On Using the Classical Monopole for Comparison with Other Electrically Small Self-Resonant Monopole Antennas of Equal Height

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Introduction

Recently, there has been much interest in electrically small monopole antennas, including those based on fractal shapes [1], [2], [3] and also non-fractal shapes generated by genetic algorithms [4]. It has been suggested that their shapes best utilise the antenna volume, resulting in lower antenna Q-factors that approach the Chu limit [5], [6]. Recently, it has been shown that fractal and non-fractal antennas have similar performance when self-resonant [7] and also tend to that of the classical monopole when electrically very short [8]. These self-resonant (or close to self-resonant) antennas have been compared with the classical monopole of equal height. However, when electrically short, the classical monopole is non-resonant with a feed-point impedance consisting of a small radiation resistance and a large capacitive reactance. Consequently, the antenna Q-factor and VSWR are inherently high. The new antenna designs are positive additions to the range of electrically small antennas (which includes normal mode helical and meander line monopoles), but comparison with the non-resonant monopole is unfair and incorrect.

This paper shows that the Q-factor and VSWR of a monopole are significantly lowered when made resonant by reactive loading (as is used in practice). Comparison with a self-resonant Koch fractal monopole of equal height gives similar values of VSWR and Q-factor. Thus, the various electrically small monopoles (self-resonant and reactively loaded) offer comparable performance when ideal and lossless. However, in selecting the optimum design, conductor losses and mechanical construction at the frequency of interest must be considered. In essence, a trade-off is necessary to obtain an efficient, electrically small antenna suitable for the application in hand.

Antenna Q-Factor

For an antenna feed-point impedance of $Z_L=R+jX$, the antenna Q-factor can be defined as [5]

$$Q = \frac{w}{2R} \cdot \left(\frac{dX}{dw} + \left| \frac{X}{w} \right| \right) \tag{1}$$

For an electrically small antenna, a fundamental lower limit on the attainable Q-factor (known as the Chu limit) is defined by [6]

$$Q_{Chu} = \frac{1}{(kr)^3} + \frac{1}{kr} \tag{2}$$

where k is the wave number ($k=2\pi/\lambda$) and r is the sphere radius, inside which the antenna can fit. For a monopole, the sphere radius is equal to its height.

Feed-point Impedance of an Electrically Short Monopole

The electrically short monopole has a feed-point impedance consisting of a low radiation resistance given by [9]

$$R_{rad} \approx 40\pi^2 \left(\frac{h}{\lambda} \right)^2 \tag{3}$$

and also a capacitive reactance given by [10]

$$X_{ant} \approx -60 \cdot \frac{\left[\ln\left(\frac{h}{2a} \right) - 1 \right]}{\tan\left(2\pi \frac{h}{\lambda} \right)} \tag{4}$$

where h is the antenna physical height and a is the monopole conductor radius.

Considering a typical system characteristic impedance of 50 Ω, a significant mismatch is present, resulting in a high VSWR. The non-resonant monopole also has a high Q-factor. Thus, by resonating the monopole, both the VSWR and Q-factor can be lowered, as occurs in practice.

Reactive Loading of Electrically Short Monopoles

A commercial NEC-2 simulation package (EZNEC 3.0) was used to determine the monopole feed-point impedance and the corresponding Q and VSWR were calculated for normalised heights (h_λ) in the range 0.01 to 0.1. A 50 Ω characteristic impedance was used for the purposes of this paper. Reactive loading (in the form of inductive base and centre loading and capacitive top loading) was then applied to resonate the classical monopole. In this paper, the capacitive top loading consists of four radials at right angles, although a solid circular disc would be preferred, as will be discussed with regard to the antenna Q-factor. A frequency of 100 MHz (λ=3 m) was arbitrarily chosen and the antenna conductor diameter ($d=2a$) was 1 mm. The conductor and reactive elements are considered ideal and lossless. Impedance matching to the system characteristic impedance has not been considered here, but in practice is essential for effective power transfer.

Figure 1 shows the radiation resistance for the reactively loaded monopoles. Note that the non-resonant monopole has the same radiation resistance as the base loaded monopole. As the position of inductive loading is raised, the radiation resistance increases, but a larger inductance is now necessary to achieve resonance. Maximum radiation resistance is obtained for capacitive top loading. Figure 2 shows that the VSWR of the reactively loaded monopole is a few orders of magnitude lower than that of the non-resonant monopole.

Figure 3 shows the antenna Q-factor and further illustrates the benefit of using reactive loading to resonate the classical monopole. It appears that the capacitively loaded monopole Q-factor is lower than the Chu limit for very small monopole heights but in this case is due to the radial lengths being significantly larger than the physical height. This particular capacitively loaded monopole occupies a much larger sphere and therefore, it is not valid to compare with the Chu limit based on the physical height alone. Greater capacitance could be obtained using a smaller solid disc rather than four long radials. The Q-factor would then be larger than the Chu limit.

Comparison with a Self-Resonant Koch Monopole

Three iterations of a Koch monopole (conductor diameter of 1 mm) have been simulated that are self-resonant at 100 MHz and compared with a reactively loaded monopole of equal height. Note that the Koch iteration 0 equates to the classical monopole with an electrical length of $\lambda/4$.

Table 1 details the physical parameters of each Koch iteration. For greater Koch iterations, the normalised height (h_λ) decreases but the normalised conductor length (l_λ) necessary for resonance increases beyond a quarter wavelength. Similarly, normal mode helical monopoles also require increased conductor lengths, which becomes relevant when skin effect losses are taken into account [11]. The radiation resistances of the Koch monopoles are between those of the base and centre loaded monopoles, as seen in table 2. Whilst the VSWR of the Koch monopole is significantly better than the non-resonant monopole, table 3 shows that it lies between those of the base and centre loaded monopoles. Table 4 shows that the antenna Q-factor for the Koch monopole is comparable to the centre loaded monopole. The top loaded monopole gave better values of radiation resistance, VSWR and Q-factor. In a comparison of fractal shapes, this was also observed for a fractal tree monopole, which is itself a form of top loaded monopole [3].

Resistive Losses of Real Antennas

A further measure of antenna performance is the radiation efficiency [10].

$$E = \frac{R_{rad}}{R_{rad} + R_{loss}} \qquad (5)$$

For electrically small antennas, where the radiation resistance is low, any conductor losses can dramatically reduce the overall efficiency. Also, the feed-point resistance is raised (R_{rad}+R_{loss}), which gives an apparent improvement in the VSWR and Q-factor.

For the different electrically small antennas, the conductor losses may vary depending on the frequency of operation (skin effect) and the conductor length. Assuming a perfect lossless ground-plane, finite inductor Q-factors will predominantly limit the efficiency of base and centre loaded monopoles, whereas for the various self-resonant antenna designs (including normal mode helical, meander line and fractal monopoles) the total resistance distributed along the considerable (relative to the physical height) conductor length may become appreciable. For real monopole systems, imperfect ground-planes and close-by objects introduce further losses [9].

Conclusions

This paper has shown that the VSWR and antenna Q-factor of the electrically small, classical monopole are significantly improved when it is made resonant by reactive loading. This fact is important when direct comparisons are to be made with other electrically small, self-resonant (or close to self-resonant) antennas of the same height. It was shown that the self-resonant Koch monopole has a VSWR and Q-factor only comparable to that of the reactively loaded monopole.

The recent works on fractal and non-fractal antennas have contributed new design techniques to the field of electrically small antennas. Fractal shapes, in particular, are deterministic and thus empirical formulae may be found that relate the fractal and physical parameters to the frequency of operation, as is known for normal mode helical antennas [11].

A greater choice of electrically small antennas is now available and it appears that they offer comparable performance when ideal and lossless. In deciding on the optimum design, conductor losses (and other losses) must be considered since these are key to the overall radiation efficiency. Although not discussed in this paper, the physical structure of the antenna is also important. In essence, an engineering trade-off is required in designing an efficient, electrically small antenna and this will be dependent on the frequency of operation and the application in hand.

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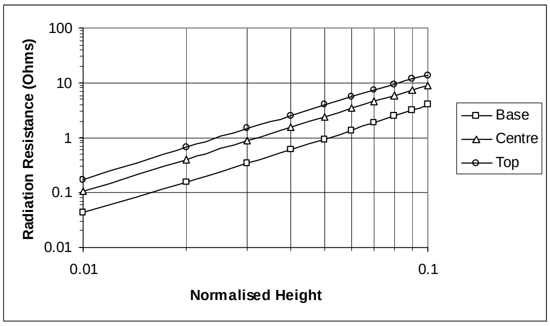

Fig. 1 Radiation resistance of classical monopole and reactively loaded monopoles
(f=100 MHz, d=1 mm).

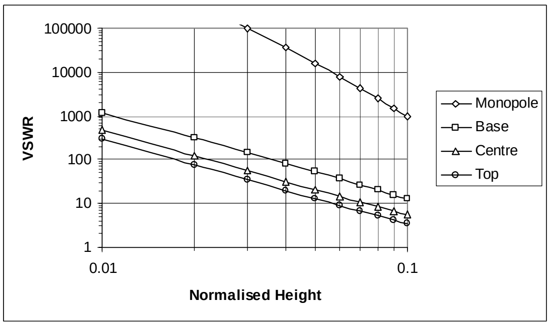

Fig. 2 VSWR of classical monopole and reactively loaded monopoles
(f=100 MHz, d=1 mm).

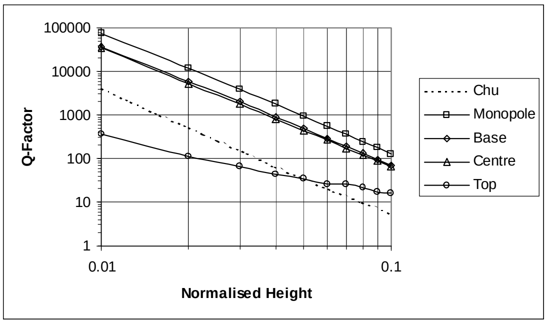

Fig. 3 Q-factor of classical monopole and reactively loaded monopoles
(f=100 MHz, d=1 mm).
Refer to text for apparent improvement in Q-factor for the top loaded monopole compared to Chu limit.

Koch Iteration	Physical Height h (mm)	Conductor Length L (mm)	Normalised Height h_λ	Normalised Length L_λ
0	722	722	0.241	0.241
1	590	787	0.197	0.262
2	505	898	0.168	0.299
3	455	1079	0.152	0.360

Table 1 Physical parameters of self-resonant Koch monopole
(f=100 MHz, d=1 mm).

Koch Iteration	Koch Radiation Resistance	Monopole Radiation Resistance with Loading			
		None	Base	Centre	Top
1	23.4	20.1	20.1	27.7	33.5
2	17.5	13.5	13.5	22.0	29.3
3	14.5	10.5	10.5	18.6	26.1

Table 2 Radiation resistances for self-resonant Koch monopole and reactively loaded monopoles
(f=100 MHz, d=1 mm).

Koch Iteration	Koch VSWR	Monopole VSWR with Loading			
		None	Base	Centre	Top
1	2.14	15.4	2.48	1.80	1.49
2	2.86	57.0	3.71	2.27	1.71
3	3.45	113.8	4.78	2.69	1.92

Table 3 VSWR for self-resonant Koch monopole and reactively loaded monopoles
(f=100 MHz, d=1 mm).

Koch Iteration	Koch Q-Factor	Monopole Q-Factor with Loading			
		None	Base	Centre	Top
1	13	16	13	13	9
2	17	26	19	18	10
3	22	36	25	23	11

Table 4 Antenna Q-factor for self-resonant Koch monopole and reactively loaded monopoles
(f=100 MHz, d=1 mm).