AN91445

Antenna Design Guide

Author: Gowrish B.
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AN91445 explains antenna design in simple terms and recommends two Cypress-tested PCB antennas that can be implemented at a very low cost for use with the Bluetooth Low Energy (BLE) solutions that are part of Cypress's PRoC™ and PSoC® family. The PRoC BLE and PSoC 4 BLE 2.4 GHz radio must be carefully matched to its antenna for optimum performance. It concludes by showing how to tune the antenna in the final product.

Contents

Introduction

The goal of this application note is to enable you to design an optimal antenna for your application with minimal time and resources. The antenna is a vital component in a wireless system. A well-designed antenna will help to optimize the performance of the PRoC BLE and PSoC 4 BLE radio in the final product.

The antenna can be considered as an energy translator. It converts electrical energy into electromagnetic waves for transmission and reconverts the electromagnetic waves into electrical energy on reception. Figure 1 gives a holistic view of a typical wireless system.

Figure 1. Typical Wireless System
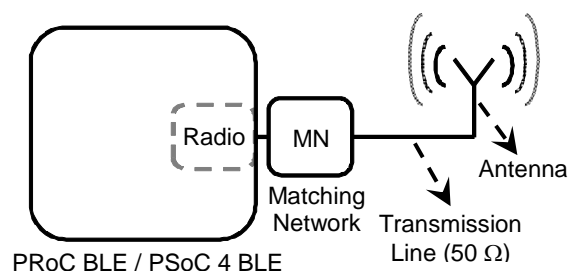
A well-designed antenna increases the operating range of the wireless product. The more power it can transmit from the radio, the larger the distance it can cover for a given packet error rate (PER). Other benefits are less obvious. For example, for a given range, a well-designed antenna radiates more power and thus has a higher margin for error (caused by interference or noise). This reduces the PER and improves the communication quality. The lower the PER (due to the higher margin for error), the fewer will be the retransmissions, thus saving battery energy.

Therefore, an optimal antenna design is important for low-energy applications. It is generally believed that antenna design is difficult because the antenna is sensitive to PCB size, nearby plastic casing, and other factors, that can detune it. This application note gives a step-by-step antenna design procedure to optimize the radio performance of a PRoC BLE or PSoC 4 BLE design.

Antenna Parameters

Following are some key antenna performance parameters, with an emphasis on physical significance.

- **Return loss:** Return loss of an antenna signifies how well the antenna is matched to the 50 Ω transmission line (TL). TL impedance is typically 50 Ω, although it could be a different value. The industry standard for commercial antennas and testing equipment is 50-Ω impedance, so it is most convenient to use this value.

  Return loss indicates how much of the incident power is reflected by the antenna due to mismatch (Equation 1). Ideally, the entire incident power is radiated without any reflection from the antenna.

  If the return loss is infinite, the antenna is said to be perfectly matched to the TL, as shown in Figure 2. S_{11} is the negation of return loss expressed in decibels. As a rule of thumb, a return loss ≥ 10 dB (equivalently, S_{11} ≤ −10 dB) is considered sufficient. Table 1 relates the return loss (dB) to the power reflected from the antenna (percent).

  Equation 1 $\quad Return\ Loss\ (dB) = 10 \log\left(\frac{P_{incident}}{P_{reflected}}\right)$
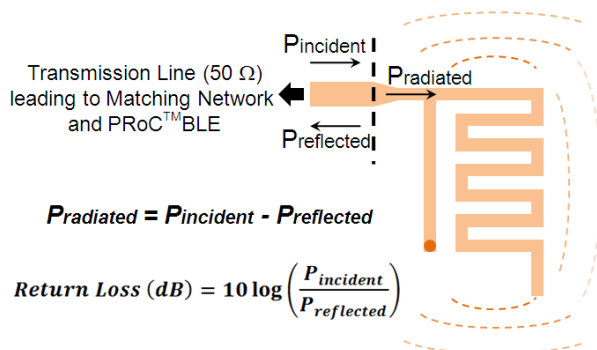
Figure 2. Return Loss

Table 1. Return Loss and Power Reflected From Antenna

S_{11} (dB)	Return Loss (dB)	$P_{reflected}$ / $P_{incident}$ (%)	$P_{radiated}$ / $P_{incident}$ (%)
−20	20	1	99
−10	10	10	90
−3	3	50	50
−1	1	79	21

- **Bandwidth:** Bandwidth indicates the frequency response of an antenna. It signifies how well the antenna is matched to the 50-Ω transmission line over the entire band of interest, that is, between 2.40 GHz and 2.48 GHz for BLE applications.

- **Radiation efficiency:** A portion of non-reflected power (Figure 2) gets dissipated as heat or as thermal loss in the antenna. Thermal loss is due to the dielectric loss in the FR4 substrate and the conductor loss in the copper trace. This information is characterized as radiation efficiency. A radiation efficiency of 100 percent indicates that all non-reflected power is radiated to air.

- **Radiation pattern:** Radiation pattern indicates the directional property of radiation, that is, which directions have more radiation and which have less. This information helps to orient the antenna properly.

- **Gain:** Gain gives information on radiation in the direction of interest, compared to the isotropic antenna, which radiates uniformly in all directions spherically. An analogy for the isotropic antenna is a point source of light, where the light intensity is equally spread in all directions spherically. However, most light sources (like most antennas) are directional, such as a flashlight.

These parameters can help you to use the recommended antennas for a specific custom application. Most often, in portable wireless consumer products, the preferred antenna is the PCB monopole and its variations. The variations include the popular inverted-F antenna (IFA—looks like an "F") and the meandered inverted-F antenna (MIFA—looks like a serpentine "F").

The benefits of IFA and MIFA are as follows:

- They are inexpensive, since they are a part of the PCB.

- They are easy to design. Tweaking the antenna length is relatively simple

- They offer good performance in the 150 MHz to 250 MHz bandwidth range.

Recommended PCB Antennas

Cypress recommends two PCB antennas for use with the PRoC BLE and PSoC 4 BLE to achieve optimal performance at 2.4 GHz: MIFA and IFA. MIFA is recommended for applications that require a minimum PCB area, like a wireless mouse, keyboard, presenter, and so on. IFA is recommended for applications where one of the antenna dimensions is required to be much shorter than the other, like a heart rate monitor. The following sections describe each antenna in detail.

## Meandered Inverted-F Antenna (MIFA)

The MIFA is a popular antenna widely used in human interface devices (HIDs), since it occupies a small PCB area. Cypress has designed a robust MIFA that offers excellent performance with a small form factor. The antenna size is 7.2 mm × 11.1 mm (that is, 284 mils × 437 mils), making it suitable for HID applications like a wireless mouse, keyboard, or presentation device. Figure 3 shows the layout details of the recommended MIFA, both top layer and bottom layer in a two-layer PCB. The antenna trace width is 20 mils throughout. The main parameter that would change, depending on the PCB stack spacing, is the value of "W," the RF trace (transmission line) width.

Figure 3. MIFA Layout

Top Layer (Antenna Layer)
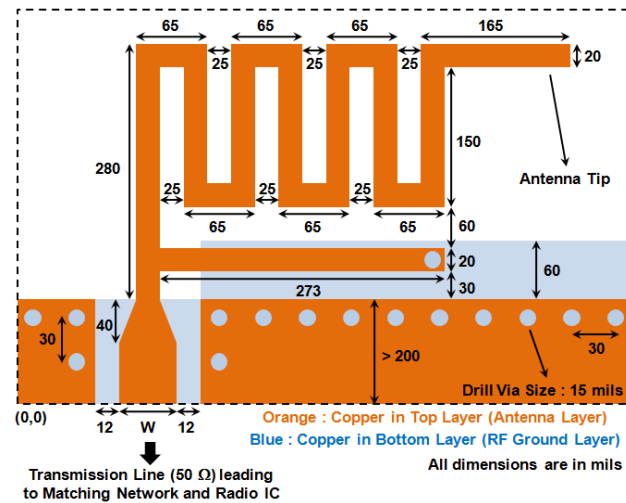
Bottom Layer (RF Ground Layer)
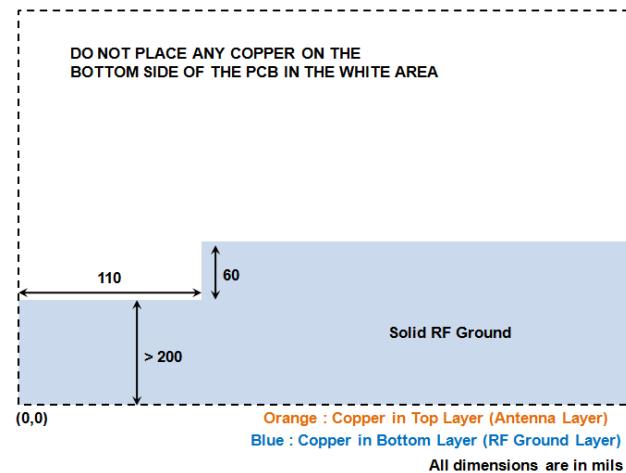
Note The Gerber and *.brd* files of MIFA for a FR4 PCB with 1.6-mm thickness are provided in the *AN91445.zip* file at www.cypress.com/go/AN91445.

Table 2 provides the "W" value for different PCB thicknesses between the top and bottom layers for a two-layer FR4 substrate (relative dielectric constant = 4.3). The top layer contains the antenna trace; the bottom layer is the immediate next layer containing the solid RF ground plane. The remaining PCB area of the bottom layer can be used as a signal ground plane (for the PSoC and other circuitry). Figure 4 relates PCB thickness to "W" for a typical two-layer PCB.

Table 2. Value of "W" for FR4 PCB: Thickness Between Antenna Layer and Adjacent RF Ground Layer

Thickness (mils)	W (mils)
60	65
50	59
40	52
30	44
20	33

Figure 4. Clarification of PCB Thickness

Figure 5 plots S_{11} of the MIFA when simulated in CST Microwave Studio, a widely used 3D electromagnetic simulator. As shown, the MIFA has a bandwidth ($S_{11} \leq -10$ dB) of 230 MHz around 2.44 GHz. This means that the reflection from the antenna is less than or equal to 10 percent over a span of 230 MHz around 2.44 GHz, which is sufficient for BLE applications.

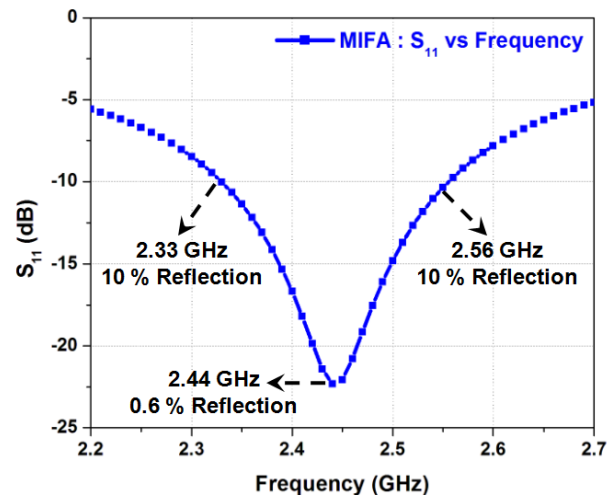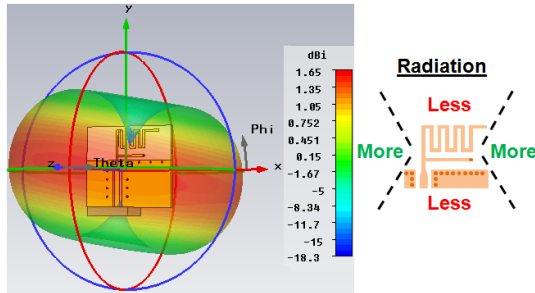Figure 5. S_{11} of the MIFA (Return Loss = $-S_{11}$)

Figure 6 shows the complete 3D radiation gain pattern of the MIFA at 2.44 GHz, where red indicates more radiation, and blue indicates less radiation. This information is helpful in placing the MIFA for custom applications to maximize radiation in the desired direction.
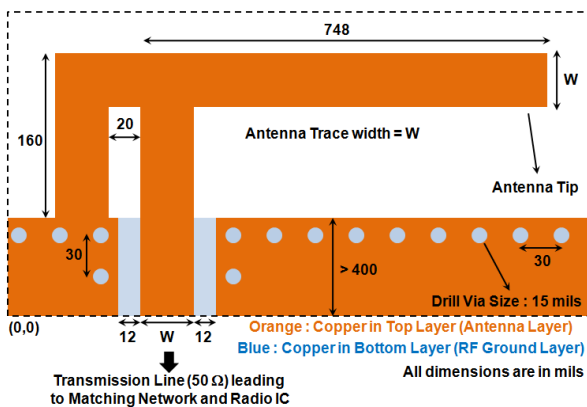
Figure 6. 3D Radiation Gain Pattern for MIFA

Inverted-F Antenna (IFA)

The IFA is recommended for applications in which one of the antenna dimensions is constrained, such as in a heart rate monitor. Figure 7 shows the layout details of the recommended IFA, both top layer and bottom layer in a two-layer PCB.

Figure 7. IFA Layout

Top Layer (Antenna Layer)

Bottom Layer (RF Ground Layer)
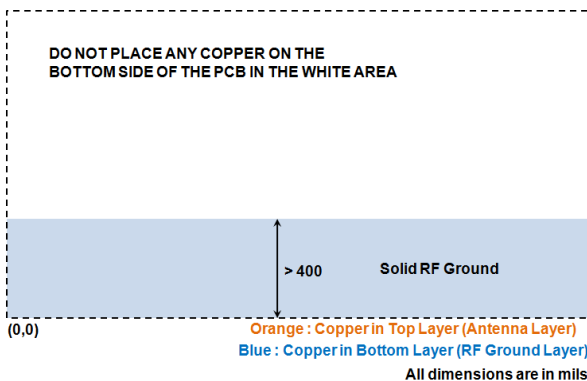
The Gerber file (as well as the *.brd* file) for an FR4 PCB with 1.6-mm thickness is provided in the *AN91445.zip* file at www.cypress.com/go/AN91445. The antenna trace width "W" is dependent on the PCB stack of the product. Table 3 provides the "W" value for different PCB thicknesses between the top layer (antenna layer) and bottom layer (adjacent RF ground layer) for an FR4 substrate (relative dielectric constant = 4.3). The top layer contains the antenna trace; the bottom layer is the immediate next layer containing the solid RF ground plane. The remaining PCB area of the bottom layer can be used as a signal ground plane (for the PSoC and other circuitry). Figure 8 relates PCB thickness to "W" for a typical two-layer PCB.

Table 3. Value of "W" for FR4 PCB: Thickness Between Antenna Layer and Adjacent RF Ground Layer

Thickness (mils)	W (mils)
60	65
50	59
40	52
30	44
20	33

Figure 8. Clarification of PCB Thickness

The IFA is designed with a size of 4 mm × 20.5 mm (that is, 157.5 mils × 807 mils) for an FR4 PCB with 1.6-mm thickness. The IFA has a larger aspect ratio (width to height) than the MIFA. The bandwidth ($S_{11} \leq -10$ dB) of the IFA is 220 MHz around 2.44 GHz, as shown in Figure 9.

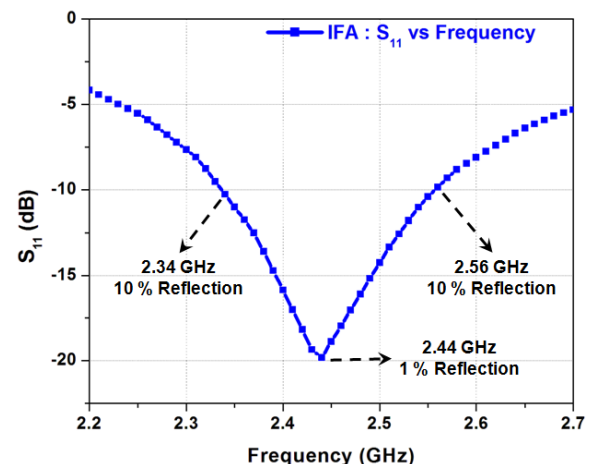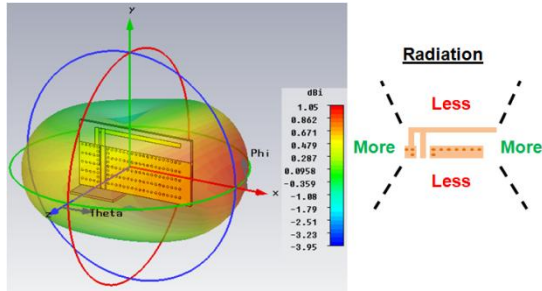Figure 9. S_{11} of the IFA (Return Loss = -S_{11})

Figure 10 shows the complete 3D radiation gain pattern of the IFA at 2.44 GHz, where red indicates more radiation, and blue indicates less radiation. This information is helpful in placing the IFA suitably for custom applications to maximize radiation in the desired direction.

Figure 10. 3D Radiation Gain Pattern for IFA

Chip Antennas

For niche applications like a Bluetooth dongle, where the PCB size is extremely small, chip antennas are a good solution (Figure 11). They are off-the-shelf antennas that take up minimal PCB area and offer reasonable performance. However, chip antennas increase the BOM and assembly expense, as they are external components that need to be purchased and assembled. Typically, the price of chip antennas ranges from 10 to 50 cents, depending on dimension and performance.

Figure 11. Chip Antenna

2450AT18B100E
Johanson Technology
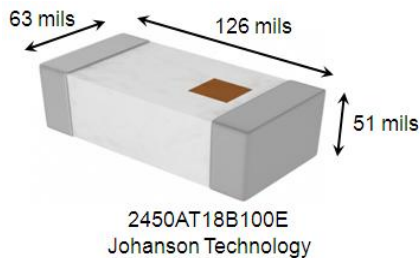
Another important factor to consider when using chip antennas is that they are sensitive to RF ground size. The manufacturer's recommendation must be followed. Unlike PCB antennas, chip antennas cannot be tuned by changing the antenna length. They require an additional matching network for antenna tuning, increasing the BOM expense even further.

Thus Cypress suggests chip antennas only for specialized applications that demand an extremely small PCB area like a nano Bluetooth dongle. For such applications, Cypress recommends the Johanson Technology 2450AT18B100E chip antenna, whose dimensions are 63 mils x 126 mils. For most applications, the recommended PCB antennas, either MIFA or IFA, serve the purpose. They are not only inexpensive but also offer excellent performance with a small form factor (small area).

Antenna Comparison

You can use Table 4 as a quick reference to select the appropriate antenna for the desired application.

Table 4. Comparison of MIFA, IFA, and Chip Antenna

Properties at 2.44 GHz	MIFA	IFA	Chip Antenna
Appearance			
Recommended Applications	Less Area (Mouse, Keyboard, Presenter)	Height Constrained (Heart Rate Monitor)	Extremely Small Area (Nano Dongle)
Dimensions (mm)	7.2 × 11.1	4 × 20.5	3.2 × 1.6
Dimensions (mils)	284 × 437	157.5 × 807	126 × 63
Gerber File	Web	Web	–
Cost (US$)	Nil	Nil	0.1–0.5
Bandwidth (MHz) ($S_{11} \leq -10$ dB)	230	220	230
Gain (dBi)	1.6	1.1	0.5
Length Tunability	Yes	Yes	No

Selecting the PCB Antenna

Follow these steps to design an antenna for your application.

1. Based on the application, select either MIFA or IFA using Table 4.
2. Pick and place the Gerber file (and the .brd file) of the selected antenna provided at www.cypress.com/go/AN91445.
3. Orient the antenna layout appropriately, depending on the radiation pattern required for the application. The 3D radiation plots in Figure 6 and Figure 10 are handy references.
4. One important variable in both MIFA and IFA is "W." Select the appropriate value for "W" from Table 2 or Table 3, depending on the PCB thickness between the antenna layer and the adjacent RF ground layer.
5. Increase the antenna tip length by 2 mm (80 mils), which will be tuned (as explained in Antenna Tuning).

The final step is to tune the antenna for optimal performance.

Antenna Tuning

In general, antennas used in consumer products are sensitive to PCB RF ground size and the product's plastic casing. The antenna can be modeled as an LC resonator whose resonant frequency decreases when either L (inductance) or C (capacitance) increases. A larger RF ground plane and plastic casing increase the effective capacitance and thus reduce the resonant frequency.

Cypress has done extensive research on the sensitivity of the antenna's resonant frequency to both RF ground plane size and nearby plastic casing. Through experimentation and measurements, Cypress has been able to quantify the issue of antenna sensitivity and has provided a simple and robust, yet effective solution to tune the antenna. The antenna tuning can be done with minimal time and resources by using the recommended antennas.

To evaluate antenna sensitivity to the size of the RF ground plane, experiments are carried out by fabricating antennas on various possible sizes of PCB. Figure 12 shows one example where MIFA is placed on a PCB with a different ground plane size. The PCB size varies from 20 mm x 20 mm to 50 mm x 50 mm. The curves show that larger RF ground planes decrease the resonant frequency.

Figure 12. Effect of PCB Ground Plane Size
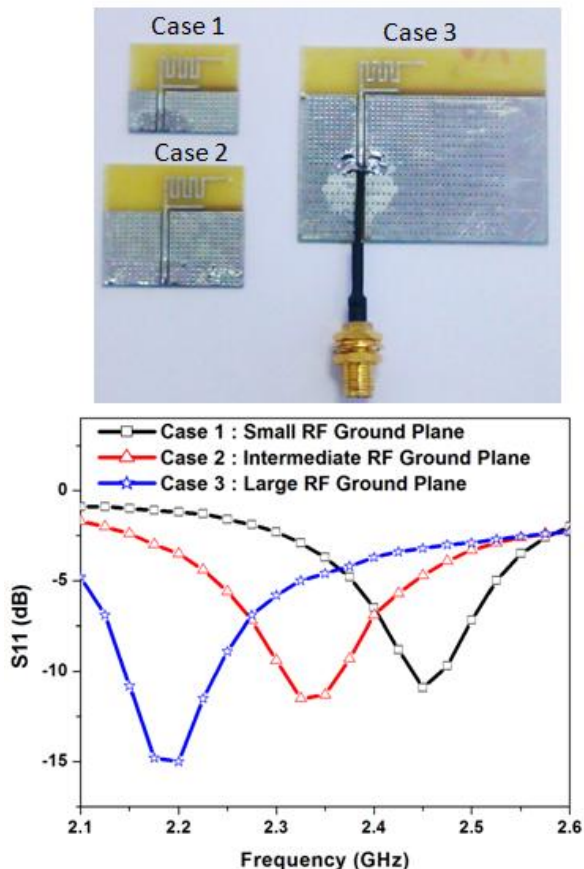
Similarly, to quantify antenna sensitivity to the product's plastic casing, experiments are performed on a wireless mouse, as shown in Figure 13. The Cypress MIFA is placed inside the plastic casing of the wireless mouse, and then measurements are made.

Figure 13. Effect of Plastic Casing
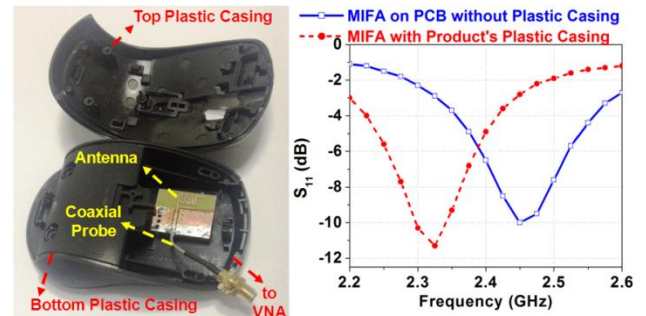
Both Figure 12 and Figure 13 reveal some important observations:

- The resonant frequency of the antenna (dip in S_{11}) shifts to a lower frequency as the size of the PCB ground plane increases, as shown in Figure 12.

- Similarly, resonance shifts to a lower frequency when the antenna is placed near plastic casing, as shown in Figure 13.

- The shift in resonant frequency is observed to be about 100 to 200 MHz

- The change in the value of the S_{11} dip is not as dominant as the shift in resonant frequency.

In conclusion, increasing the ground plane size and plastic casing tends to decrease the resonant frequency of the antenna approximately 100 MHz to 200 MHz.

The following sections explain how to restore the antenna resonance to the desired 2.4-GHz band.

Solution 1: Antenna Length Tuning

Tuning the resonant frequency of the antenna to the 2.44-GHz radio enables optimum Bluetooth performance. Observations regarding the sensitivity of the antenna reveal that a robust and effective solution is to tweak (change) the antenna length to correct for the shift in resonant frequency. Since the resonant frequency shifts towards a lower frequency, the only requirement is to reduce the antenna length and restore the resonance to 2.44 GHz. Reducing the antenna length shifts the resonance to a higher frequency. All that is required is a coaxial cable, a sharp blade, and a vector network analyzer (VNA).

Tweaking the PCB Antenna

Previously, you chose either the MIFA or the IFA, depending on the application, and oriented it suitably for maximum radiation in the desired direction. Also, you determined the value of "W," depending on the thickness between the antenna layer and the ground layer using Table 2 or Table 3. Then you deliberately increased the antenna length (either MIFA or IFA) by 2 mm (80 mils) for antenna tuning.

Follow these steps to tweak the antenna length to correct the resonant frequency shift.

1. Connect the coaxial probe to the PCB antenna feed, as shown in Figure 14.

2. Place the PCB back in the product casing and connect the SMA end of the probe to the VNA for S_{11} measurement.

3. Measure the S_{11} in decibels and determine the dip. It should be shifted to a lower frequency due to the PCB ground size and the product's casing. Make sure that the VNA is calibrated prior to measurement.

4. Start reducing the antenna length in small steps using a sharp blade, and keep measuring S_{11}. Gradually, the resonance should start shifting to a higher frequency. Figure 15 shows where to cut the antenna.

5. Repeat step 4 until the resonance shifts back to 2.44 GHz. At this point, the antenna is operating in the required band (2.4 GHz) for the entire final product, with the plastic casing present as well.

6. Measure the reduced antenna dimension and replicate this dimension for high-volume production.

Figure 14. Coaxial Probing
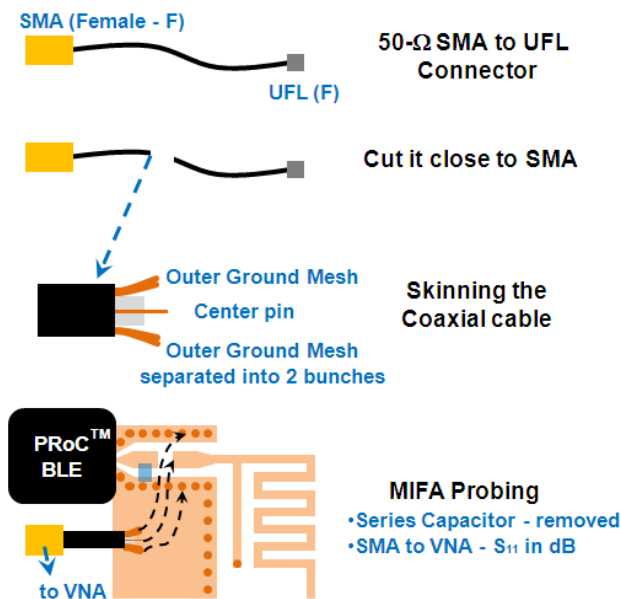
Figure 15 illustrates the previous steps for a wireless mouse case. The strength of antenna length tuning is that it is based on measurement of the final product in place, making it realistic. Plus, the solution is robust and takes minimal time, and the final product works without any additional matching network for the antenna.

Figure 15. Antenna Length Tuning
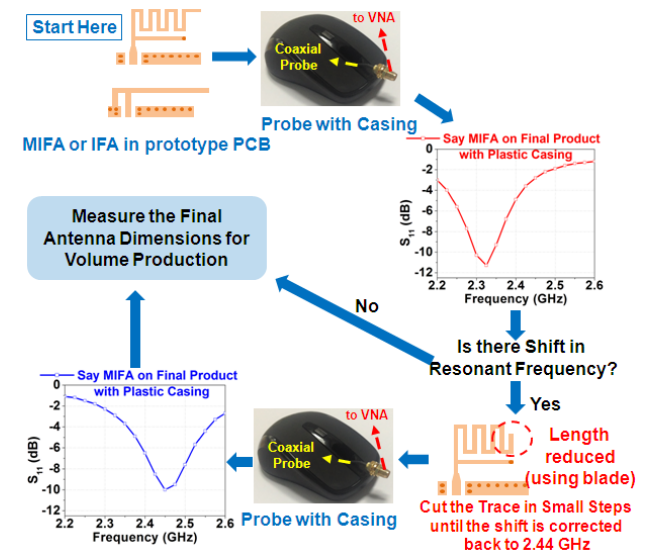
Solution 2: Antenna Matching Network

An alternative solution for correcting the shift of antenna resonant frequency is to use an additional lumped matching network for the antenna. This additional matching network matches the changed antenna impedance back to 50 Ω.
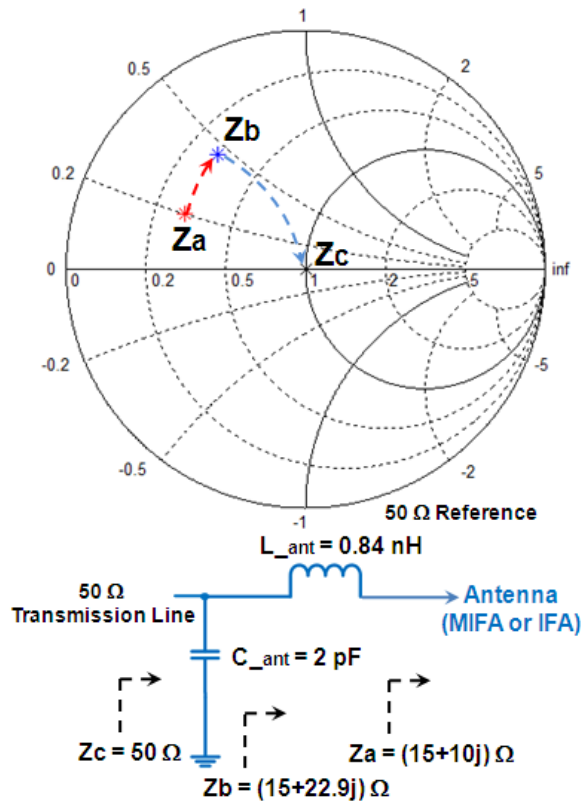
Designing the Antenna Matching Network

Follow these steps to design a matching network for the detuned antenna.

1. Measure the antenna impedance accurately at 2.44 GHz. It is important that the antenna impedance be measured on the final product, with all casing present.

2. Determine L (or Pi or T) lumped matching at the plane of reference to match it to 50 Ω. The matching network can be designed using analytical equations, the Smith chart, or free software (see Appendix C: References).

3. Generally, the L matching network would be sufficient. Prefer 0402-sized lumped components and confirm whether the antenna is matched to 50 Ω again by probing and measuring the impedance with the designed matching network.

4. Append this additional antenna lumped matching network for volume production.

Figure 16 depicts the matching network design using the Smith chart.

Figure 16. Antenna Matching Network Design Using Smith Chart

Solution 1 Versus Solution 2

The antenna matching network (solution 2) adds BOM and assembly cost. Also, determining the antenna impedance with the final casing present is complicated. Moreover, the VNA needs to be calibrated with custom coaxial probe calibrations like Short-Open-Load (SOL) or Through-Reflect-Line (TRL). In addition to increasing the product cost and design time, this solution is prone to error, particularly when determining the antenna impedance in the first step. Inaccurate antenna impedance makes the entire procedure of solution 2 a difficult exercise.

Therefore, antenna length tuning (solution 1) is the preferred solution. It addresses the issue of antenna resonant frequency shift in a simple and effective way. Additionally, as experimentally observed, there is little change in the depth of S_{11}, with the main effect being a resonant frequency shift. Therefore, tweaking the antenna length is sufficient for most designs. Cypress can provide support to help you tune your antenna with the VNA.

The antenna matching network (solution 2) is required only when the S_{11} depth itself is drastically shifted to a higher value (for example, from –10 dB to –3 dB). Table 5 shows a detailed comparison of both solutions.

Table 5. Solution 1 (Antenna Length Tuning) Versus Solution 2 (Antenna Matching Network)

Properties	Antenna Length Tuning	Antenna Matching Network
Method of correcting frequency shift	Length tweaking	Additional matching network
BOM and assembly cost	No change	Increases
Involvement and RF expertise	Bare minimum	Detailed RF skill essential
When to use	S_{11} shifts in frequency No change in depth of S_{11}	S_{11} depth significantly changes to higher value (for example, from –10 dB to –3 dB)
Preferred solution	Yes	No

Summary

This application note described how you can easily design the optimal antenna for a custom product using the PRoC BLE and PSoC 4 BLE radio and the Cypress-recommended PCB antenna, either MIFA or IFA, by following these steps.

1. Choose either MIFA or IFA for the application and orient the antenna suitably. Choose the value of "W" for the PCB stack (thickness between the antenna layer and the adjacent RF ground layer immediately below).

2. Deliberately increase the antenna length by 2 mm (80 mils).

3. Probe the antenna using a coaxial probe, with the final casing present.

4. Cut the antenna length in small steps to restore the antenna resonance to 2.44 GHz, if it is shifted.

Appendix A: 7-Step Design has a quick reference for designing an optimal antenna.

About the Author

Name:	Gowrish B.
Title:	Systems Engineer
Background:	Gowrish B. received his M. Tech degree in Radio Frequency Design and Technology from Indian Institute of Technology Delhi (IIT Delhi) in 2013. Currently, he is working at Cypress Semiconductor Technology India Pvt. Ltd., Bangalore, India. He is a member of the IEEE Microwave Theory and Techniques Society (MTTS) and Antennas and Propagation Society (APS).
Contact:	gowb@cypress.com

Appendix A: 7-Step Design

You can use the following seven steps for designing an optimal antenna for your custom product.

Step	Design Flow	Description	Reference
1	Selection	Select the type of antenna (MIFA or IFA) in the prototype PCB.	Table 4 – Page 5
2	Orientation	Orient the chosen antenna suitably for the given application.	MIFA: Figure 6 – Page 4 IFA: Figure 10 – Page 5
3	Determine "W"	Determine the trace width (W) based on PCB thickness between the antenna layer and the adjacent RF ground layer	MIFA: Table 2 – Page 3 IFA: Table 3 – Page 4
4	Elongation	Deliberately increase the antenna tip length by 2 mm to enable antenna tuning.	-
5	Probe	Perform coaxial probing with the final product casing.	Figure 14 – Page 7
6	Tune	Monitor S_{11} in VNA and keep cutting the antenna length in small steps (until resonance is back to 2.44 GHz).	Figure 15 – Page 7
7	Measure	Measure the new dimension of the tuned antenna and use it in volume production.	-

Appendix B: Checklist

You can use the checklist in Table 6 while designing the antenna to track your progress.

Table 6. Checklist for Optimal Antenna Design

Check	Step
	Decide on the PCB antenna type based on the application at hand: MIFA or IFA. See Table 4.
	Note the chosen antenna layout (dimension). Gerber files can be obtained from www.cypress.com/go/AN91445. For MIFA, see Figure 3. For IFA, see Figure 7.
	Orient the antenna suitably for maximum radiation in the desired direction. For MIFA, see Figure 6. For IFA, see Figure 10.
	Determine the "W" value to be used in the antenna layout, based on the PCB thickness (stack). See Table 2 or Table 3.
	Increase the antenna tip length by 2 mm (80 mils).
	Ensure that the coaxial probe is ready. See Figure 14.
	Remove the series capacitor for probing and solder the probe. See Figure 14.
	Calibrate the VNA (one port calibration is sufficient).
	Measure S_{11} (dB) with the complete product casing present. See Figure 15.
	Reduce the antenna length by cutting the antenna tip until S_{11} (dip) shifts to the desired 2.44 GHz with the complete product casing present. See Figure 15.
	Note the final dimension of the antenna (after tweaking or cutting), and use it for volume production.

Appendix C: References

The following references provide further detailed information.

Antenna Basics

■ Constantine A. Balanis, *Antenna Theory: Analysis and Design*, 3rd edition. Wiley - Interscience, 2005 (Chapters 2 and 5).

Antenna Sensitivity

■ Arkko, A.T., "Effect of ground plane size on the free-space performance of a mobile handset PIFA antenna," *Antennas and Propagation, 2003. (ICAP 2003). Twelfth International Conference on (Conf. Publ. No. 491)*, vol.1, pp. 316–319, 31 March–3 April 2003.

■ Gowrish B., Basu A., Deepak J., Settu D., Koul S. K., "Novel Mechanical Reconfigurable PCB Antenna for 2.4 GHz Wireless Consumer Product – Minimizing Time to Market," IEEE, Asia Pacific Conference on Antenna and Propagation 2014, July, Harbin China.

■ Gowrish B., Basu A., "Casing and Hand Effect on PCB Antenna in 2.4 GHz Wireless Mouse – A Measurement based Characterization," IEEE, Asia Pacific Conference on Antenna and Propagation 2014, July, Harbin China.

Smith Chart Basics

■ David M. Pozar, "Microwave Engineering," 4th edition, Wiley, 2011 (Chapters 2, 4, and 5).

■ Christopher Bowick, John Blyler, Cheryl Ajluni, "RF Circuit Design," 2nd edition, Newnes, 2007 (Chapter 4).

Useful Free Online Software

■ Transmission line calculator: Grounded CPW (air gap = 12 mil, ε_r = 4.3 for FR4):
www1.sphere.ne.jp/i-lab/ilab/tool/cpw_g_e.htm

■ Smith Chart based matching: L or Pi matching:
http://cgi.www.telestrian.co.uk/cgi-bin/www.telestrian.co.uk/smiths.pl

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