Radiation Characteristics of a Quarter-Wave Monopole Antenna above Virtual Ground

Niazul Islam Khan, Anwarul Azim, and Shadli Islam

***Abstract*—In recent years, monopole antennas have become one of the vital components of cellular mobile communications and internet networks across the globe. Their relatively easy and low fabrication cost and faster installation makes them an obvious choice for developing countries. The most common form is the quarter-wave monopole, in which the antenna is approximately 1/4 of a wavelength of the radio waves. In this paper, we present the analytical treatment of a quarter-wave monopole antenna above virtual ground. Virtual ground is realized by using bent radials around the vertical monopole element. Radiation resistance and gain of the quarter-wave monopole are mathematically derived and three-dimensional radiation patterns are simulated using sinusoidal current distribution. It is observed that for the case of the quarter-wave monopole, we achieve twice the gain of a dipole antenna of half-wave-length long. As the radiated power is limited to upper hemisphere of the ground plane, the total radiated power of the quarter-wave monopole is half of that of a dipole. Hence, the value of radiation resistance of the monopole is half of that of a dipole.**

***Index Terms*—Ground plane, radiation pattern, directivity, half-wave dipole, monopole antenna.**

I. Introduction

Monopole antenna above virtual ground, as the name itself indicates, is an antenna with a quarter wavelength long vertical radiator on a virtual ground plane. In telecommunication, a ground plane is a flat or nearly flat horizontal conducting surface that serves as part of an antenna, to reflect the radio waves from the other antenna elements. The plane does not necessarily have to be connected to the Earth [1]. Rather it can be realized virtually. The ground plane must have good conductivity because any resistance in the ground plane comes in series with the antenna. This series resistance causes power dissipation from the transmitter. In a quarter-wave monopole antenna above virtual ground, a near-perfect conducting ground plane is realized by several 1/4 wavelength long radials as seen in Fig. 1. The feedline from the transmitter or receiver is connected between the bottom end of the radiator element and the virtually formed ground plane. So when current flows, there will also be radiation from the radials. As the radials are symmetrically arranged about the vertical element, the current in each radial is flowing in an opposite direction (away from the center) to the current on the radial directly opposite to it and the total radiation in the horizontal plane will cancel. Thus a virtual conducting ground plane is formed. A typical feedline for the monopole antenna is a coaxial cable with its inner conductor connected through a hole to the ground plane to the vertical monopole element and its outer conductor connected by means of a flange to the ground plane [2]. Typically the inner conductor's diameter is equal to the monopole element's diameter and the outer conductor's diameter is equal to the ground plane hole diameter [2]. Impedance matching between the 50 Ω coaxial cable feedline and the antenna feedpoint is achieved by bending the radials 45^0 downwards with respect to the horizontal plane [3]. A monopole antenna above virtual ground with bent radius can be seen in Fig. 2 (a) with its current distribution shown in Fig. 2(b). Ground losses are avoided by elevating the antenna as higher as possible at least at quarter wavelength height from the earth's surface [2]. The other possibility is to add as many radials as possible in order to minimize the current on each radial. The current on each radial will be equal to the total current on the vertical element divided by the number of radials. So the guideline for this antenna is "the higher the better" about the elevation height and "the more the better" about the number of the radials [3]. Invented by the famous radio pioneer G. Marconi in 1895, it is sometimes called a Marconi antenna [4]. As being realized on a ground plane, it is also known as a ground plane antenna.

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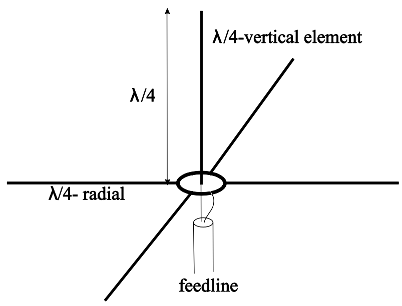

Fig. 1. Basic configuration of a monopole antenna above virtual ground. Symmetrically arranged four horizontal radials can be seen.

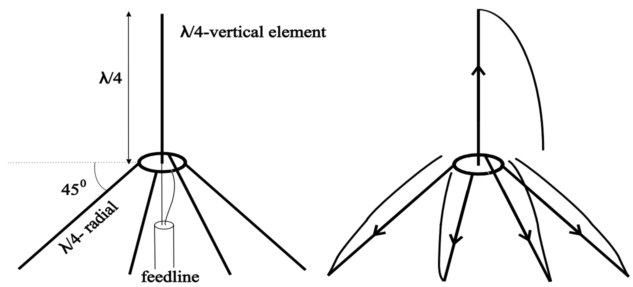

Fig. 2. (a) Radials of a monopole antenna above virtual ground are bent 45^0 downwards with respect to the horizontal plane. (b) Curent distribution in a monopole antenna above virtual ground.

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Monopole antennas, having omni-directional radiation pattern characteristics, are very suitable for indoor applications, such as airplane, shopping center, hospital, etc. Particularly, their directivity on or near the radio horizon makes them suitable for communication systems where maximum operational range often depends on the directivity on the radio horizon [5]. Although designs for monopole antenna with coaxial cable involving double-folded [6] and triangular constructions [7] have been proposed in the past, those antennas only dealt with around 3/20 wavelength on similar impedance characteristics. The monopole antenna presented operates on 1/4 wavelength above virtual ground with its low angle radiation and minimized ground losses which makes them suitable for MIMO wireless communication systems [8]. Considering different operating frequencies especially in VHF and UHF bands, quarter-wave monopole offers several wide ranging advantages over dipole antennas. They are favored at frequencies above approximately 10 MHz where the dimensions are manageable [9]. They are a good choice for VHF (very high frequency) and UHF (ultra high frequency) bands making them popular for FM broadcasting [10]. At VHF band ranging from 30 MHz to 300 MHz, a quarter-wave monopole can be 2.5 m (approximately 8 ft) long. At UHF band ranging from 300 MHz to 3 GHz, a quarter-wave whip is approx. 15 cm (6 in) long. For both cases, dipole antenna requires twice the length causing structural and placement limitations for various system designs.

Vertical monopole antennas above ground are also extensively used for amplitude modulated (AM) broadcasting in the frequency range 535-1605 kHz. For this application, monopole antennas are immensely helpful in reducing the required height [11]. They 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. But for these applications, lower h/λ ratio deteriorates the radiation efficiency which can be improved by top shading [11]. At around 800 MHz band, performance of quarter-wave monopole can be enhanced by stacking two monopoles around a phasing coil is used [12]. Open-ended monopole antennas are also used up to UHF and microwave frequencies where metallic conducting sheets, either solid or in the form of a screen, may be used instead of the ground to create the image antenna [11].

When ground is not available (such as in a vehicle) other metallic surfaces can serve as a ground plane (typically the vehicle's roof). Alternatively, radial wires placed at the base of the antenna can simulate a ground plane. For VHF bands, the radiating and ground plane elements can be constructed from rigid rods or tubes [13].

II. Analytical Deduction of the Radiation Characteristics of the Monopole

We derive the properties of the monopole antenna above ground assuming a sinusoidal current distribution throughout the length of the antenna. As stated before, the radiation from the four radials cancels each other forming a virtual conducting ground plane. So the only radiating element is the 1/4 wavelength long vertical element. Therefore, the monopole antenna on the ground plane can be modeled as a half-wave dipole using the method of images [14]. In this case, the ground plane prevents monopole radiation into the hemisphere below the ground plane, but allows a radiation pattern identical to that of a dipole in the upper hemisphere [2]. Fig. 3 shows the quarter-wave monopole on the ground and its quarter-wave image forming a half-wave dipole. The bold dotted curved line represents the current distribution throughout the length of the antenna. We can write the expression for current distribution for the vertical elements as

$$\tilde{I} = I_0 \cos(\beta z) \tag{1}$$

where I_0 is the maximum value of the current, and

$$\beta = \text{phase constant} = \frac{2\pi}{\lambda}$$

At a point $P(r, \theta,\varphi)$ the magnetic vector potential is given by

$$\vec{A} = \vec{A}_Z = \frac{\mu}{4\pi} \int_{z=-\lambda/4}^{\lambda/4} \frac{\tilde{I}}{R} e^{-j\beta R} dz \tag{2}$$

Substituting the value of $\tilde{I}$ in equation (2), the vector magnetic potential becomes,

$$\vec{A}_Z = \frac{\mu I_0}{4\pi} \int_{z=-\lambda/4}^{\lambda/4} \frac{\cos\beta z}{R} e^{-j\beta R} dz \tag{3}$$

When the point $P(r,\theta,\varphi)$ is located far away from the antenna, we can write the equation $R \approx r - z\cos\theta$ to account for the phase shift and approximate it as $R \approx r$ for the distance in the denominator.

Moreover, we can use the following trigonometric formula

$$\cos\beta z = \frac{e^{j\beta z} + e^{-j\beta z}}{2} \tag{4}$$

to rewrite (3) as

$$\vec{A}_Z = \frac{\mu I_0}{8\pi r} e^{-j\beta r} \int_{z=-\lambda/4}^{\lambda/4} (e^{j\beta z} + e^{-j\beta z}) e^{j\beta z\cos\theta} dz \tag{5}$$

After carrying out the whole calculation and required calculations, we reach the following expression for the z-component of magnetic vector potential

$$\vec{A}_Z = \frac{\mu I_0 e^{-j\beta r} \cos(\pi/2 \cos\theta)}{2\pi\beta r \sin^2\theta} \tag{6}$$

Now the magnetic field intensity in the radiation zone can be obtained using the following formula,

$$\vec{H} = \frac{j\beta}{\mu} \sin\theta \vec{A}_Z \hat{a}_\varphi \tag{7}$$

where $\hat{a}_\varphi$ is the unit vector along φ direction. Substituting the expression of vector magnetic potential from (6) into (7), we obtain,

$$\vec{H} = \frac{jI_0 e^{-j\beta r}\cos(\pi/2 \cos\theta)}{2\pi r\sin\theta}\hat{a}_\varphi \tag{8}$$

The electric field intensity in the Fraunhofer zone can be obtained as,

$$\vec{E} = \eta\vec{H}\hat{a}_\theta \tag{9}$$

Here, $\hat{a}_\theta$ is the unit vector along θ direction and η is the intrinsic impedance of the medium (air, in this case). Substituting the expression for the magnetic field from (8) into (9), we obtain the following as the expression of electric field,

$$\vec{E} = \frac{j\eta I_0 e^{-j\beta r}\cos(\pi/2 \cos\theta)}{2\pi r\sin\theta}\hat{a}_\varphi \tag{10}$$

Using the expressions of magnetic and electric field intensity from (9) and (11), we obtain the expression for the average radiated power per unit area of the antenna as,

$$\left\langle \vec{S} \right\rangle = \frac{1}{2}\mathrm{Re}\left|\vec{E}\times\vec{H}^*\right| = \frac{1}{2}\frac{\left|\vec{E}\right|^2}{\eta} \tag{11}$$

After performing the necessary calculation, finally we reach to the following expression as,

$$\left\langle \vec{S} \right\rangle = \frac{\eta I_0^2\cos^2(\frac{\pi}{2}\cos\theta)}{8\pi^2 r^2\sin^2\theta} = \frac{\eta I_0^2}{8\pi^2 r^2}\left(\frac{\cos(\frac{\pi}{2}\cos\theta)}{\sin\theta}\right)^2 \tag{12}$$

For a monopole antenna above virtual ground, the above expression is valid for the range $0 \le \theta \le \frac{\pi}{2}$.

Using the following approximation [3]

$$\left(\frac{\cos(\frac{\pi}{2}\cos\theta)}{\sin\theta}\right)^2 \approx \sin^3\theta \tag{13}$$

which is valid for the range $0 \le \theta \le \pi$, we can write (12) as

$$\left\langle \vec{S} \right\rangle = \frac{\eta I_0^2}{8\pi^2 r^2}\sin^3\theta \tag{14}$$

The total power radiated by the monopole is obtained by carrying out the following integration [7],

$$P_{rad} = \oint_s \left\langle \vec{S} \right\rangle . d\vec{S}$$
$$= \int_\theta\int_\phi \left\langle \vec{S} \right\rangle r^2 \sin\theta d\theta d\phi$$
$$= r^2\int_{\theta=0}^{\pi/2}\left\langle \vec{S} \right\rangle \sin\theta d\theta\int_{\phi=0}^{2\pi} d\phi$$
$$= \frac{\eta I_0^2}{8\pi^2}\int_{\theta=0}^{\pi/2}\sin^4\theta d\theta\int_{\phi=0}^{2\pi} d\phi$$

After integration, we ultimately reach to the final form,

$$P_{rad} = \frac{3\eta I_0^2}{64} \tag{15}$$

The radiation resistance is defined by the equation,

$$P_{rad} = \frac{1}{2}I_0^2 R_{rad} \tag{16}$$

Using (15) and (16), we obtain the expression for radiation resistance for the quarter-wave monopole as,

$$R_{rad} = \frac{3\eta}{32} \tag{17}$$

In free space, $\eta = 120\pi\ \Omega$. Inserting this value in (17), we get the value for radiation resistance for the monopole which is

$$R_{rad} = 35.343\Omega \tag{18}$$

which is one-half of a half-wave dipole antenna in free space.

Now we calculate the directive gain of the antenna using the following formula,

$$G = \frac{4\pi r^2\left\langle \vec{S} \right\rangle}{P_{rad}} \tag{19}$$

Substituting the values for $\left\langle \vec{S} \right\rangle$ and P_{rad} from (14) and (15), we decisively obtain the following equation of directive gain,

$$G = \frac{32}{3\pi}\sin^3\theta \tag{20}$$

Finally, the directivity of the monopole is found to be,

$$D = \frac{32}{3\pi} = 3.39 \approx 5.31dB \tag{21}$$

Therefore, we deduce the antenna gain of a quarter-wave monopole antenna above virtual ground as 5.31 dB which is little bit more than twice the gain of a center-fed half-wave dipole antenna that is 2.16 dB. Fig. 4 shows the radiation pattern of a quarter-wave monopole where the radiation is only limited to the upper hemisphere of the ground plane. Fig. 5 shows the corresponding radiation pattern of a half-wavelength dipole antenna where the radiation occurs in both the upper and lower hemisphere.

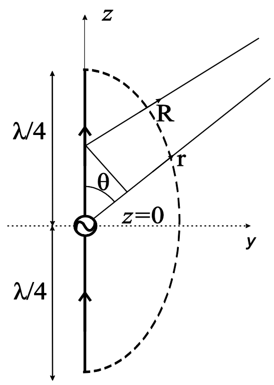

Fig. 3. Analysis of monopole antenna above virtual ground with sinusoidal current distribution/

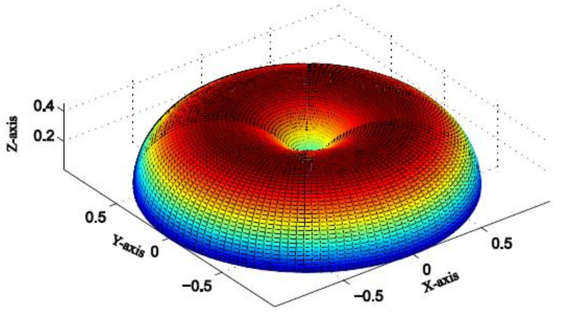

Fig. 4. Radiation pattern of a quarter-wave monopole antenna above virtual ground.

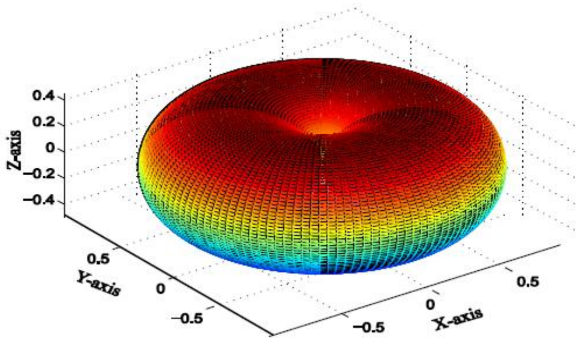

Fig. 5. Radiation pattern of a half-wave dipole antenna.

III. Conclusion

In this paper, we derived the analytical model of a quarter-wave monopole antenna above virtual ground. Directivity of 5.31 dB is calculated which is 3 dB better than that of a dipole antenna of half-wavelength long. The radiation pattern of the monopole is limited to the upper hemisphere of the ground plane. It is seen from the radiation pattern that maximum directivity is at the radio horizon which makes them a good choice for communication systems.

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