

Antenna Design Guide for Compact Devices

As wireless devices shrink, antenna design becomes a critical bottleneck. This guide explores several techniques to overcome size constraints without sacrificing performance or compliance.

The rapid evolution of wireless technologies has led to increasingly compact yet powerful electronic devices. This trend presents significant challenges for system engineers, including electromagnetic compatibility (EMC), electromagnetic interference (EMI), antenna miniaturization, and antenna coexistence. Among these, antenna miniaturization is particularly critical, as it directly impacts overall electrical performance.

Designing antennas for compact devices requires a delicate balance between performance, cost, size, and regulatory compliance. This article offers design guidance to help engineers create industrially elegant products with robust wireless performance, considering real-world product constraints.

Antenna Design Metrics

The following section provides an overview of some key antenna design and performance parameters, some regulatory compliance requirements, and the size/cost factors:

Key Design/Performance Parameters

- **Gain:** Measures an antenna's ability to direct radio-frequency (RF) energy in a specific direction relative to a reference antenna (isotropic radiator or dipole). Higher gain indicates stronger directional radiation. For omnidirectional applications, such as phones, wearables, point-of-sale (POS) devices, and other portable products, lower gain with acceptable efficiency is often preferred to ensure 360-degree signal coverage.
- **Efficiency:** Antenna efficiency represents the ratio of radiated power to the input power accepted by the antenna. It accounts for various losses, including antenna conductor losses, antenna carrier dielectric losses, and impedance mismatch losses. Higher efficiency translates to longer communication distances, extended battery life, and improved signal quality, making it a critical parameter for optimal performance.

- **Radiation pattern:** A graphical representation of the antenna's far-field radiation characteristics. Omnidirectional radiation patterns, characterized by uniform signal distribution in all directions, are essential for common protocols like 5G, 4G LTE, LoRa, Wi-Fi, UWB, and Bluetooth. In contrast, directional radiation patterns, which concentrate signal energy in a specific direction, are indispensable for applications such as satellite communications (GPS/GNSS, L-band).
- **Return loss:** Return loss measures the amount of RF power reflected back toward the source due to impedance mismatch between the transmission line and the antenna. High return loss, indicating minimal reflections, ensures maximum power transfer to the antenna, thereby enhancing efficiency and gain. Conversely, impedance mismatches lead to signal losses, excessive heating, and potential damage to the transmitter.

Regulatory Compliance

Wireless devices, by their very nature, operate within a regulated electromagnetic environment, necessitating adherence to stringent global regulatory standards to ensure proper operation and safeguard human health.

- **Specific absorption rate (SAR):** SAR quantifies the rate at which the human body absorbs RF energy from a wireless device. Regulatory bodies, such as the Federal Communications Commission (FCC) and the European Commission (CE), establish strict limits on SAR to protect users from potential health hazards. For example, the FCC mandates a SAR limit of 1.6 W/kg, while the CE enforces a limit of 2.0 W/kg. Compliance with relevant standards, including FCC IEEE C95.1-2019, CE ICNIRP, and EN 50360, should be considered for all wireless devices during antenna design.
- The FCC also sets **maximum antenna gain and radiation pattern requirements**¹ to ensure the wireless devices deliver optimal real-world performance.



1. Shown are some antenna manufacturing processes: FPC on carrier, stamping on carrier, and LDS technologies. (Photo by Chris Zhong)

Antenna Size and Cost

As wireless devices continue to shrink, available space on printed circuit boards (PCBs) is increasingly limited. Antenna size is therefore critical in compact devices, as it directly impacts both device dimensions and manufacturing costs. However, smaller antenna footprints typically result in reduced performance due to fundamental physical constraints, requiring a careful balance between size and functionality.

Cost is an ever-present consideration in product development. Different antenna design approaches can significantly influence overall project expenses, encompassing both component costs and assembly costs. Therefore, engineers must carefully evaluate the cost implications of various antenna solutions to ensure that they align with project budgets.

Strategies for Successful Antenna Designs

Balancing the aforementioned factors presents a formidable challenge for design engineers. However, successful resolution of these challenges can lead to the development of industry-leading products. Before embarking on antenna design, engineers must thoroughly understand the performance requirements, regulatory constraints, and cost considerations. Several strategies can help designers create high-efficiency antenna solutions without compromising performance.

3D Antenna Manufacturing Technology: Breaking the 2D Barrier

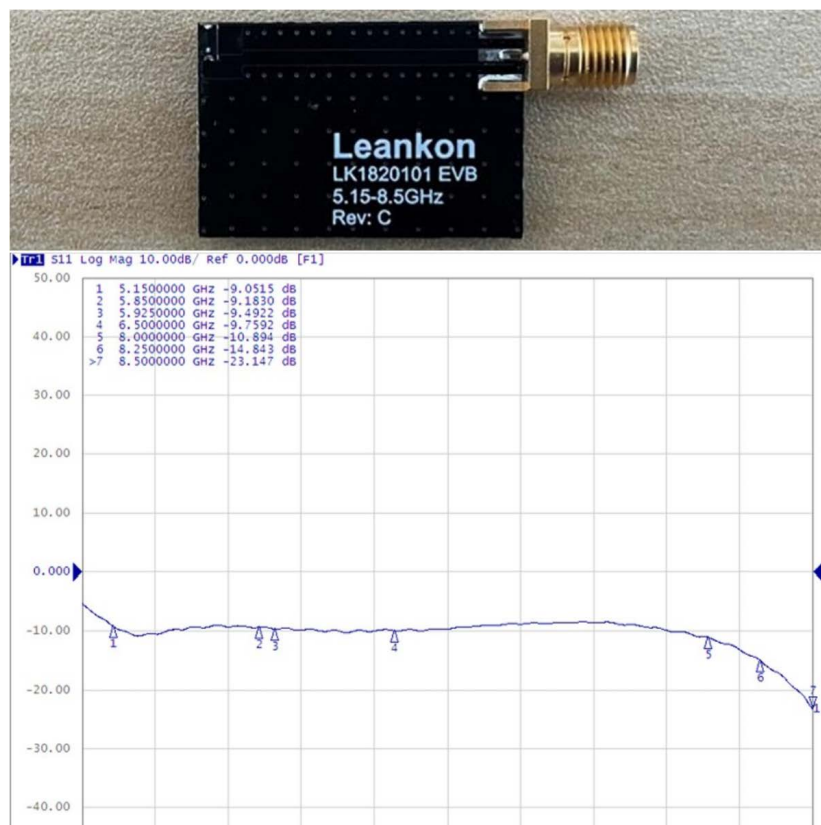
Most modern wireless devices currently use traditional 2D antenna manufacturing processes, such as flexible printed circuits or flexible PCBs, on-board trace antennas, and stamped metal antennas. While these methods work well for devices without space constraints, they impose significant

limitations when creating complex 3D antenna patterns.

These limitations often result in larger antenna footprints and inefficient use of PCB space. Such tradeoffs may be acceptable for non-space-constrained devices, but they become problematic for compact designs.

3D manufacturing technologies like laser direct structuring (LDS) and plastic direct structuring (PDS) overcome these limitations by enabling the fabrication of complex 3D antenna structures directly on plastic housings (*Fig. 1*).

This approach allows for optimal antenna placement on curved surfaces (commonly found in smartphones and automotive components) and facilitates integration into structural elements. In addition, the metallized traces embedded



2. Here's an example of a wide-bandwidth antenna product that combines coupling-fed antenna technology with a monopole. (Photo by Chris Zhong)



3. A Wi-Fi and Bluetooth LDS antenna fabricated with LCP material, as shown here, offers significant size reductions without degrading performance. (Photo by Chris Zhong)

in plastic offer enhanced resistance to vibration, moisture, and corrosion, ensuring superior long-term reliability.

Wide-Bandwidth Antenna Technology: Covering Multiple Wireless Protocols

Modern wireless devices support a multitude of wireless protocols, such as Wi-Fi, Bluetooth, GPS, UWB, and cellular 5G/4G LTE. Wide-bandwidth antenna technology enables coverage of multiple frequency bands with a single antenna, reducing the overall antenna count and simplifying system design.

Traditional antenna technologies, such as planar inverted-F antennas (PIFAs), monopoles, and dipoles, often struggle to achieve sufficient bandwidth for multiple wireless protocols. In contrast, coupling-fed antenna technology offers significantly wider bandwidths—typically exceeding 20%—compared to direct-fed antenna technologies like PIFAs or patches, which usually achieve only 5% to 10% bandwidth.²

This superior bandwidth is demonstrated by a coupling-fed antenna combined with a monopole concept (Fig. 2). The design allows for simultaneous coverage of UWB (6 to 8.5 GHz), V2X (5.85 to 5.925 GHz), and Wi-Fi (5.15 to 7.125 GHz) within a remarkably compact space of 5×4 mm, while maintaining an excellent S_{11} of < -9 dB across all operating frequency bands.

High-Permittivity (High- ϵ_r) Substrates: Miniaturization Through Material Science

In compact devices where space is at a premium, integrating antennas requires careful design consideration. High-dielectric-constant (Dk) materials with low loss are essential for antenna miniaturization, as higher permittivity reduces the guided wavelength and enables smaller antenna dimensions.

Common plastics, such as polycarbonate (PC) and PC/ABS blends, have dielectric constants of approximately 2.8 to 3.0, while LDS liquid-crystal polymer (LCP) can achieve dielectric constants of around 4, resulting in significant size

reductions (Fig. 3). Due to its excellent electrical and mechanical properties, LDS LCP is widely used in mobile phones.

But even as higher Dk leads to smaller antenna dimensions, it also reduces antenna efficiency. Therefore, a comprehensive tradeoff analysis is necessary to balance antenna performance with material selection.

In summary, a successful antenna design for compact wireless devices requires a holistic approach that balances performance, cost, regulatory compliance, and size constraints. By combining 3D manufacturing techniques,

wide-bandwidth antenna technology, and high-permittivity substrates, engineers can develop high-efficiency antenna solutions that overcome the space constraints of modern wireless devices.

Early consideration of antenna design is crucial, as the surrounding environment, antenna placement, and PCB layout significantly impact overall system performance—including EMC, EMI, and radiation characteristics.



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References

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