E-GUIDE

How to Implement Aperture Tuning:

Best Practices for 4G/5G Smartphones

What's Inside

- What is aperture tuning?
- What are its key properties?
- What makes aperture tuning unique?
- What are the implementation challenges?

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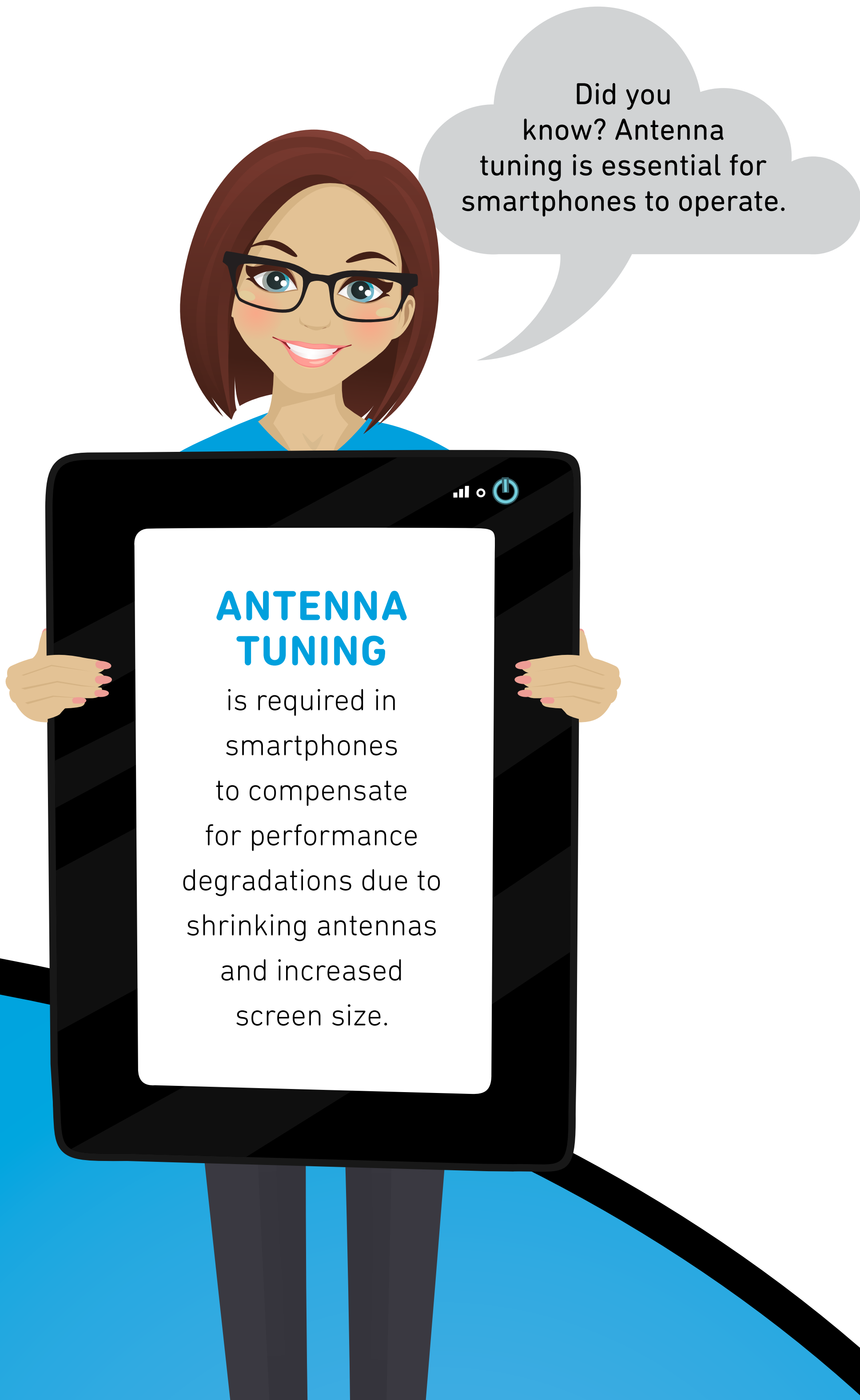

Did you know? Antenna tuning is essential for smartphones to operate.
ANTENNA TUNING
is required in smartphones to compensate for performance degradations due to shrinking antennas and increased screen size.

QUICK SUMMARY

Antenna aperture tuning is essential to enable smartphones to operate efficiently over the ever-increasing range of RF frequency bands and support the transition to 5G. Smartphones need more antennas to support growing RF requirements such as new 5G bands, MIMO and carrier aggregation, but there is less space for these antennas due to changes in smartphone industrial design. As a result, antennas are becoming smaller, potentially reducing antenna efficiency and bandwidth.

Aperture tuning compensates for this problem by allowing antennas to be tuned to operate efficiently on multiple bands and increasing Tx and Rx performance by 3 dB or more. Aperture tuning is implemented with tunable capacitors or tuner switches combined with tuning components; switches with low RON and low COFF are critical to maximizing efficiency. Aperture tuning also lets antennas communicate on multiple bands simultaneously to support carrier aggregation. Implementing aperture tuning requires in-depth knowledge of how to apply the technology for each application.

INTRODUCTION

Antenna efficiency plays a critical role in overall smartphone RF performance. However, current broad trends in RF requirements – especially the forthcoming transition to 5G – and in smartphone industrial design, mean that smartphones must fit more antennas into less space. As a result, antennas are shrinking in size, which reduces antenna efficiency. Without compensating for this problem, the reduced efficiency can impact transmit (Tx) and receive (Rx) performance, causing shorter battery life, lower data rates and connectivity problems.

Faster Data Rates Mean More Antennas

The transition to 5G, which continues the quest to deliver higher data rates, will drive a significant increase in the typical number of antennas in each handset.

Two primary techniques for delivering higher data rates, carrier aggregation (CA) and multiple input/multiple output (MIMO), both require multiple antennas that operate simultaneously. 5G will further drive this trend because it mandates support for four independent downlink channels receiving signals simultaneously for most bands. It will also require handsets to include at least four antennas for cellular communications.

At the same time, handset antennas will need to support a wider range of frequency bands, largely due to the introduction of new 5G bands. 5G handsets may need to support frequencies ranging from 600 MHz at the low end to as high as 6 GHz.

To support these requirements as well as Wi-Fi, GPS, and **Bluetooth**® technologies, the typical number of antennas will increase from 4-6 in today's LTE handsets to 6-10 in 5G smartphones (Figure 1). It is becoming increasingly difficult to fit all these antennas into the limited space available.

More Antennas, Less Antenna Area = Tougher Challenge

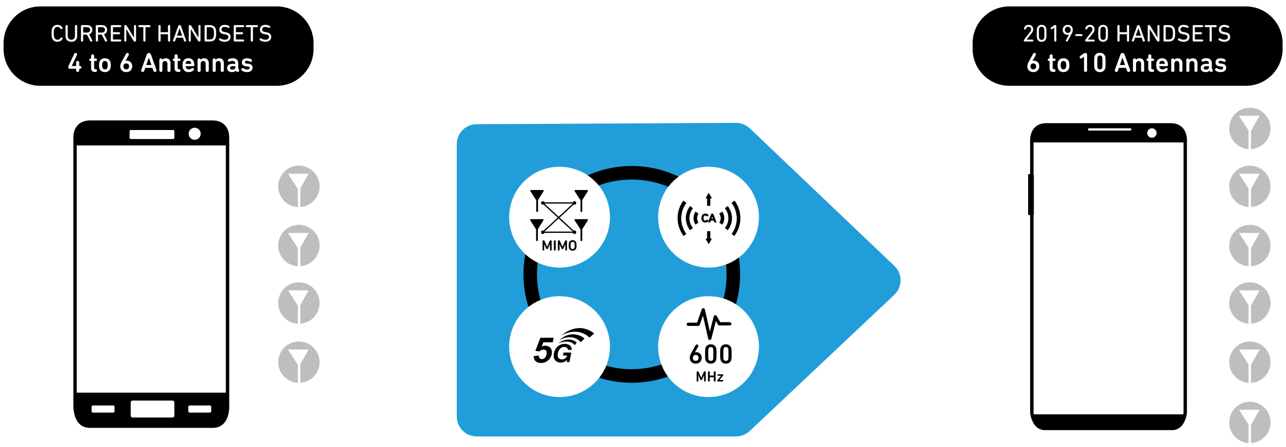


Figure 1. *The number of antennas is increasing, particularly with the transition to 5G, to support new frequency bands as well as MIMO and CA requirements.*

Antenna efficiency plays a critical role in overall smartphone RF performance. Watch out! Smartphone design trends are shortening battery life, lowering data rates and causing connectivity problems.

Reduced Antenna Area

Exacerbating the problem, the space available for antennas is shrinking as manufacturers make industrial design changes and add new features. One key change is the shift to full-screen handsets, in which the display occupies nearly the entire face of the phone; as a result, there is less space available outside the screen for cellular antennas. Manufacturers are also adding more cameras, further reducing the space available within the handset.

The need to fit more antennas into less space means antennas are becoming smaller, and the reduced antenna size results in lower antenna efficiency. Figure 2 shows how antenna efficiency decreases in full-screen designs as the space between the radiating element at the top of the phone and the ground (located at the screen edge) shrinks.

The higher number of antennas, combined with their reduced size, also means the handset is more sensitive to transient effects caused by changes in its environment, such as handling the phone. These transient effects may include reduced efficiency and shifts in frequency response.

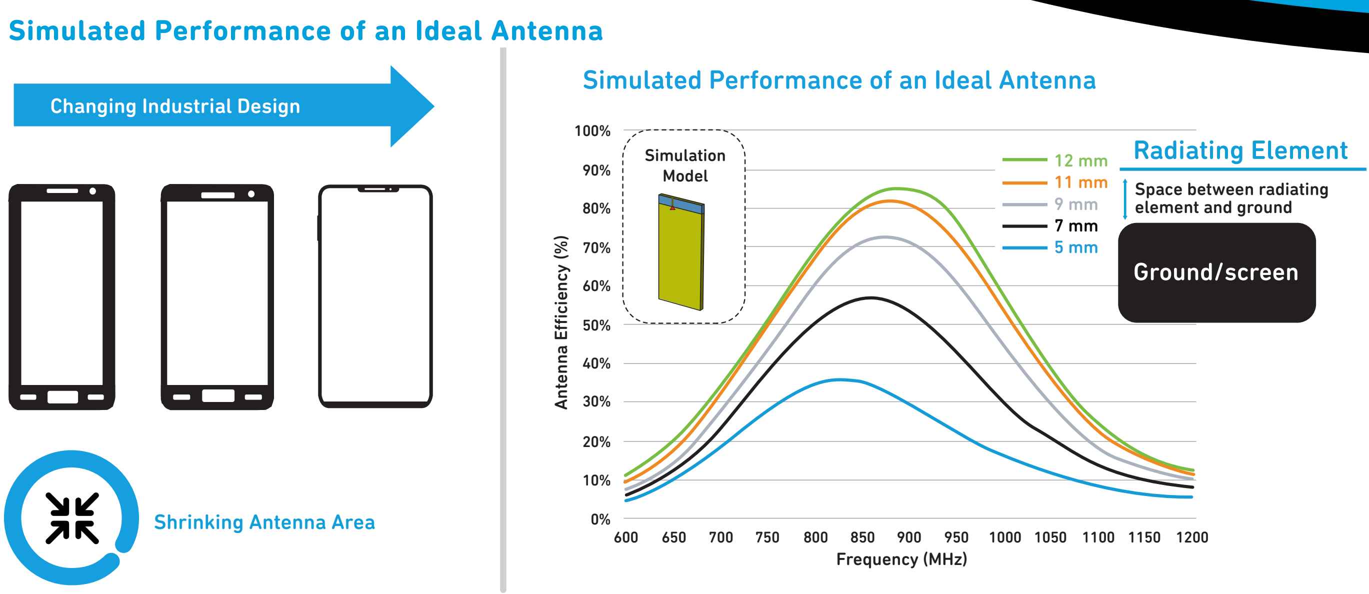
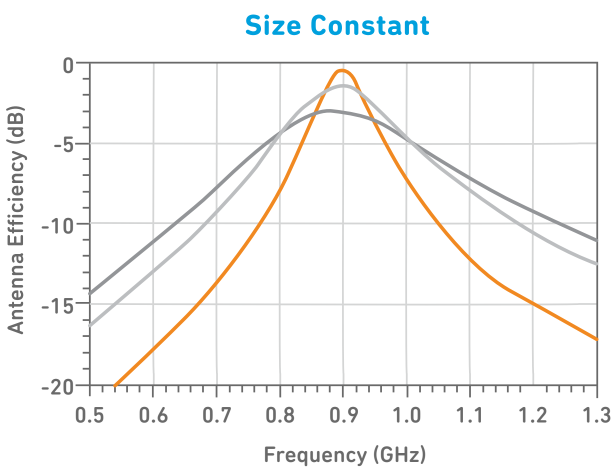
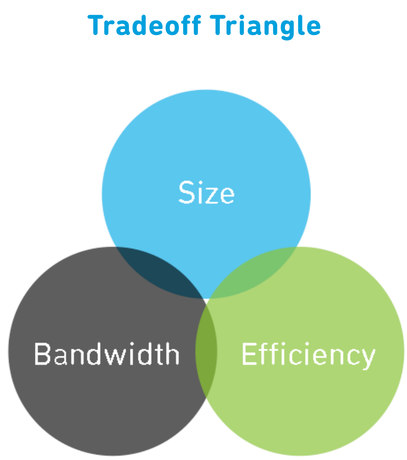


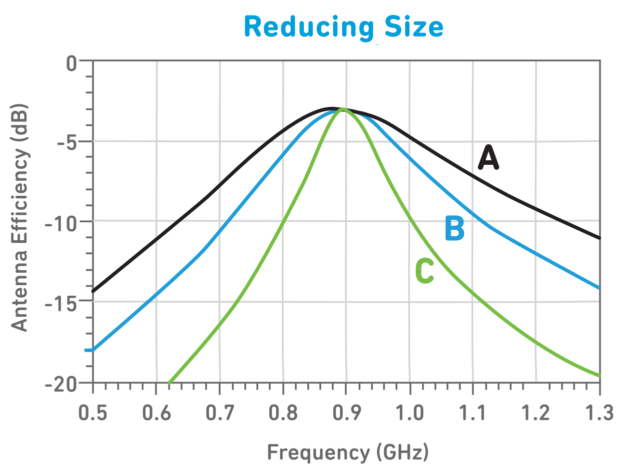
Figure 2. *Full-screen smartphone designs shrink the available antenna area, reducing antenna efficiency.*

The Antenna Performance Tradeoff Triangle

The antenna "tradeoff triangle," shown in Figure 3, illustrates the impact of reduced antenna size on efficiency and bandwidth. If the antenna size remains constant, efficiency can be traded in exchange for greater bandwidth. In older-generation phones with larger antennas, this tradeoff may be acceptable because the antenna may still be able to meet performance requirements while supporting a wider range of bands. But as the antenna size decreases, this tradeoff is no longer possible; with new full-screen designs, the antenna can only achieve the required level of efficiency over a narrow frequency range. Therefore, to support the wide range of frequencies supported in current handset designs, the antenna must be tuned to operate efficiently on each frequency.







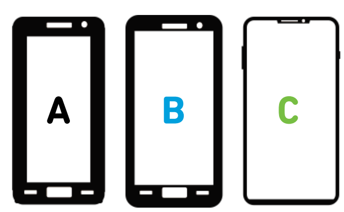


Figure 3. *The antenna performance tradeoff triangle.*

APERTURE TUNING: TUNING WITH A SWITCH

Today, aperture tuning is the primary method used in handsets to overcome the problems caused by reduced antenna area and efficiency. It is essential to enable smartphones to support the ever-broadening range of frequency bands, especially with the transition to 5G.

Aperture tuning can make a large impact on antenna efficiency for both Tx and Rx communications, improving total radiated power (TRP) and total isotropic sensitivity (TIS) by 3 dB or even more depending on the application.

The antenna tuning concept is shown in Figure 4. A switch is connected between the antenna and the ground and used to adjust the resonant frequency of the antenna to match the frequency that the phone is currently using to communicate.

Adding different tuning components (a capacitor or inductor) between the switch and the radiating element can be used to further adjust the resonant frequency, to support different bands. Figure 4 shows the resonant frequency of an antenna when the switch is off, when it is on, and when an inductor or capacitor is inserted into the circuit.

In Figure 4, each component is connected to a simple switch, to illustrate the aperture tuning concept. However, in some applications, such as primary cellular antennas, more complex multi-throw switches may be used to connect multiple tuning components and support a broader range of frequency bands.

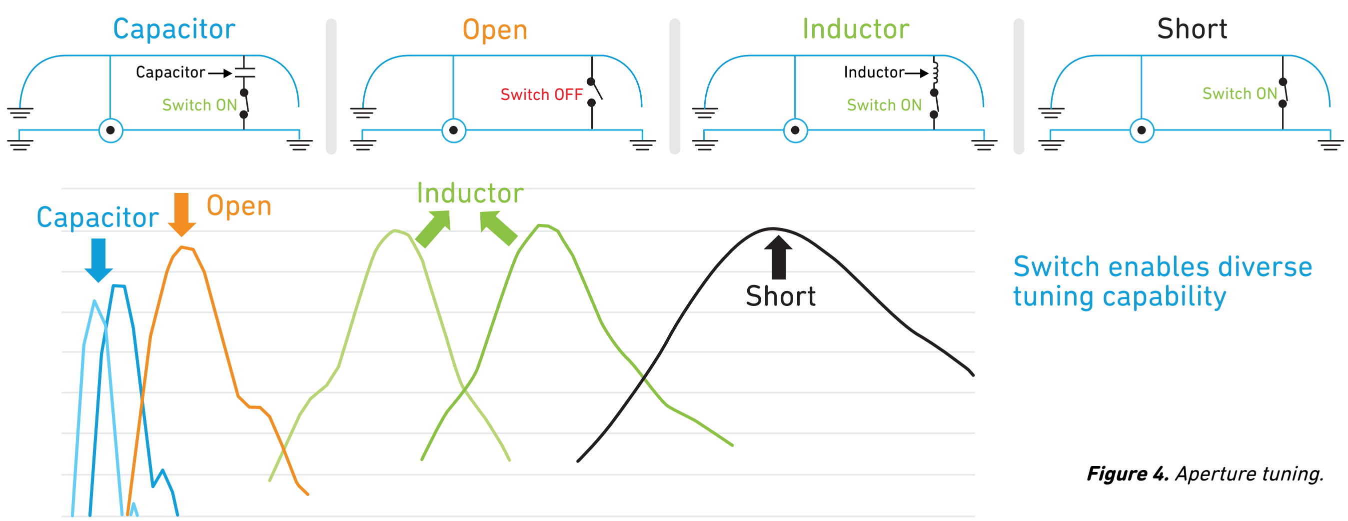


Figure 4. *Aperture tuning.*

Select the Right Tuning Components

It's important to choose the proper tuning components. For example, it's best to avoid using inductors with a value greater than 36 nH, because of the lower self-resonant frequency. Additionally, the parasitics due to PC board layout can cause the self-resonant frequency of the inductor to reduce further such that the resonances fall in the cellular frequency range.

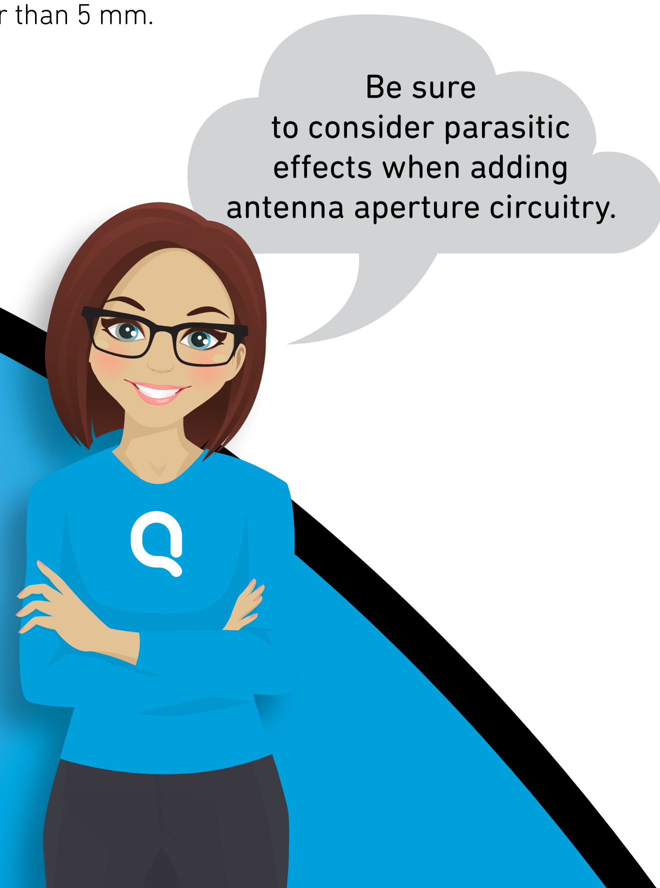
Using capacitor values of less than 0.5 pF most likely means selecting a component with high tolerance. However, capacitors with high tolerances can cause the capacitance value to vary more than desired, creating both tuning and efficiency issues.

Layout and Design Guidelines

When designing an RF system and adding antenna aperture circuitry, it's necessary to take parasitic effects into consideration. It's important to understand where parasitics are generated when laying out the circuitry, as they lead to loss and changes in resonance frequency. When laying out the phone's PC board, consider the landing pad sizes and pad shapes, because improper pad or trace layouts can increase parasitic capacitances and inductances.

Work to:

- Reduce stub junctions because they can cause signal integrity problems.
- Reduce abrupt trace width changes such as 90-degree bends. Smooth transitions are best. (See Figure 5.)
- Optimize pad sizes and location as they can increase parasitic capacitances.
- Minimize the distance between the aperture tuner and RF antenna feed point to minimize the impact of parasitics on antenna response.
- Create a good RF return current path. Care should be taken in placing ground closer to the antenna as it can cause antenna efficiency to reduce.
- Minimize inductance to ground by using one or more dedicated vias for each ground connection.
  – Place vias in the ground pads and fill vias with epoxy.
  – Use one or more vias to reduce inductance and resistance.
- Ensure your ground paths connect to the board ground through a low resistance path. This minimizes noise coupling and improves the linearity of the tuner.
- Provide adequate ground clearance around all RF components. Minimize placing ground close to RF ports as this can increase parasitic capacitance. (See Figure 6.)
- Avoid running supply and control lines under the tuner, because the noise from the supply and control lines can couple onto the antenna. Use ground layers between the aperture tuner and any supply and control lines that may have noise.
- Use ferrite beads or chokes for supply line traces longer than 5 mm.



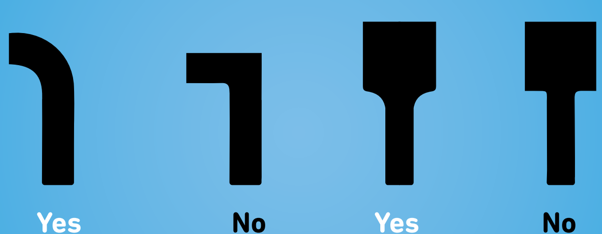
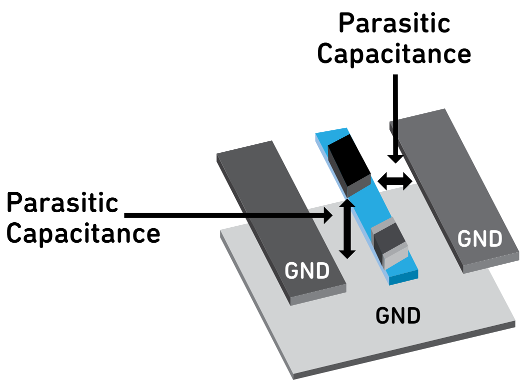


Figure 5. *PC board traces and landing pads.*



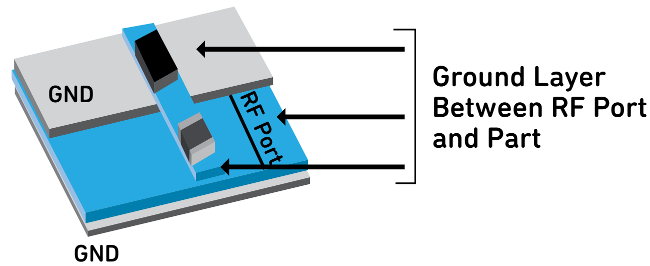


Figure 6. *Inductance versus ground and components.*

Avoid:

- Using thermal relief for RF connections.
- Routing RF traces through multiple layers. This can distort the trace impedances and increase the reflected power and insertion loss through the trace.
- Placing floating ground planes under or around the tuner and RF traces connecting the switch and antenna.

Tuning an Antenna for Multiple Frequency Ranges

An antenna has multiple natural resonant frequencies. These are harmonically related: for example, an antenna may have resonant frequencies at 900 MHz, at 1800 MHz (2nd order harmonic), at 2700 MHz (3rd order harmonic) and so on. By using aperture tuning switches to tune each of these frequencies, a single antenna can support many bands distributed across a very wide spectrum range.

Figure 7 shows how this works. Each resonant frequency has a different voltage distribution along the antenna. The voltage pattern varies depending on the type of antenna; Figure 7 shows one example.

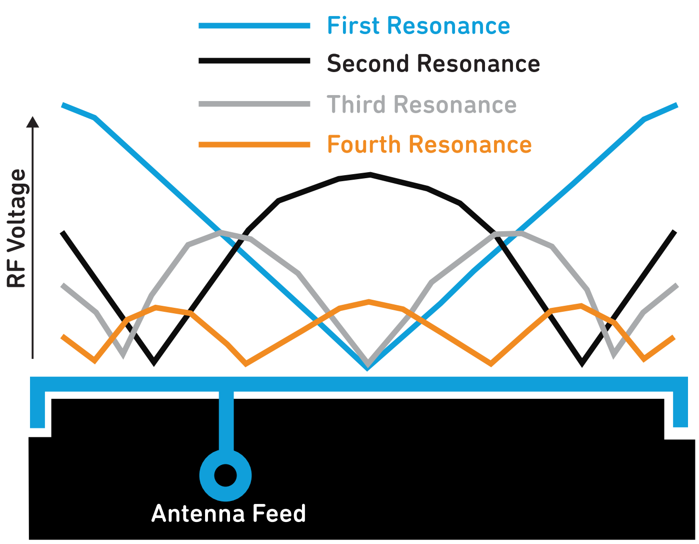


Figure 7. *Voltage distributions for an antenna's different resonant frequencies.*

Each of these resonant frequencies can be tuned independently by placing an aperture tuning switch at the point where it has the greatest effect, which is generally close to the apex of the voltage distribution for that frequency.

By positioning multiple switches in different locations along the antenna, and using multiple tuning components with each switch, a single cellular antenna can support a very wide range of low-, mid- and high-frequency bands (Figure 8).

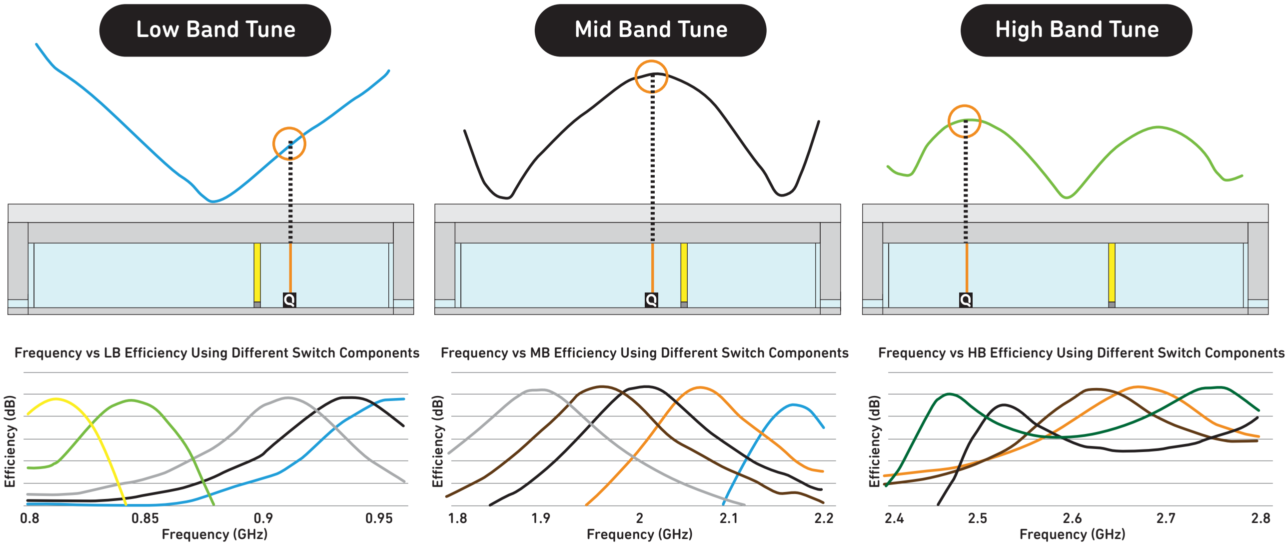


Figure 8. *By placing tuning switches at multiple locations, a single antenna can support a wide range of low-, mid- and high-frequency bands.*

Return Loss Versus Antenna Efficiency

In many circumstances, return loss is a good measure of antenna efficiency. But these two measurements don't always align.

- **Total antenna efficiency** is the ratio of the power radiated by the antenna to the power from the transceiver.
- **Antenna radiation efficiency** is the ratio of the power radiated by the antenna to the power delivered to the antenna. Some of the power from the transceiver isn't delivered to the antenna due to impedance mismatch and other losses in the path.
- **Mismatch loss** is the power lost due to impedance mismatch between the antenna and transceiver. Maximum power transfer between the antenna and transceiver occurs when the antenna impedance is equal to the complex conjugate of the transceiver impedance.
- **Return loss** is the ratio of transmitted power to reflected power. If the impedance of the transceiver is very well matched to the antenna impedance, then very little power is reflected back. High return loss indicates an efficient power transfer between the antenna and transceiver. Return loss of >10 dB is desired, as it provides >90% of the power transfer.

Antenna radiation efficiency doesn't cover reflected power due to return loss. Thus, the best way to judge the antenna performance is to look at the total antenna efficiency [i.e., total antenna efficiency (dB) = radiation efficiency (dB) + mismatch loss (dB)], as shown in Figure 9.

The total antenna efficiency comprises antenna radiation efficiency and the mismatch loss between the antenna and the RF front end. Return loss provides a good metric of the amount of signal power that is delivered to the antenna, whereas radiation efficiency of an antenna is the antenna's ability to radiate this signal power. The antenna could be very well matched to the RF front end (thus providing very good return loss) but may not have the capability to radiate that signal effectively.

Typically return loss is good when efficiency is good but this isn't true all the time. Why?

Total Antenna Efficiency (dB) = Radiation Efficiency (dB) + Mismatch Loss (dB)

Figure 9. *Comparison of return loss versus total antenna efficiency.*

The Importance of RON and COFF

Aperture tuning primarily uses tuner switches and tunable capacitors. The main figures of merit for these switches are ON state resistance (RON) and OFF state capacitance (COFF), as shown in Figure 10. For tunable capacitors, it is critical to have a wide range for tuning capacitance and a good Q factor. Selecting components with low RON is critical to keep the resistive loss in the system to a minimum.

RON and COFF significantly affect antenna efficiency. Decreasing RON can improve efficiency in both inductive and capacitive tuning by several dB (see Figure 11), with a correspondingly large impact on a handset's overall RF performance. Low COFF is similarly important.

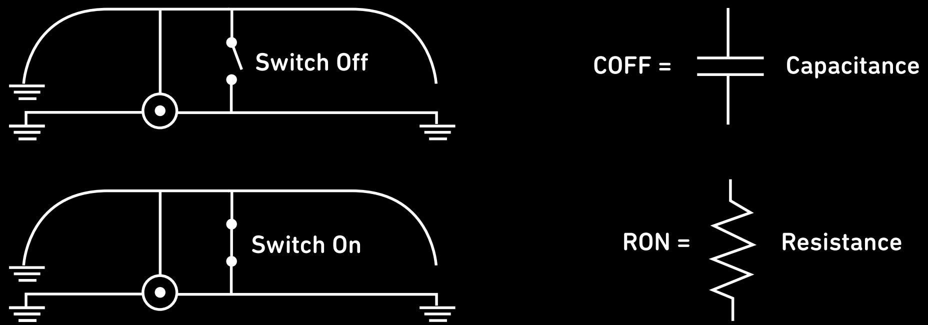


Figure 10. *COFF and RON.*

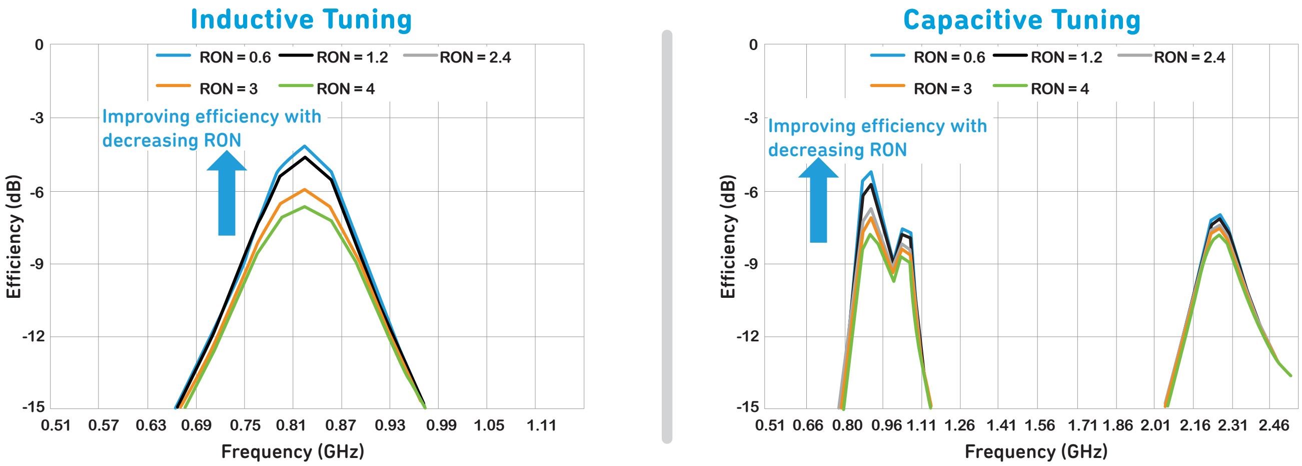


Figure 11. *Effect of decreasing RON on inductive and capacitive tuning efficiency.*

However, RON and COFF have differing impacts along the length of the antenna, depending on the voltage distribution. The impact of low RON is greatest where the voltage is low; the impact of COFF is greatest where the voltage is high. Strategic placement of switches with low RON or low COFF can be used to optimize tuning for different frequencies.

The parasitic capacitance from the OFF switch, COFF, can impact the resonant frequency and efficiency depending on the location on the antenna and the value of COFF. This is illustrated in Figure 12 using the COFF from an SPST switch and a planar inverted-F antenna (PIFA). The placement of the switch on the antenna is moved from left (lower impedance) to right (higher impedance) and the COFF of the switch varies from 0.1 pF to 0.4 pF. At the lower impedance region (left) of the antenna, the value of COFF has very little impact on loss and RF response. But as the switch location is moved toward the higher impedance region (right) of the antenna, the COFF of the SPST switch starts shifting the resonant frequency and causing higher loss. So, it is critical to select tuners with very low COFF when they are being placed in the high impedance regions of the antenna.

Apart from COFF of the tuner, performance can be degraded by parasitic capacitance due to traces and pads. For PIFA applications, the impact of COFF increases with distance from the feed/ground. As COFF is moved away from the tuner location, the RF response and switch loss efficiency change. Figure 12 shows how the location and COFF capacitance affect the RF response, creating more loss as both distance and capacitance increase.

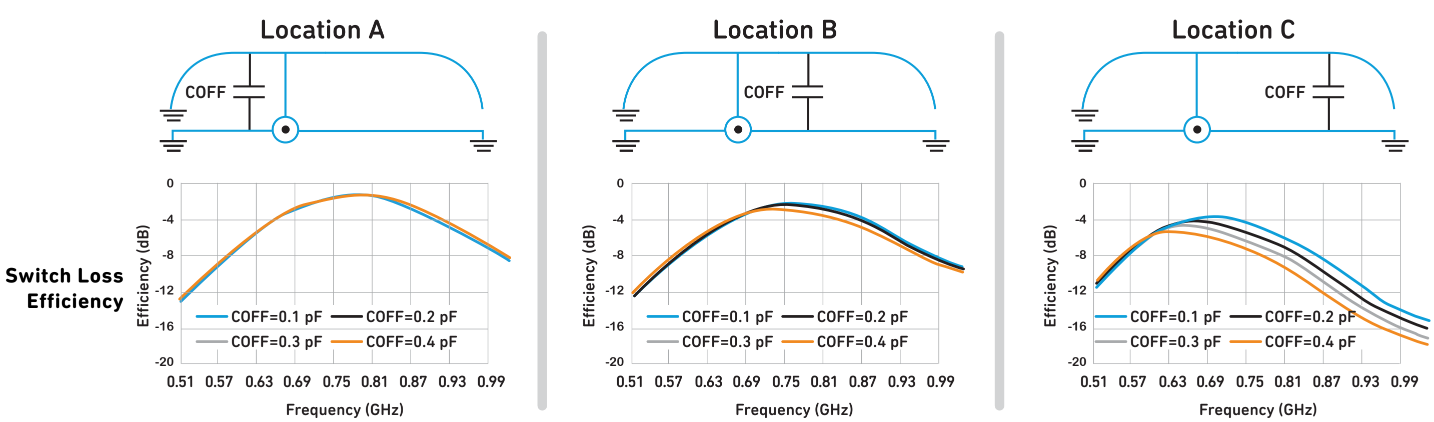
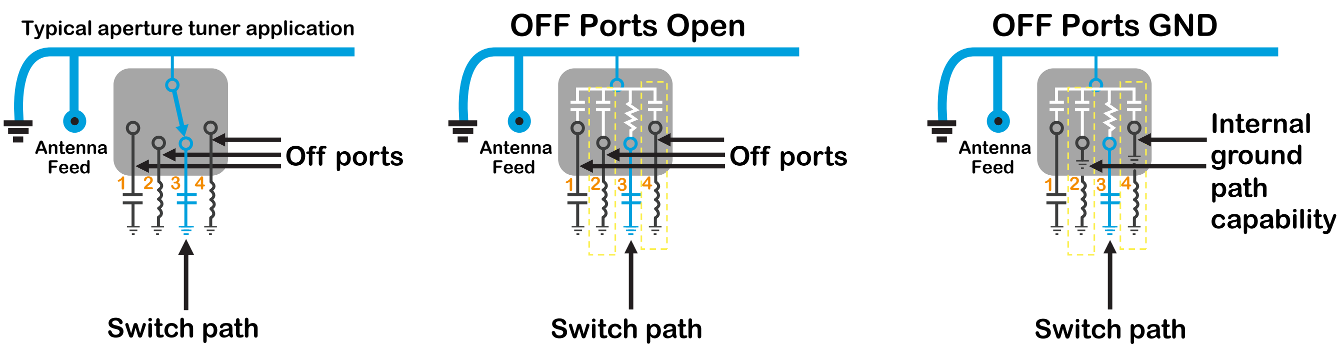


Figure 12. *COFF versus tuner location.*

Removing Unwanted Resonances

It's also important to address unwanted resonances, which can be caused by the COFF of the tuner switch in situations where a tuning inductor is connected to that RF port.

Figure 13 shows a typical aperture tuner application and what it looks like with and without internally grounded ports. An SP4T tuner switch is connected between an antenna and tuning elements to tune the antenna to different frequency bands. The antenna is connected to a capacitor via the RF3 port whereas the other three ports are switched OFF. Common aperture switches are capacitive in their OFF state and resistive in their ON state. Thus, in their OFF state like in RF1, RF2 and RF4, unwanted resonance can occur due to tuning inductor and OFF state capacitance (COFF). However, to suppress unwanted resonance, the RF2 and RF4 inductor OFF ports can be internally grounded using the switch, thus disconnecting tuning inductors from the resonance-causing circuit.



These unwanted resonances can distort the RF response and also reduce the isolation between antennas. As shown in the far right of Figure 13, tuner switches have the capability to connect RF ports to ground internally such that the external tuning inductors are disconnected from the circuit, thus eliminating the unwanted resonance.

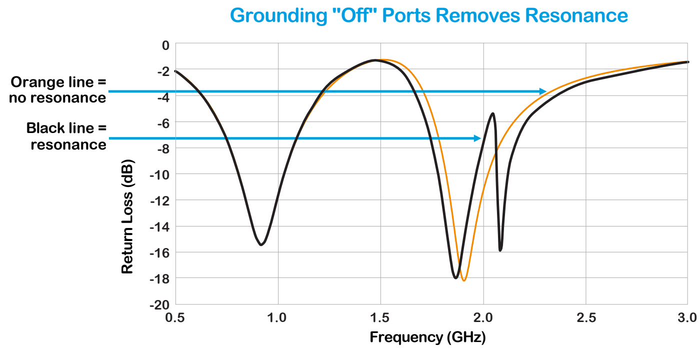


Figure 13. *Removing resonance using ground switch capability.*

Aperture Tuning for Carrier Aggregation

LTE operators worldwide are using carrier aggregation (CA) to provide higher data rates. CA combines two or more LTE carriers, often in different frequency bands, to deliver increased bandwidth. Due to the limited total number of antennas in handsets, this often means that a single antenna must communicate on two bands simultaneously.

Carefully placed aperture tuning switches can meet this requirement. As previously described, placing a tuning switch near the peak voltage of a resonant frequency has the greatest tuning effect on that frequency. Conversely, placing a tuner at the null voltage of a resonant frequency has little tuning effect. By positioning a switch so that it is close to the peak voltage for one resonant frequency but near the null of a second frequency, the first frequency can be tuned without impacting the second.

Figure 14 shows aperture tuning used to support the combination of Band 39 and Band 41, which is commonly used in China. Placing a switch near each frequency's peak voltage allows high-efficiency tuning of each band with minimal impact on the other band.

Antenna Switch Placement

Combination Tuning: B39 + B41

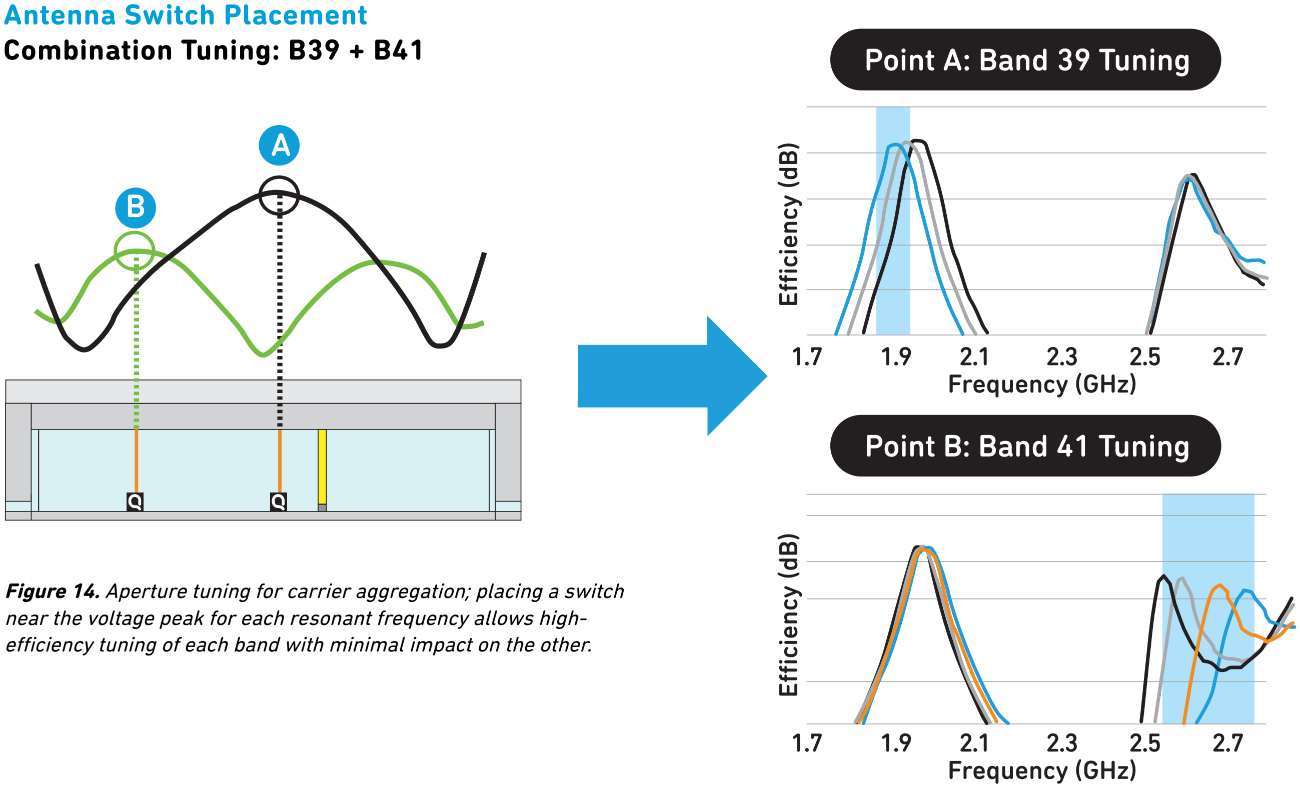


Figure 14. *Aperture tuning for carrier aggregation; placing a switch near the voltage peak for each resonant frequency allows high-efficiency tuning of each band with minimal impact on the other.*

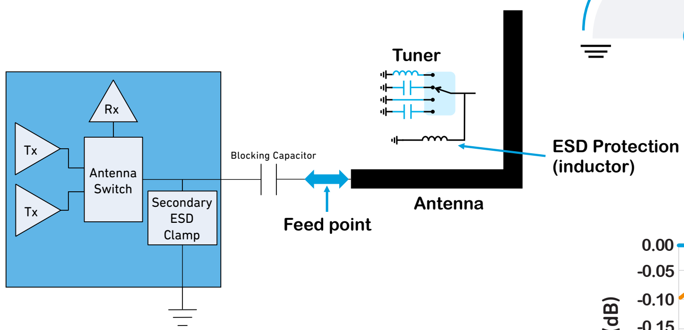
ESD Protection

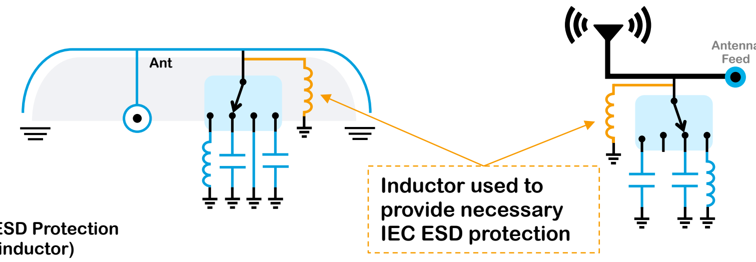
Mobile designers continue to face challenges when addressing electrostatic discharge (ESD) in mobile devices. A good design practice for ESD is to use a multifaceted, system-level approach – at the component level, during design and at final testing. Part of this approach encompasses designing and testing according to the International Electrotechnical Commission (IEC) ESD standard 61000-4-2. Recognized as the industry standard for end-product ESD testing and rating, IEC 61000-4-2 helps to determine the vulnerability of the system to external ESD events in the field.

We recommend using system-efficient ESD design (SEED) methodology when designing mobile ESD solutions. SEED is a co-design methodology that realizes both on-board and on-chip ESD protection. Using SEED in combination with modeling and simulation can help a designer analyze and achieve system-level ESD robustness.

We also recommend placing all ESD protection ahead of the aperture tuner, because this provides the best assurance the ESD event will be mitigated. Also, be sure to minimize trace lengths between ESD protective devices as these provide unwanted inductance.

When using inductors for ESD protection, choose low inductor values as they provide more protection. (See Figure 15.) But be aware that these inductors can affect insertion loss.





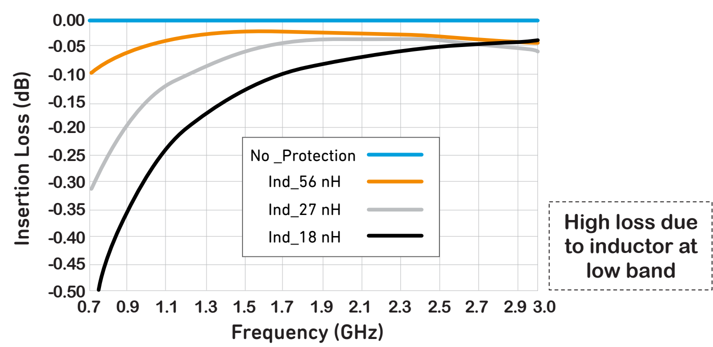
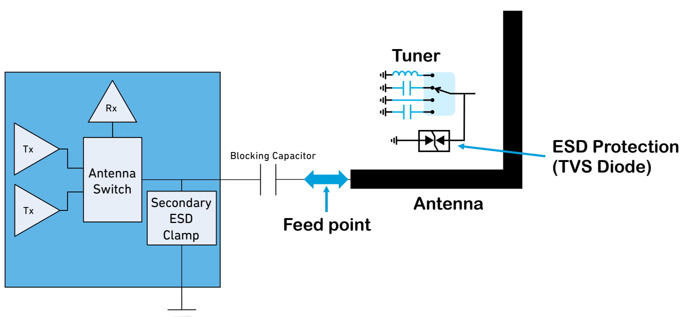


Figure 15. *IEC 61000-4-2 ESD protection with an inductor.*

Sometimes it works best to use transient voltage suppressor (TVS) diodes as the primary ESD clamps, as illustrated in Figure 16. Using TVS diodes that have small capacitances avoids de-tuning of the antenna input and creates less harmonic distortion. Under normal operation, the TVS diode is an open circuit. It provides a low impedance path to ground if an ESD event occurs. After the ESD event, the TVS returns to an open circuit.



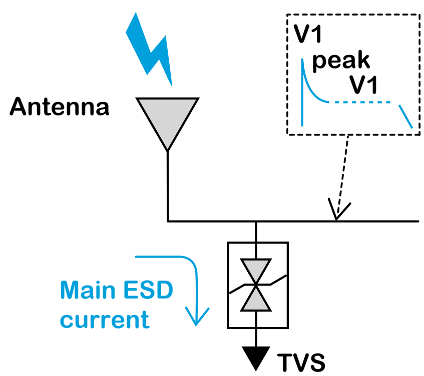


Figure 16. *IEC 61000-4-2 ESD protection with TVS diode.*

Go in Depth: SEED Methodology and ESD

Watch a step-by-step tutorial video and read our 3-part blog series about using SEED to overcome ESD challenges in mobile devices.

https://www.qorvo.com/design-hub/videos/system-efficient-esd-design-seed-methodology

Conclusion

Aperture tuning is essential in enabling today's smartphones to support the ever-growing range of frequency bands. It significantly increases Tx and Rx performance, overcoming the challenges caused by handset industrial design changes and making it possible to meet increasingly complex RF requirements. The effective implementation of aperture tuning requires considerable knowledge of how to apply the technology to optimize each application. The increasing number of antennas also means that aperture tuning solutions must be small to fit into the shrinking available space.

Qorvo is the recognized market leader in aperture tuning products, with deep experience in helping leading manufacturers use aperture tuning to meet their goals. Qorvo's extensive portfolio of highly compact solutions offers the combination of ultra-low COFF and low RON necessary to maximize performance.

About Qorvo

Qorvo (NASDAQ:QRVO) makes a better world possible by providing innovative RF solutions at the center of connectivity. We combine product and technology leadership, systems-level expertise and global manufacturing scale to quickly solve our customers' most complex technical challenges. Qorvo serves diverse high-growth segments of large global markets, including advanced wireless devices, wired and wireless networks and defense radar and communications. We also leverage our unique competitive strengths to advance 5G networks, cloud computing, the Internet of Things, and other emerging applications that expand the global framework interconnecting people, places and things.

For more information, please visit www.qorvo.com.

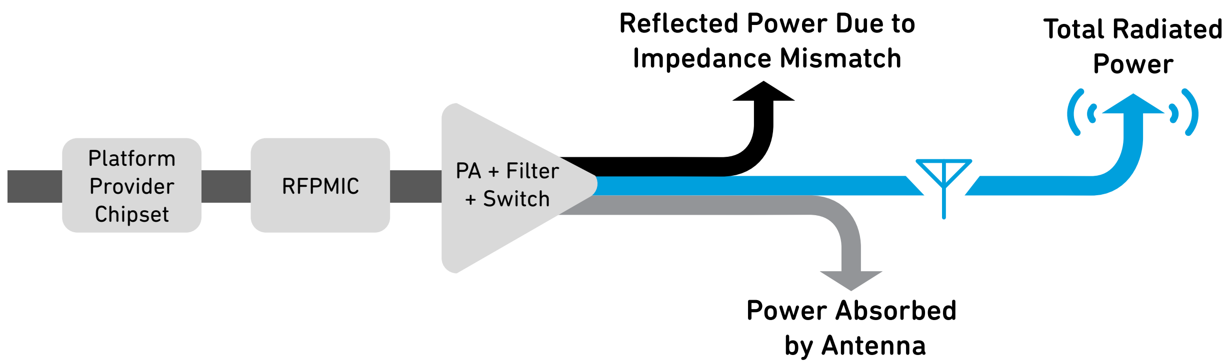
About the Author

Abhinay Kuchikulla is a senior marketing manager at Qorvo, leading the product strategy and direction for antenna tuners. Abhinay supports Qorvo with a strong technical background in RF design engineering, enabling him to understand customer problems and solve them effectively. He works to define new products and manage their development, bringing optimum solutions to the market on time and meeting customer's future RF requirements. Abhinay was awarded the Marketing Person of the Year Award in 2016 for outstanding achievement in growing Qorvo's tuner business. He received his Master's degrees from the University of Kansas in Electrical Engineering, 2004, and Engineering Management, 2013.

QORVO'S ANTENNA CONTROL SOLUTIONS PORTFOLIO

Improve System Efficiency and Reduce Complexity of the RF System

Multiple Portfolios Address Antenna Performance



Antenna Control

Aperture Tuner
Improve Total Antenna Efficiency

Impedance Tuner
Reduce Mismatch Loss

Antenna Selection

Antenna Selection
Switch to Optimum Antenna

Why Qorvo ACS

Best-in-class performance with low RON & COFF

Broad portfolio providing tuner for every application maximizing TRP/TIS

High quality and reliable supply chain

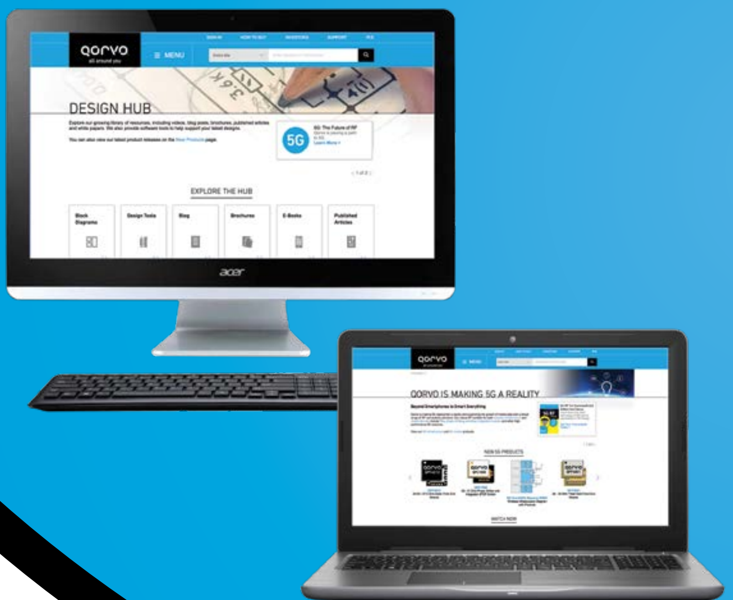
GLOSSARY OF TERMS

5G: fifth generation
ACS: antenna control solutions
ANT: antenna
B39: Band 39
B41: Band 41
CA: carrier aggregation
COFF: off capacitance
dB: decibel
DPDT: double pole, double throw
ESD: electrostatic discharge
GHz: gigahertz
GND: ground
GPS: global positioning system
HB: high band
IEC: International Electrotechnical Commission
LB: low band
LTE: long term evolution
MB: midband
MHz: megahertz
MIMO: multiple input/multiple output
mm: millimeter
nH: nanohenry
PA: power amplifier
PC: printed circuit
pF: picofarad
PIFA: planar inverted-F antenna
Q factor: quality factor
RF: radio frequency
RFFE: RF front end
RFPMIC: RF power management integrated circuit
RON: on resistance
Rx: receive
SEED: system-efficient ESD design
SP4T: single pole, four throw
SPST: single pole, single throw
TIS: total isotropic sensitivity
TRP: total radiated power
TVS: transient voltage suppressor
Tx: transmit

Qorvo is your smart RF partner in building tomorrow's connected world.

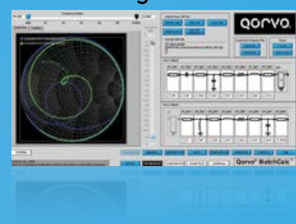
Check out a few helpful resources on our web.

Design Hub - Qorvo.com/Design-Hub



5G: The Future of RF - Qorvo.com/5G

MatchCalc™
RF Design Calculator



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