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Design and Optimisation of Folded Spherical Helix Antennas: Performance and Bandwidth Analysis

Dr Abhishek Kumar[1*], Arpana Kumari[2]

[1*]Assistant Professor EEE Department RTCIT Ranchi, India, Email: abhirtc2013@gmail.com
[2]Former Assistant Professor, IMS Ghaziabad, India, Email: arpanakumari22@gmail.com

Abstract
This paper examines the performance of different fundamental small antenna designs in terms of how they scale with overall length and size (measured by the electrical size parameter, ka). The goal is to identify which design approach, if any, provides the best performance in achieving a good impedance match, favourable radiation pattern, high radiation efficiency, a broad half-power bandwidth, and a 2:1 VSWR bandwidth. The antenna designs analysed include the spherical folded helix and, cylindrical folded helix. The paper discusses the methods used for impedance matching and bandwidth optimisation, presenting both simulation and experimental results.

Key Word: Voltage standing wave ratio (VSWR), antenna, radiation, efficiency, bandwidth.

Introduction

Some parts of this paper were presented at the Antenna Application Symposium. This version expands with additional background on the design approaches for small antennas, details on optimising their operating bandwidths, and includes measured data.

The optimisation of small antenna performance has been a significant focus recently. Main design objectives are to obtain proper impedance matching (ensuring low VSWR), maximise radiation efficiency, and achieve either a low-quality factor (Q) or a broad operating bandwidth. For ideal performance, the VSWR should approach 1:1, and radiation efficiency should approach 100% across the intended bandwidth. Small antennas are generally optimised to achieve the maximum possible bandwidth, often beyond the channel's bandwidth to avoid detuning. Achieving this often requires comparing the antenna's Q and bandwidth against fundamental limits. Any electrically small antenna can be impedance-matched to achieve a low VSWR at a specific single frequency by using an external matching network. However, this approach is generally limited to narrowband applications, as the impedance match is only optimised at that frequency. For broader bandwidths, different design techniques are required, often involving modifications to the antenna structure itself rather than relying solely on external matching components.[1]

Using an external matching network, which often includes lossy reactive components, allows impedance matching without altering the antenna's structure for better radiation efficiency or bandwidth. However, these matching networks can introduce losses that may exceed the antenna's own radiation resistance, leading to lower overall efficiency. In some cases, though, the mismatch reduction achieved by the external network improves performance enough to offset these losses, resulting in better efficiency compared to an unmatched antenna. Additionally, while this approach may reduce efficiency, it can widen the antenna's operating bandwidth, which is sometimes an acceptable trade-off to achieve the necessary bandwidth and reduce environmental detuning effects.[2]

In simpler terms, instead of using an external matching network to achieve impedance matching for small antennas, better performance can often be achieved by modifying the antenna's structure itself. Various structural modification techniques have been introduced to achieve this goal, such as:

1. Using multiple folded arms in wire monopole or dipole antennas.
2. Incorporating inductive loading (like increasing conductor length) in wire antennas.
3. Using advanced materials, such as metamaterials and multi-arm coupled resonators.

These structural techniques can embed impedance matching directly into the antenna's design, often more efficiently than using external networks. For instance, approaches like folded arms and parallel or shunt matching stubs have been shown to help achieve low Voltage Standing Wave Ratio (VSWR) and high radiation efficiency in electrically small antennas.

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2. Fundamental limitation on Q and Bandwidth

This section discusses the fundamental limitations on the quality factor (Q) and bandwidth of small antennas. The content here summarises previous research and is meant to provide background information for comparing the performance of different small antennas.

An antenna is considered "electrically small" if its size or volume is small relative to the operating wavelength. Specifically, an antenna is defined as electrically small if ka≤0.5, where: k is the wavenumber, given by $\frac{2\pi}{\lambda}$, a is the radius of an imaginary sphere that just encloses the antenna.

The threshold ka=0.5 is used because, below this value, the radiation resistance of many small antennas (with dipole-like characteristics) approaches the radiation resistance of a straight-wire dipole antenna of the same length, regardless of their design or wire length.

The impedance of a small antenna varies with frequency and is represented by

$Z_A(\omega) = R_A(\omega) - jX_A(\omega)$ where ω radian frequency

R(ω) is the total resistance at the antenna's feed point, which includes both radiation resistance and loss resistance, X(ω)is the reactance at the antenna's feed point.

For small antennas, the bandwidth and quality factor (Q) are usually defined at a specific angular frequency ω_0, where the antenna is designed to be resonant—either naturally, by tuning, or by using a lossless series reactance.[3]

The Q factor of the antenna is important because it relates to bandwidth: a higher Q corresponds to a narrower bandwidth, while a lower Q allows for a wider bandwidth. For small antennas, there is a known lower bound on the achievable Q, which means no electrically small antenna can have a Q below this limit.

The exact Q factor for an electrically small, resonant antenna is defined as:

$$Q(\omega_0) = \frac{\omega_0|W|}{P} \quad (1)$$

where:

ω_0 is the angular frequency of resonance, |W| is the stored energy, and P is the power radiated by the antenna.

The document discusses the quality factor Q, radiation efficiency, and bandwidth of a small antenna operating near its resonance frequency ω_0

1. **Quality Factor (Q):**
   - The quality factor Q measures the antenna's stored energy relative to the energy dissipated per cycle. A high Q implies a narrow bandwidth.
     - For a small antenna with a single resonance, the quality factor Q can be estimated from the antenna's impedance properties as given in equation (2):

$$Q(\omega_0) \approx \frac{\omega_0}{2R(\omega_0)} \sqrt{\left(R'(\omega_0)\right)^2 + \left(\frac{X'(\omega_0) + \frac{X(\omega_0)}{\omega_0}}{\omega_0}\right)^2} \quad (2)$$

where $R'(\omega_0)$ and $X'(\omega_0)$ are the derivatives of the antenna's resistance and reactance with respect to frequency.

Lower Bound of Q (Equation 3):

- The theoretical minimum quality factor Q_{lb} which depends on the antenna's size (in terms of ka), is given by:

$$Q_{lb} = \eta_r \left[\frac{1}{(ka)^3} + \frac{1}{ka}\right], \quad (3)$$

where η_r is the frequency-dependent radiation efficiency, and ka is a dimensionless parameter representing the size of the antenna relative to the wavelength.

Bandwidth Definition:

- Bandwidth is characterized by the fractional matched VSWR bandwidth $FBW_V(\omega_0)$ which represents the range of frequencies over which the antenna can operate with a specified voltage standing wave ratio (VSWR) at the Characteristic impedance Z_{CH} The fractional VSWR bandwidth, shown in equation (4), is defined a

$$FBW_V(\omega_0) = \frac{\omega_+ - \omega_-}{\omega_0}, \quad (4)$$

where ω_+ and $\omega\_$ are the frequencies above and below ω_O respectively, and where the *VSWR* is equal to any arbitrary value denoted by in most instances, the maximum extent of the defined matched *VSWR* bandwidth is limited to values of s 5.828 (half power). The fractional matched *VSWR* bandwidth and the Q are related by

$$Q(\omega_0) \approx \frac{2\sqrt{\beta}}{FBW_V(\omega_0)},$$

$$\sqrt{\beta} = \frac{s-1}{2\sqrt{s}} \leq 1. \quad (5)$$

In simpler terms, the approximations given in Equations (2) and (5) rely on certain conditions about the antenna's behaviour Specifically:

1. Single Resonance: These approximations assume that the antenna has only one dominant resonance within its VSWR bandwidth. This means there is a

single, clear peak in its response around a specific frequency.

2. Narrow Bandwidth: The calculations also assume that the bandwidth is relatively narrow—enough that the quality factor and VSWR relationship remain predictable. In this case, the "half-power matched VSWR bandwidth" is set to a VSWR value of 5.828, which is small enough for the approximations to work.

If the antenna, however, has multiple closely spaced resonances within its bandwidth, or if the bandwidth is wider than expected, then these simplifications may no longer be accurate. In such situations, the behaviour of the antenna becomes more complex, and these equations (2 and 5) may not correctly describe the quality factor and bandwidth. The smallest possible quality factor Q that can be achieved for a small antenna with a single resonance is constrained by the theoretical lower bound given in Equation (3). This means that no matter how well the antenna is designed or tuned, its Q cannot go below this limit, which is determined by factors such as the antenna's size and efficiency. Furthermore, because Q is inversely related to bandwidth, this lower bound on Q also limits the maximum achievable bandwidth for the antenna under a matched VSWR condition.
Since the quality factor Q and bandwidth are inversely related, the matched VSWR bandwidth of a small antenna with a single resonance cannot exceed the limit set by 1/Q. Equation (6) provides an expression for the upper bound on the fractional matched VSWR bandwidth $FBW_{V_{ub}}$ which is given by:

$$FBW_{Vub} = \frac{1}{\eta_r} \frac{(ka)^3}{1+(ka)^2} \frac{s-1}{\sqrt{s}}. \tag{6}$$

η_r is the frequency-dependent radiation efficiency, Ka represents the electrical size of the antenna (with k being the wavenumber and the antenna radius), s is the specified VSWR value.
This equation sets an upper limit on the bandwidth, indicating the maximum achievable bandwidth for a given antenna size, efficiency, and VSWR requirement.

Additionally, the passage notes that this upper bound is specifically for the fractional matched VSWR bandwidth. In some cases, if a wider operational bandwidth is desired, the antenna's actual bandwidth can be extended by intentionally mismatching the antenna, which means allowing a VSWR that exceeds the matched condition. This approach can help in applications where bandwidth is prioritized over perfect impedance matching.[4]

3. The Fundamental Design Technique

Electrically small straight-wire antennas, such as dipoles and monopoles, have an impedance $Z_A(\omega) = R_A(\omega) - jX_A(\omega)$,where the reactive part $X_A(\omega)$ is mostly due to the capacitance created by the structure. This capacitance (represented by $\frac{1}{\omega c}$) comes from the physical characteristics of the antenna, like the spacing between elements or between the antenna and the ground. To counteract this dominant capacitive behaviour and bring the antenna closer to resonance (where it can radiate more effectively), designers can add capacitive or inductive elements to the antenna structure. These modifications could include:

- Capacitive top-loading: Adding elements that increase capacitance, helping to balance the antenna's reactance.
- Inductive loading: Extending the wire length or adding inductive structures to add inductance and balance out the capacitance.

In the example discussed, a baseline straight-wire monopole antenna was tested. It had a height of 8.48 cm and a diameter of 0.707 mm, designed to operate around 300 MHz The NEC4 simulation results show it had an impedance of 3.0–j461.4Ω3.0 with a high Q factor of 171, indicating a very narrow bandwidth. This setup did not account for any real-world power losses, meaning the results are idealized for theoretical analysis.

To make the antenna self-resonant at around 300 MHz, an inductive configuration was used by adding extra wire arranged in a meander-line shape. This approach increased the effective length of the wire to 65.43 cm (significantly longer than the original 8.48 cm and more $\frac{\lambda}{4}$ while keeping the antenna's physical height unchanged. The meander-line structure helped bring the reactance XA to zero, achieving resonance.
With this setup: The impedance of the antenna became 5.1+j0 Ω which is near-resonant with low reactance (the imaginary part is zero). The quality factor Q dropped to 58.6, much lower than the original, indicating a broader bandwidth. This reduction in Q is typical for self-resonant designs, as they allow more bandwidth by trading off some of the antenna’s stored energy. The ka value (a parameter related to the antenna's electrical size) for the meander-line antenna was 0.538, meaning it is still electrically small but has been optimized for resonance.

1. Meander-Line Antenna Comparison:

The meander-line antenna had a quality factor Q was 7.1 times its theoretical lower bound, meaning it was still quite high compared to the lowest possible Q. This antenna design was effective for resonance, but there might be more efficient alternatives to further reduce Q.

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2. **Top-Hat Antenna Design:**
   - To achieve self-resonance with a capacitive top-hat configuration, a wire-grid top-hat was added to the antenna. This increased the effective size of the antenna, allowing it to reach resonance (where $X_A = 0$) at around 300 MHz
   - The top-hat's diameter was adjusted to 8.34 cm, and simulations showed it had an impedance of 10.6+j0Ω and a Q of 13.9, which is much lower.
3. This means the top-hat configuration achieved better performance, with higher radiation resistance (indicating more efficient radiation) and a lower Q, implying a broader bandwidth than the meander-line version.

4. **Importance of Comparison Using ka and Q_{lb}**
   - Comparing these two designs based solely on height does not capture all aspects of their performance. In practical applications, height is often restricted, so the top-hat configuration might be preferred in those cases.
   - To fairly evaluate small antennas, it's better to consider how closely the actual Q approaches the lower bound Q_{lb}as well as the ka value (indicating the antenna's electrical size).
   - For the top-hat monopole antenna, ka was 0.594, with a Q_{lb} of 6.451, meaning its Q was 2.15 times the lower bound.

This is an improvement over the meander-line antenna, making the top-hat design more efficient in terms of approaching the fundamental limits on Q.
In summary, the top-hat configuration outperformed the meander-line design by achieving a lower Qand higher radiation efficiency, making it a better choice when both height and Q efficiency are important. The comparison between the top-hat monopole and the meander-line antenna using the ratio Q/Q_{lb} actual quality factor relative to the theoretical minimum) shows that the top-hat monopole performs much better. This result aligns with a common view in small antenna design: top-loaded antennas generally perform better than inductively loaded antennas (like the meander-line) when the antennas have the same overall height.
However, it's important to note that neither of these antenna designs is fully optimized. Both designs only partially utilize the available spherical volume defined by the ka parameter, which represents the maximum volume for a given antenna size relative to wavelength. By not fully exploiting this volume, the designs leave room for further improvements in efficiency and bandwidth.
The next section will explore various antenna designs that attempt to fully utilize the available spherical volume. These designs aim to achieve better performance by maximizing the use of the space, potentially lowering Q and increasing bandwidth and efficiency.

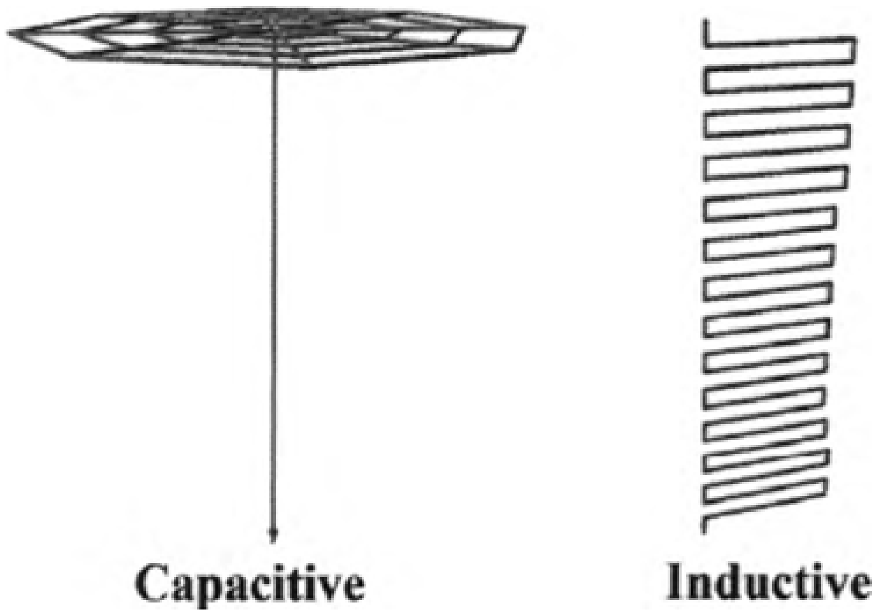

Figure 1 shows images of two antenna designs—a capacitive top-hat-loaded monopole and an inductively loaded monopole. Both antennas have the same overall height of 8.48 cm and are designed to operate at the same resonant frequency, approximately 300 MHz

This setup allows for a direct performance comparison between the two configurations under identical size and frequency conditions. Particularly the ratio of Q/Q_{lb}
The comparison begins with antennas of the same overall length and the same operating frequency, to

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establish a baseline of their respective performance properties. The comparison then continues where all the antennas were designed to have the same value of *ka.* In all cases, the antennas were designed to operate at or very near to 300 MHz

In this section, the fundamental antenna configurations are presented The fundamental antennas the folded spherical helix. To establish their relative baseline performance, all the antennas - with the. This designed to operate at or near 300 MHz Performance properties considered include the antenna's impedance, radiation efficiency, pattern characteristics (including polarisation), matched VSWR bandwidth, and Q.

4 The Folded Spherical Helix

For these small antennas, the goal was to design each one to achieve a matched VSWR, high radiation efficiency, and the lowest possible Q (or equivalently, the widest possible bandwidth). For antennas with inductive loading, minimizing Q involved winding the antenna's wire on the outer boundary of the available space. In the case of a spherical antenna, this meant winding the wire around the outer surface of the ka sphere. To attain high radiation efficiency, it was necessary to use wire with a large enough diameter so that the antenna's radiation resistance significantly exceeded its loss resistance. Generally, it's feasible to achieve high radiation efficiency within practical limits.

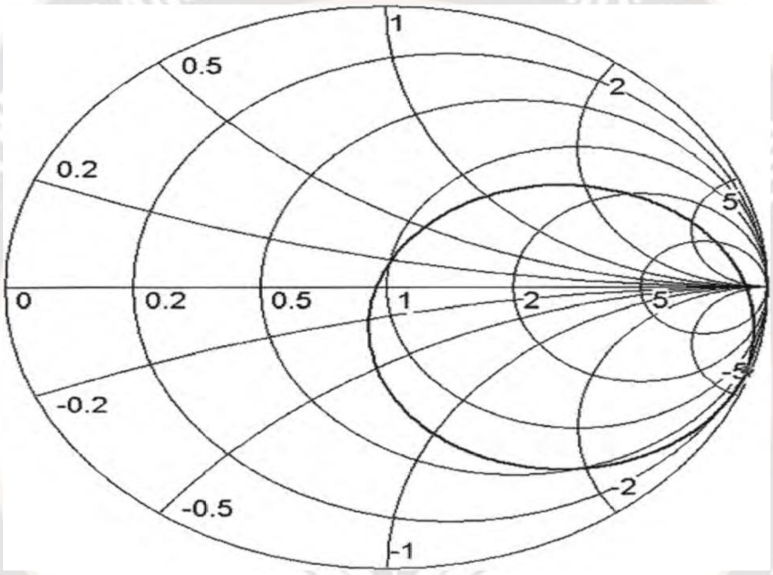

Fig 2 The impedance of the four-arm folded spherical helix over a frequency range of 270 to 330 MHz .

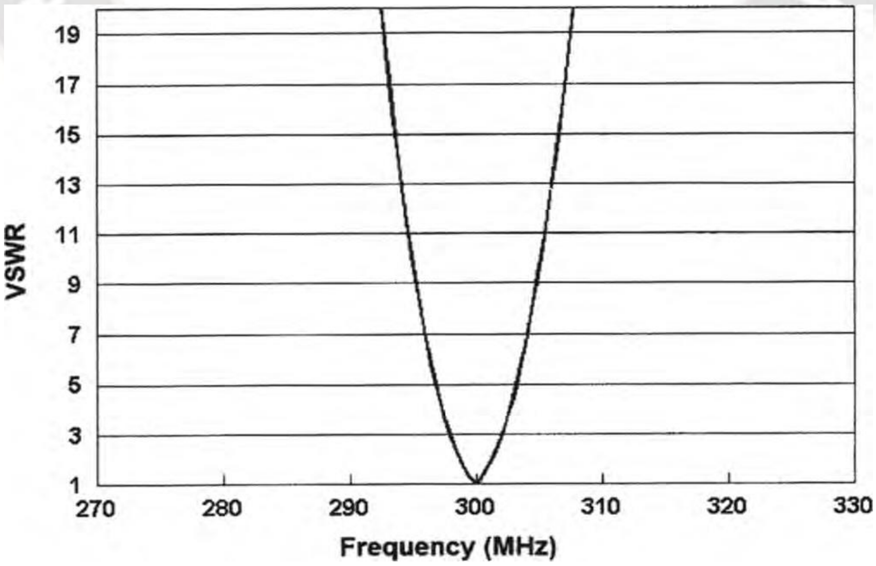

Fig 3 The matched VSWR of the four-arm folded spherical helix.

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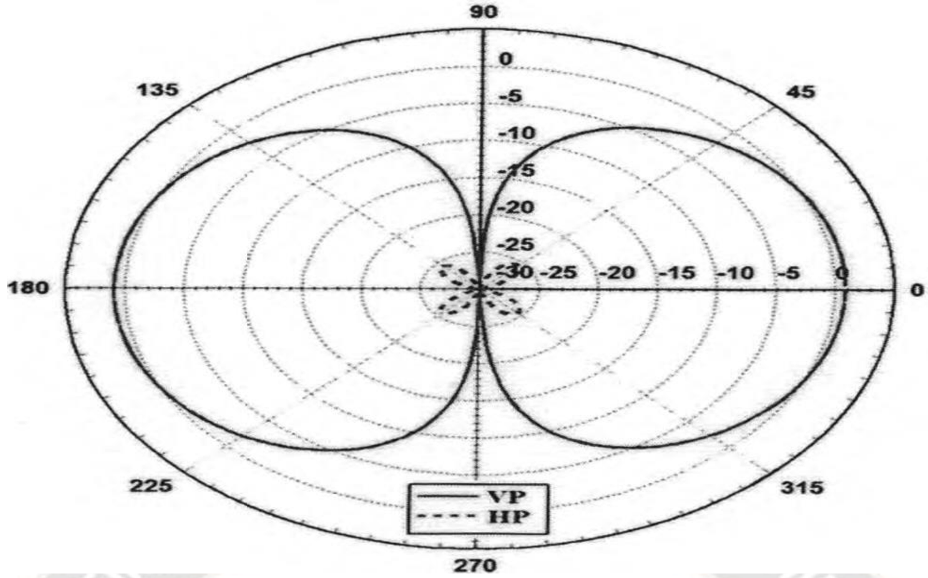

Fig 4 The resonant radiation pattern of the four-arm folded spherical helix.

The four-folded spherical helix was specifically designed to have a low *VSWR* in a 50-n system, high radiation efficiency, and a low Q. It exhibited a single resonance and had a Q that was within 1.5 times the lower bound at a value of $ka \sim 0.263$. The folded spherical helix was considered the baseline antenna for this study. The antennas compared to the folded spherical the design objective was to operate all of the antennas as close to 300 MHz, Overall length 8.3cm, ka 0.265 η_r97.9%, Q_{lb}=55.1 Q=84.64 Half Power VSWR Band width(%) 2.37.

Conclusion

This paper has presented a comparative analysis of fundamental small antenna designs, specifically focusing on their scaling behaviour with respect to the electrical size parameter, ka. The performance metrics considered include impedance matching, radiation pattern, radiation efficiency, half-power bandwidth, and 2:1 VSWR bandwidth. These results emphasize the importance of tailoring antenna design to specific application requirements. No single design was universally superior, but the insights gained from this study can guide the selection of antenna architectures for optimized performance in small antenna systems. Future work could extend this analysis by exploring hybrid designs and advanced impedance matching techniques to further improve performance across all metrics.

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