center-to-center spacing between the two arms of the antenna, generally much smaller than the height of each of the arms. For a folded monopole antenna where equal radii arms are used, the feed-point impedance is, therefore, four times higher than that for a monopole antenna that is not folded. This can be truly advantageous, because the feed-point resistance may now be comparable to the characteristic impedance Z_0 of the transmission or feeder line, and the reactance of the antenna may easily be compensated by using a lumped element with a reactance that is negative of the reactance $(1 + c)^2 X_{\mathrm{a}}$ at the terminals of the folded monopole antenna.

Shunt-Fed Monopoles. A typical arrangement of a shunt-fed grounded monopole is shown in Fig. 6(b). This corresponds to one-half of a delta match that is often used for dipoles. Because the base of the monopole is grounded for this arrangement, the antenna is fed typically 15 to 20% farther up on the antenna; the exact location is determined by matching the feeder line of characteristic impedance Z_0, which is typically 200 to 600 Ω. Shunt-fed monopole antennas were often used in the early days of AM broadcasting when high-quality insulators were not generally available and it was convenient to ground the tall steel/aluminum masts being used for monopole antennas. With the advent of high compression strength insulators, the masts are now more typically mounted on these insulators, and the monopole towers are fed at the base of these antennas.

Parasitic Monopoles. Much like the Yagi-Uda arrays of dipoles (3), parasitic monopoles of grounded elements are used to help direct the beams away from the reflector monopoles in the direction of director monopoles. An illustration of a four-element Yagi-Uda array of monopoles is shown as Fig. 6(c). Forward gains on the order of 10 to 12 dB with front-to-back ratios of 5 to 8 dB may be obtained using such arrangements. One or more of the parasitic monopoles have also been occasionally used for beam shaping by AM broadcast stations. Two-element antenna arrays consisting of a parasitic reflector monopole and a driven monopole antenna have also been proposed for use in hand-held wireless telephones (see, for example, Ref. 4). If they are carefully designed, such antennas may allow electromagnetic fields to be partially directed away from the human head.

Arrays of Monopole Antennas. Like arrays of dipole elements, monopole arrays of equal or arbitrarily spaced and phased elements may be used for directing principal lobe(s) of radiation in desired directions. Arrays of monopole antennas are used for VLF/LF communications, for AM broadcasting, and, in general, for all frequencies up to microwave frequencies. AM broadcasters for non-clear-channel stations have, for example, used this technique to alter the day and night radiation patterns by varying the phases and the magnitudes of excitations in the various elements.

Conical Monopole. A conical monopole, realized as a cone above a perfect ground plane, is commonly used because of its broadband properties. The cone may be either solid or built from a series of wires above a ground plane. Similar to conventional monopoles, the ground may also be built from a series of radial wires as shown in Fig. 7.

The analysis of this antenna may be done either using rigorous analytical solutions (5,6) or an approximate method (6).

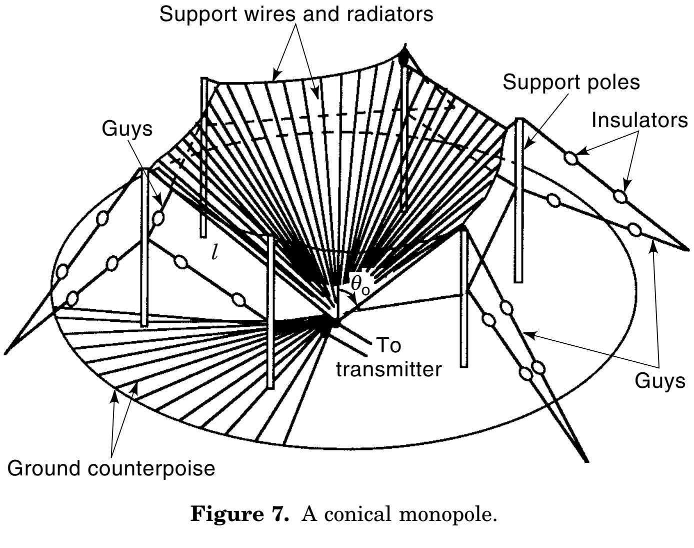


Figure 7. A conical monopole.

The rigorous approach is based on a series expansion of transverse magnetic (TM) modes and is computationally complex. Numerical methods, based on the assumption that the antenna is built from a series of wires, have been commonly used for specific monopole arrangements.

An example of a conical monopole constructed of 60 evenly spaced wires above a ground plane is an antenna that has been in use by the U.S. Navy (7). For use in the HF band 2 to 14 MHz, the dimensions of the monopole are $l = 30.6$ m, $a = 0.001$ m, $\theta_0 = 45°$ (see Fig. 7). The radius of the ground screen is approximately 37.5 m, constructed of 120 radial wires over average soil ($\epsilon_r = 15$ and $\sigma = 0.012$ S/m), and the radius of the screen wire is 0.002 m. This antenna performs over a 7 : 1 frequency band (2 to 14 MHz) with an input resistance varying from 44 to 64 Ω (6). Because of the fairly narrow range of variation of input resistance, matching of this antenna to a 50 Ω line is possible over at least a 7 : 1 frequency range.

Monopole Antennas for Car Radio and Mobile Communications. Monopole antennas used for car radio and mobile communications commonly rely on the body of the vehicle to provide the ground plane. Variations in the shape of the vehicle and placement of the antenna affect the radiation pattern and performance of these antennas (8). For an antenna mounted on the automobile, it would no longer radiate isotropically in the horizontal plane but may radiate with a slightly higher gain in directions where the automobile body extends farther, thus simulating a larger width ground plane in such directions.

For communication antennas in general, it is often desirable to have the shortest possible antenna. Although a quarter-wave monopole is easier to match, a shorter antenna has an associated capacitive reactance. This can, however, be canceled out by adding a loading coil (inductance) to the base of the antenna.

Another arrangement often used is to place an inductive coil at the center of the antenna (9). Because of the altered current distribution along the length of the antenna (similar to a top-loaded monopole), this increases the feed-point impedance of the end-fed antenna to roughly twice the value, making it easier to match to such an antenna. The value of the inductance needed at the center is approximately double that which would be needed at the ends. This consequently increases the coil resistance.

In order to reduce the inductance of the loading coil required to match the antenna at either the center or top, a capacitive load (a small metal ball) may be added to the tip of the antenna.

In all this discussion of monopoles, we have assumed that the wave propagation from the antenna is over a perfectly conducting or infinite conductivity ground plane. This is hardly ever the case. For ground wave propagation ($\theta = 90°$) over a finite conductivity ground plane, the fields drop off more rapidly than $1/r^2$ given by Eq. (2). This effect is more pronounced for higher frequencies and is generally small only at very low frequencies less than a few tens of kilohertz. Also, as expected, the departure from the idealized Eq. (2) is more pronounced the lower the conductivity of the soil. Rocky and jagged hilly ground, for example, would result in a more rapid drop off of the power density S along the ground plane than propagation over sea water.

Yet another factor that has an impact on surface wave propagation is the curvature of the earth. For distances larger than about 100 miles (62 km), the power density at the ground level diminishes very rapidly particularly for frequencies in excess of about 1 MHz.

EFFECT OF FINITE-SIZE GROUND PLANE ON IMPEDANCE AND RADIATION PATTERN

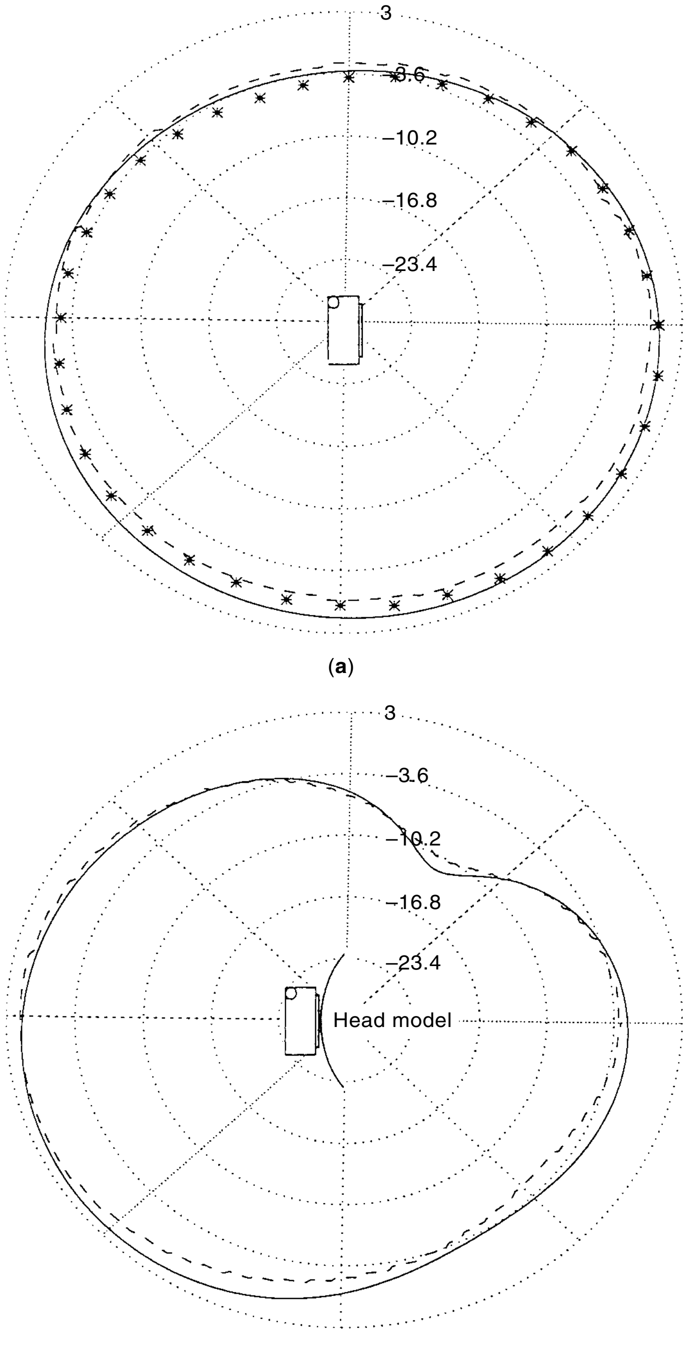
Whereas a ground plane of diameter 10 wavelength or larger has a fairly small effect on the feedpoint impedance of a monopole antenna as compared to the values given in Fig. 2, finite-size ground plane has a fairly significant effect both on the feedpoint impedance and radiation pattern (10).

An example of the effect on the radiation pattern is illustrated in Fig. 8(a) for the radiation pattern of a monopole antenna of a cellular telephone in free space. Since this monopole antenna is mounted on a plastic-covered metal box of finite dimensions, only a finite-size ground plane of box shape is used for this radiator. One effect is to alter the radiation pattern [see Fig. 8(a)] from a perfect circle in the azimuthal plane to one that is crooked with a lower gain in the sector where the extent of the ground plane is minimal, i.e., on the side where the antenna shown by a circle in the insert of Fig. 8(a) is mounted. Also the gain for this quarter wave monopole antenna of about 1 dBi is considerably lower than 5.16 dBi (a factor of 3.28) for the same antenna mounted on a flat, infinite ground plane. The actual reason for this considerably reduced gain is that part of the energy is also radiated in the lower half space for this vertical monopole antenna above the box while none would be radiated for this antenna mounted above an infinite ground plane.

SOME RECENT APPLICATIONS OF MONOPOLE ANTENNAS FOR PERSONAL WIRELESS DEVICES

A monopole antenna with or without a helix is the antenna of choice for today's personal wireless devices, including cellular telephones (11). Antennas of different lengths, typically from a quarter wavelength to a half wavelength at the irradiation frequency, are generally used for hand-held devices that operate at 800 to 900 MHz for cellular telephones and 1800 to 1900 MHz for PCS (personal communication system) devices. Often, these monopole antennas are in the form of a whip antenna, which can be pulled out to its full length during a telephone conversation. At times, a small length helical antenna is permanently mounted on the top of the handset through which the monopole antenna can be retracted and to which this monopole connects when it is completely pulled out, giving a monopole loaded with a helix at the bottom as the radiating antenna during telephone usage. Of necessity, these antennas use a finite-size reflecting plane, which is generally the metallic shielding box used either for the top RF section, or at times for the entire handset. Several authors have calculated and/or measured the radiation patterns of such monopole antennas mounted on a handset held in air or against the human head (12–14).

Given in Fig. 8(a, b) are the computed and measured radiation patterns in the azimuthal plane for a typical commercial telephone at the center-band frequency of 835 MHz in free space and in the presence of the human head, respectively



(a)

(b)

Figure 8. The computed and measured radiation patterns (in dBi) in the azimuthal plane for a commercial cellular telephone at 835 MHz (a) in free space and (b) held against the human head.

(14). This telephone uses a short helical antenna of diameter 4.2 mm, pitch 1.4 mm, and total length 16 mm. Dimensions of the handset are similar to those for many telephones and are approximately 2.4 × 5.2 × 14.7 cm along the three axes, respectively. Fairly similar radiation patterns are also obtained for antennas using either monopoles or monopole-helix combinations. In the presence of the human head, gains on the order of 1.0 to 3.0 dBi are obtained away from the human head, with gains in directions through the head that are substantially lower due to absorption in the tissues of the head. Radiation efficiencies for monopole antennas used for personal wireless devices are typically on the order of 30 to 50%, with 30 to 50% of the power being absorbed in the head and another 5 to 15% of the power being absorbed in the hand (13,15).

Medical Applications

End-fed monopole antennas excited by a coaxial line have been used for a number of medical applications such as hyperthermia for cancer therapy (16) and cardiac ablation catheters (17). For these applications, both straight wire and small-diameter helix monopoles have been used.

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O. P. Gandhi
G. Lazzi
C. M. Furse
University of Utah