Qualcomm Technologies International, Ltd.

Antenna Design Guidelines for Wireless Earbuds

Application Note

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1 Practical antenna design approach for in-ear applications

This document describes the challenges of designing an antenna for in-ear applications using Bluetooth in the ISM band (2.4 GHz – 2.483 GHz). It includes descriptions of the main effects caused by the proximity of the body, on-body propagation, and discusses practical antenna design approaches to overcome the challenges.

Explanation of antenna theory concepts is not included. References are included for more technical information on this topic.

1.1 On-body communications

On-body communications are those in which most of the radio channel is on the surface of the body and both antennas are placed within close proximity of the body. TrueWireless Stereo (TWS) requires two different radio links to be established, both classified as on-body communications:

- Ear-to-Ear (E2E): Radio link between the two earbuds
- Ear-to-Pocket (E2P): Radio link from one of the earbuds to the phone. In the worst case scenario, the phone is in the hip pocket opposite to the earbud acting as the TWS primary.

NOTE: Refer to *Body-Centric Wireless Communications* for a detailed description of what constitutes on-body communications.

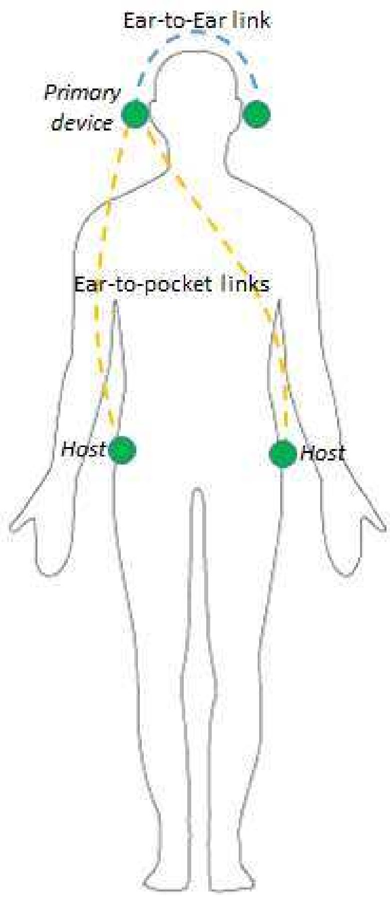

Figure 1-1 Ear-to-Ear and Ear-to-Pocket links

1.1.1 The body effect

At high frequencies, such as the Bluetooth operational band, the human body has a high relative permittivity (~50 F/m). As a result, electromagnetic waves through the body suffer a high level of absorption. Figure 1-2 shows the absolute value of the E-field plotted on 2D plane for one transmitting earbud.

NOTE: The Ear-to-Ear link is non-line-of-sight.

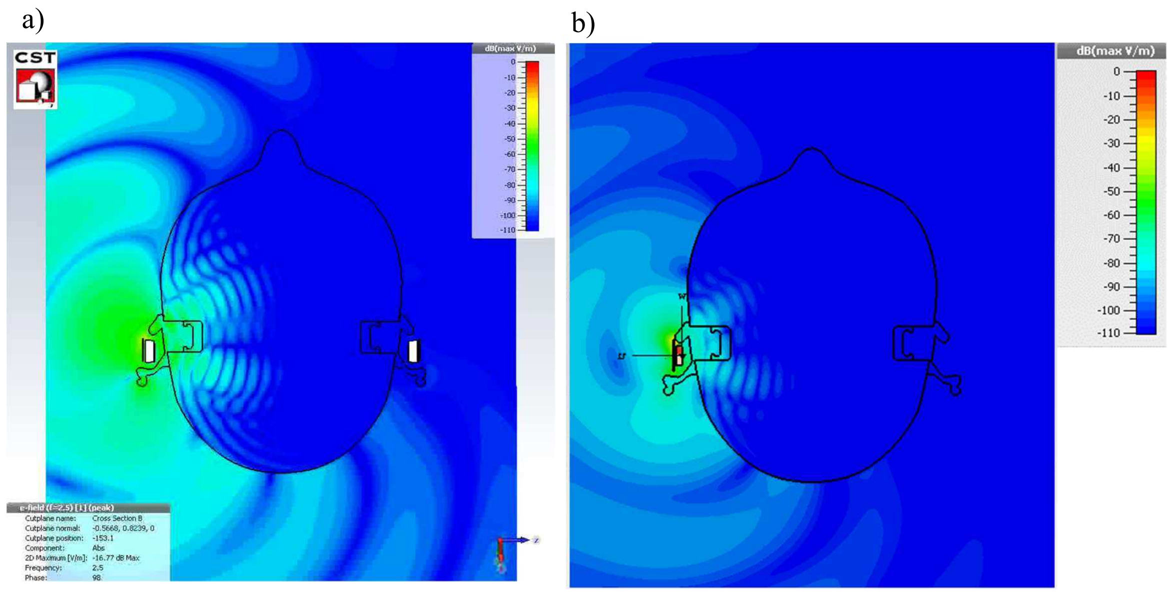

Figure 1-2 Comparison of absolute E-field around the head when E-field is polarized in a plane a) perpendicular and b) tangential to the head

Figure 1-2 shows that that the wave fronts within the skull are closer together as a result of the higher permittivity. The signal does not propagate through the head to the other ear as it is totally absorbed by the tissue within the head.

Therefore, the only way for a radio wave in the ISM band to propagate in on-body networks is around the body surface. Investigations have demonstrated that the so-called *creeping waves* propagation causes the least attenuation in on-body communications. The main requirement to efficiently excite creeping waves is to create currents perpendicular to the body surface. For reference see:

- *P. S. Hall and Y. Hao, Body-Centric Wireless communications, Artech House, 2013.*
- *L. Akhoondzadeh-Asl, Y. Nechayev and P. S. Hall, "Surface and creeping waves excitation by body-worn antennas," in Loughborough Antennas & Propagation Conference, Loughborough , 2010.*
- *S. H. Kvist, S. Özden, K. Jakobsen and J.Thaysen, "Improvement of the ear-to-ear path gain at 2.45 GHz using parasitic antenna element," in European Conference on Antennas and Propagation (EUCAP), Prague, 2012.*
- *S. H. Kvist, P. F. Medina, J. Thaysen and K. B. Jakobsen, "On-body and off-body 2.45 GHz MIMO communications for hearing instrument applications," in EuCAP, 2013.*
- *S. H. Kvist, J. Thaysen and K. B. Jakobsen, "Polarization of unbalanced antennas for ear-to-ear on-body communications at 2.45 GHz," in Loughborough Antennas & Propagation Conference, Loughborough, 2011.*

Figure 1-2 a) shows that a much stronger E-fields reaches the opposite ear compared to Figure 1-2 b).

These details must to be taken into account when designing an antenna for in-ear applications. Section 1.2 contains details that can help designers to design an antenna for E2E and E2P links.

1.2 Antenna design for in-ear applications

In-ear devices are small and there is typically insufficient space to fit a balanced antenna.

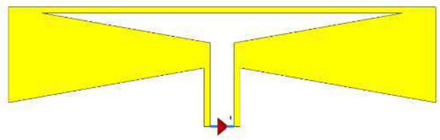

Figure 1-3 Folded dipole antenna

Therefore, an unbalanced and asymmetric antenna approach is used. The most common designs include monopoles, inverted-F antennas (IFA) or antennas using parasitic elements.

An unbalanced antenna design implies that currents are not zero at the RF port. This requires the use of a conductive layer with a similar size to the antenna element to compensate the RF currents. This extended element is known as the ground plane, which for an in-ear device is the PCB with all the sensors, tracks and components.

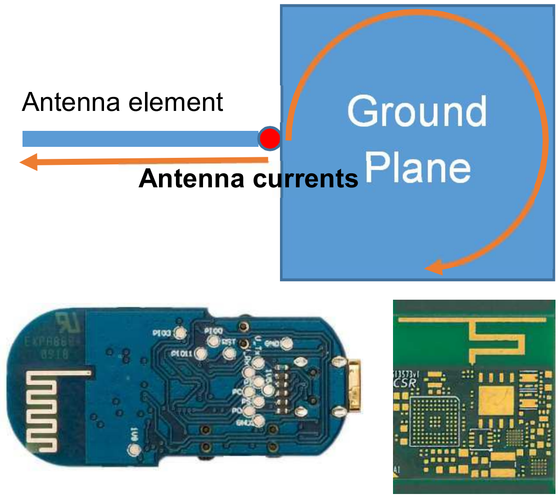

Figure 1-4 Graphical and real examples of an antenna element and PCB

The designer needs to understand that the ground is not really a ground, but one of the antenna arms of an asymmetric dipole. See *Antenna Design for Mobile Devices* for further reference. The antenna system is formed by the antenna element and the PCB, and also other components such as the battery and even loudspeaker wires. In fact, all RF currents around these components contribute to the radiation pattern, impedance and gain/loss of the antenna. For further reference see:

- *Antenna Theory Analysis and Design*
- *Integrating an Antenna into a Product Application Note*

1.2.1 Antenna and PCB size

It is important to keep in mind that for each antenna type there is a boundary that regulates its size and performance. Refer to the *Antenna Design for Mobile Devices* for details.

A quick way to estimate the size of an antenna system is to calculate the wavelength. In the simplest designs the antenna element is formed by a track on a PCB. The most common PCB construction uses FR-4 laminate as insulator and for mechanical support (relative permittivity ~4.3@2.45 GHz). For the Bluetooth frequencies (2.4-2.48 GHz) the following general rules apply:

- Antenna element:
  - For an unbalanced antenna the element should have length of quarter of the wavelength (λ/4). At the Bluetooth frequencies this is around 15 mm including the dielectric effect.
    - $\lambda = \frac{c}{f*\sqrt{\varepsilon_r}} = \frac{3*10^8}{2.45*10^9*\sqrt{4.3}} = 0.059\ m;$

      Where:

      c = speed of light (m/s)

      f = frequency (Hz)

      ε_r = relative permittivity.
  - $\text{Antenna lenght} = \frac{\lambda}{4} = 0.0147m$

  This calculation can be used as a starting point for length of the antenna element. The proximity of the body will most likely cause impedance detuning. In general the antenna length will need to be reduced by a couple of millimeters to compensate for this effect.
- The PCB should have a similar size to the antenna element, for a square ground plane its vertical length should be a quarter of the wavelength (15 mm including the dielectric effect in Bluetooth applications).

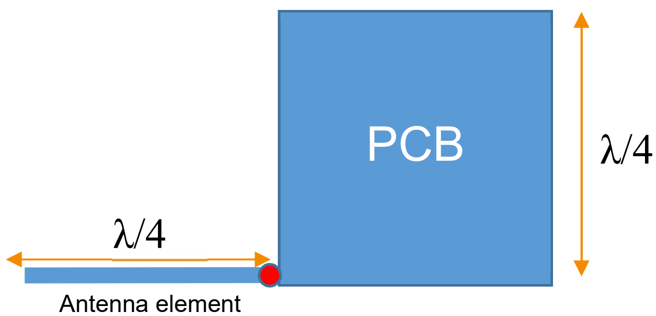

Figure 1-5 Antenna element and PCB size

Fitting a straight antenna element and a PCB ground plane of this size into an earbud represents a challenge. Miniaturizing techniques such as bending, shrinking or the use of dielectric materials with higher permittivity have to be used. While this has the advantage of fitting an antenna into a small area, it also has the disadvantage of reducing the overall antenna radiation performance. The result is limited bandwidth and low antenna efficiency (refer to *Antenna Theory Analysis and Design*).

It is also important to remember that the RF components, sensors, tracks, and vias hollow the PCB layers affecting antenna performance. For small Bluetooth devices, the ground layer is typically not a perfect solid plane, see Figure 1-6.

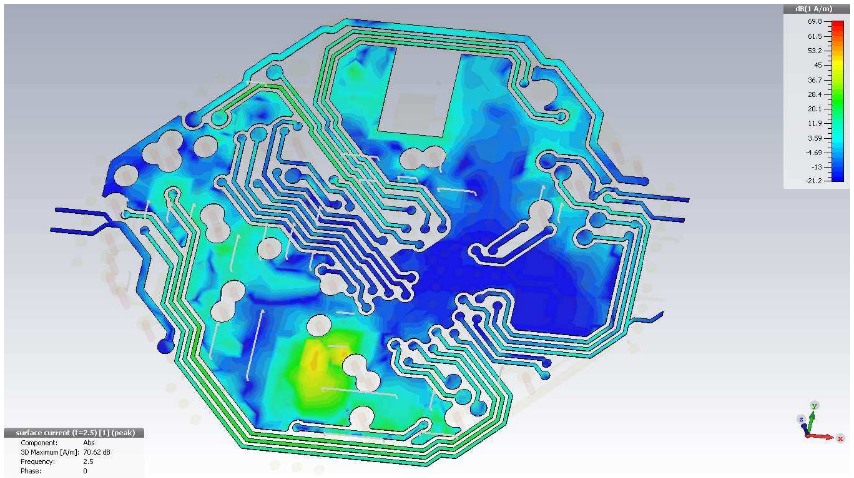

Figure 1-6 Realistic ground layer in a PCB design.

1.2.2 Antenna polarization

Antenna polarization is major factor in on-body wireless communications. For best performance the excited Electric Field (E-Field) should be polarized perpendicular to the surface of the head. For reference see:

- *Polarization of unbalanced antennas for ear-to-ear on-body communications at 2.45 GHz*
- *Investigation of the ear-to-ear radio propagation channel*
- *Influence on the ear-to-ear link loss from heterogeneous head phantom variations*
- *Measurement and characterization of the path loss for ear-to-ear wireless communication*

The performance of a hypothetical earbud can be simulated using a monopole antenna oriented as per Figure 1-7.

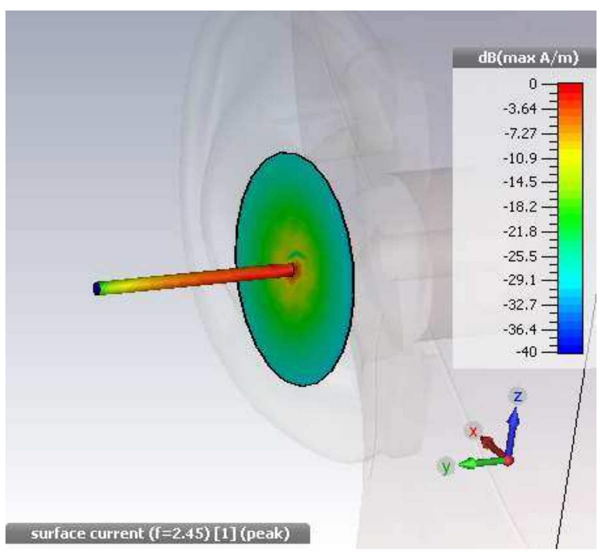

Figure 1-7 Currents in a monopole oriented perpendicular to the surface of the head

With two such antennas in the model, it is possible to plot the magnitude of S21, see Figure 1-8. With two ~0 dBi monopole antennas the path loss of the creeping wave is around 46 dB.

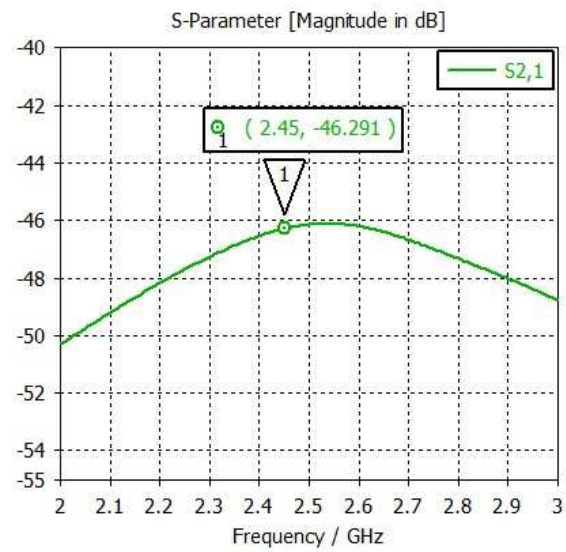

Figure 1-8 Ear-to-Ear S21 magnitude with two monopole antennas

With two realistic in-ear antennas (loss of about –10 dBi) with correct polarisation the magnitude of S21 drops to around –64 dB, see Figure 1-9.

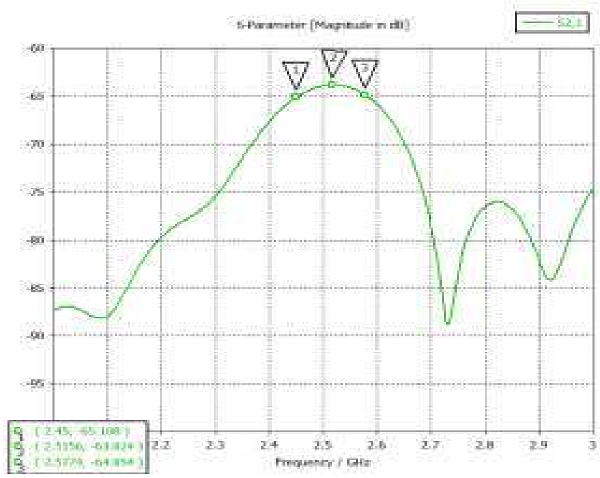

Figure 1-9 Ear-to-Ear S21 magnitude with two realistic in-ear antennas

NOTE: These results use only one model of a head of a fixed size. In practice varying skin conductivity and head size give different results. Neck length has also been reported as a factor in some academic publications as shoulders can act as reflectors.

1.2.3 Practical antenna design

The antenna should be designed in such way that RF currents are polarized perpendicular to the head surface. This enhances the launching of creeping waves and improves the radio link around the body.

1.2.3.1 Antenna RF currents and voltage

To achieve this, it is important to understand how RF current and voltage vary across the length of a straight metal wire. Figure 1-10 shows this variation over a wavelength.

NOTE: Both current and voltage vary between minimum and maximum every half of a wavelength with a phase difference of quarter of a wavelength.

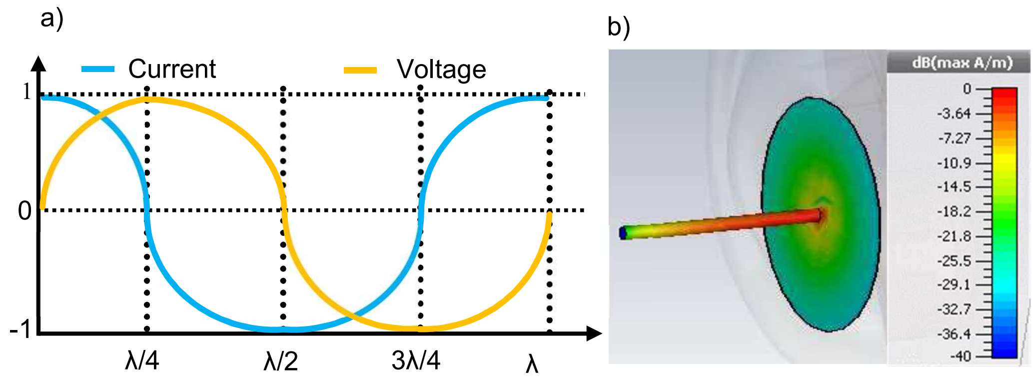

Figure 1-10 a) RF current and voltage variation across a length of a conductor; b) Currents in a λ/4 monopole.

With the antenna element the length of a quarter of a wavelength the area of highest current is located right next to the feed point. The voltage is minimum at that point and maximum at the end of the antenna element. This can be seen in Figure 1-10 b) in which the feed point is at the centre of the circular ground plane.

1.2.3.2 Printed circuit board

Regardless of the overall shape, the most common earbud designs use either a single rigid PCB or two rigid PCBs joined with a flexible bridge.

One piece PCB

One piece PCB designs use a single rigid PCB unit to place the antenna system as well as the rest of the RF components. The PCB is typically mounted on top of the battery and positioned parallel to the surface of the head.

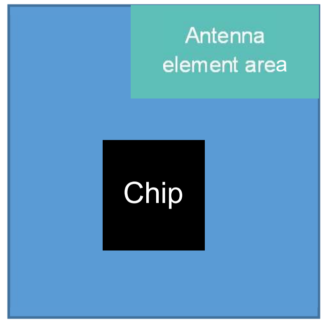

Figure 1-11 Single PCB

QTIL do not recommend single PCB constructions as this design tends to place the antenna currents parallel to the surface of the head. This results in high attenuation of electromagnetic wave propagating around the body and reduces the quality of any on-body or off-body link.

However, single PCB designs can be improved. One possible option is to detach the antenna element from the rigid PCB and provide room inside the earbud for a λ/4 antenna element. The element has to connect perpendicularly to the PCB, but may be bent inside the earbud to limit the height of the design.

A few considerations to follow during the antenna design are:

1. Antenna placement:

   The aim is to reduce the body effect, to do this the design needs to place the antenna element as far away from the body as possible, see Figure 1-12.

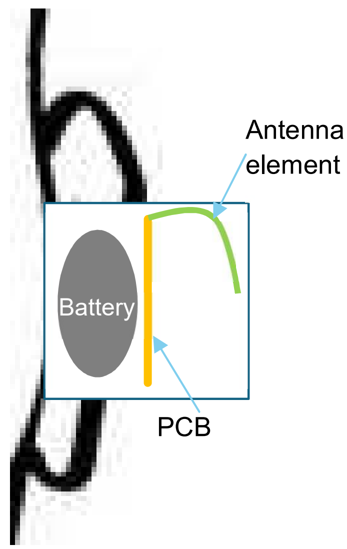

Figure 1-12 Antenna placed away from the battery and the body

2. The bending of the antenna should be such that the high voltage areas are sufficiently far away from the ground plane and the battery.

   The high voltage area is located towards the end of the antenna. This part of the antenna should have the maximum clearance. At least 5 mm or more is advisable. See Figure 1-13.

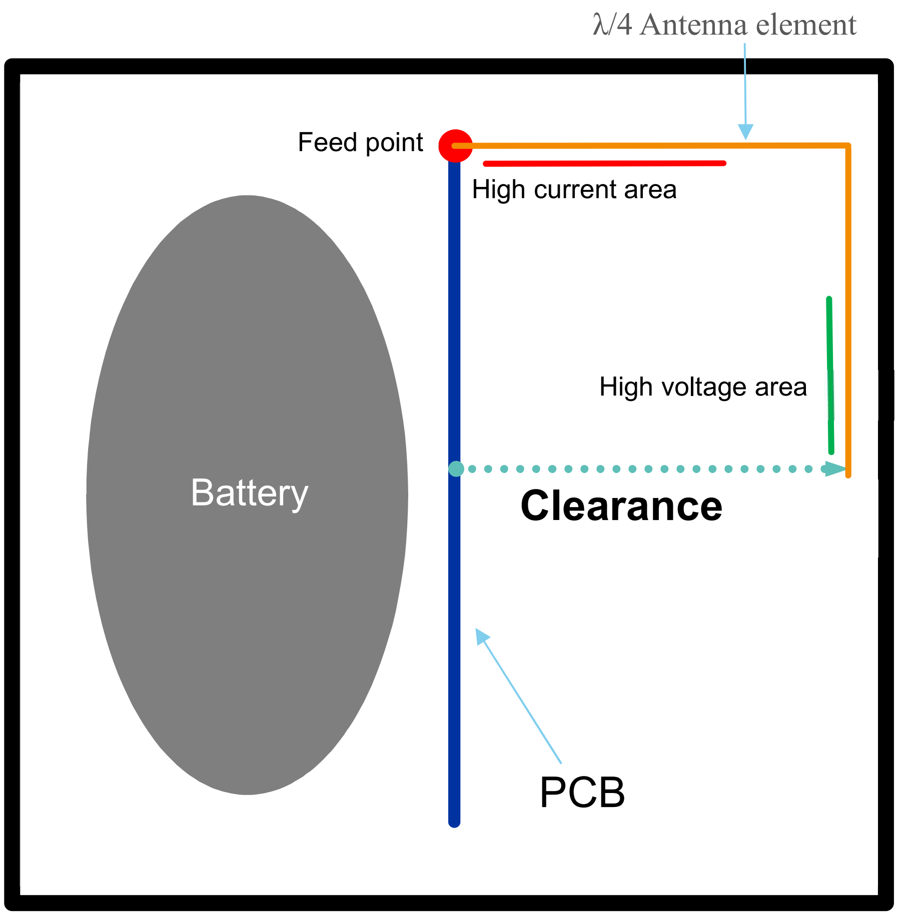

Figure 1-13 View of PCB, battery and antenna.

3. Antenna feed location and matching network

   The RF port of the chip and the matching network should be placed as close as possible to the antenna element.

4. High RF currents

   On-body communications improve when the E-field is excited in a plane perpendicular to the surface of the body. Figure 1-13 shows the high current area of the antenna element oriented perpendicular to the head surface.

A single PCB design increases the overall size of the earbud as additional space is required for the antenna.

Two piece PCB

The two piece PCB approach uses the flexi-rigid PCB technology. The battery is mounted between the two rigid PCB parts.

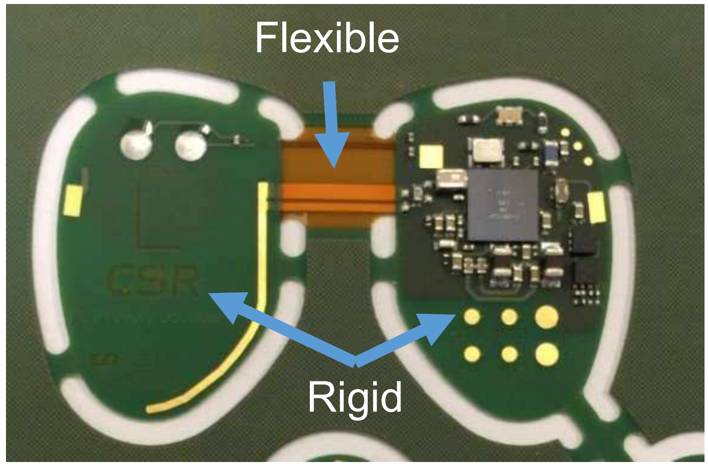

Figure 1-14 Flexi-rigid PCB

The antenna design for two piece PCBs is the same as for single piece PCBs. The design should provide clearance between the antenna and the battery and place the high RF currents of the antenna element perpendicular to the surface of the head.

Figure 1-15 shows the antenna to battery clearance. It is important to provide at least a 5 mm gap.

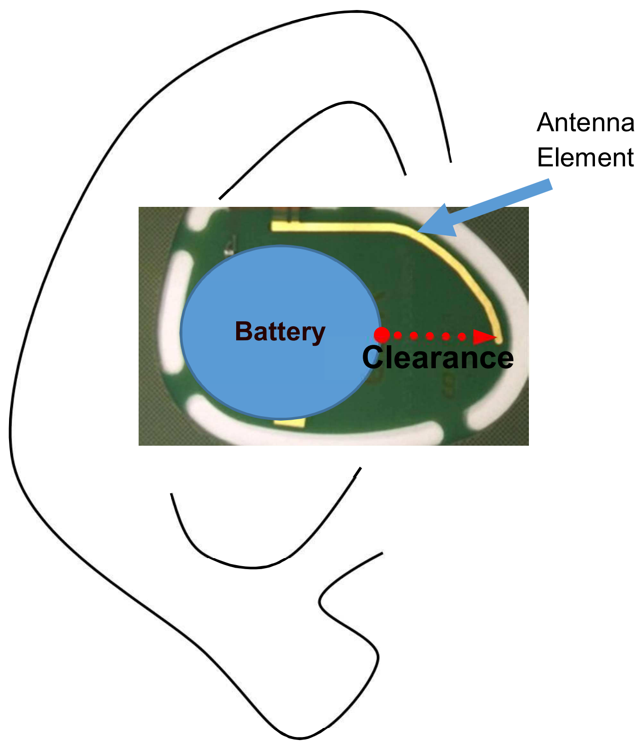

Figure 1-15 Side view of ear and antenna system.

The design takes advantage of the flexible PCB bridge to locate the high current area of the antenna element perpendicular to the head. The feed point and matching network is located as close to the bridge as possible, see Figure 1-16.

a) Outer side **b) Inner side**

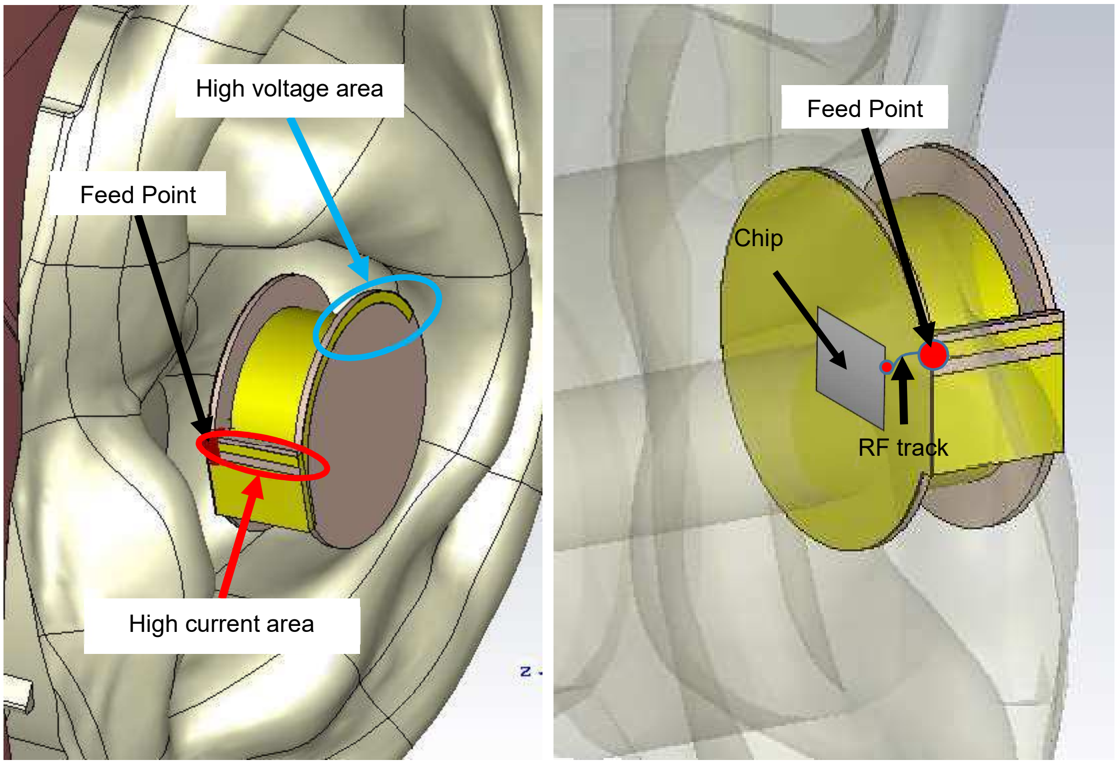

Figure 1-16 a) Location of the high current area in the ear; b) Location of the chip in the ear

1.2.3.3 PCB mirroring

The antenna system performance is also related to its position in the ear. Different antenna positions in the ear lead to different coupling to the head. This implies that a single PCB design cannot be used in both left and right earbuds as the antenna position would be different in the left and right ear, see Figure 1-17. To avoid this problem, it is important that the left and right devices are mirror images of each other, see Figure 1-18.

NOTE: When it is not possible to use mirror image PCBs, QTIL recommends that the device with the best radiation performance is used as the TWS primary (the device which connects to the phone).

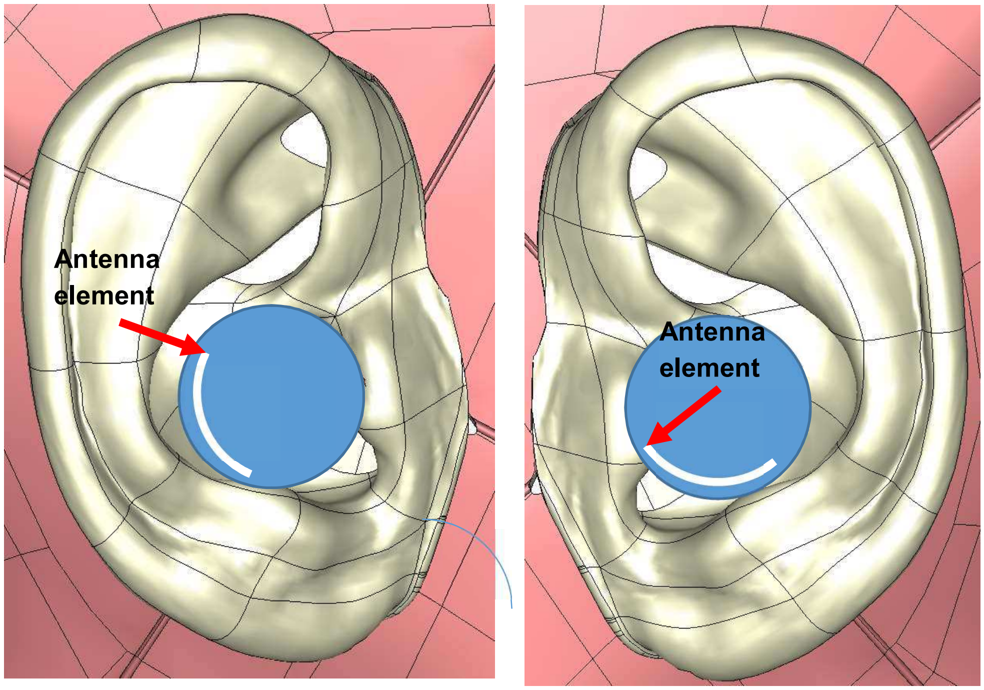

Figure 1-17 The antenna element is in a different position on each side when the PCB designs are identical.

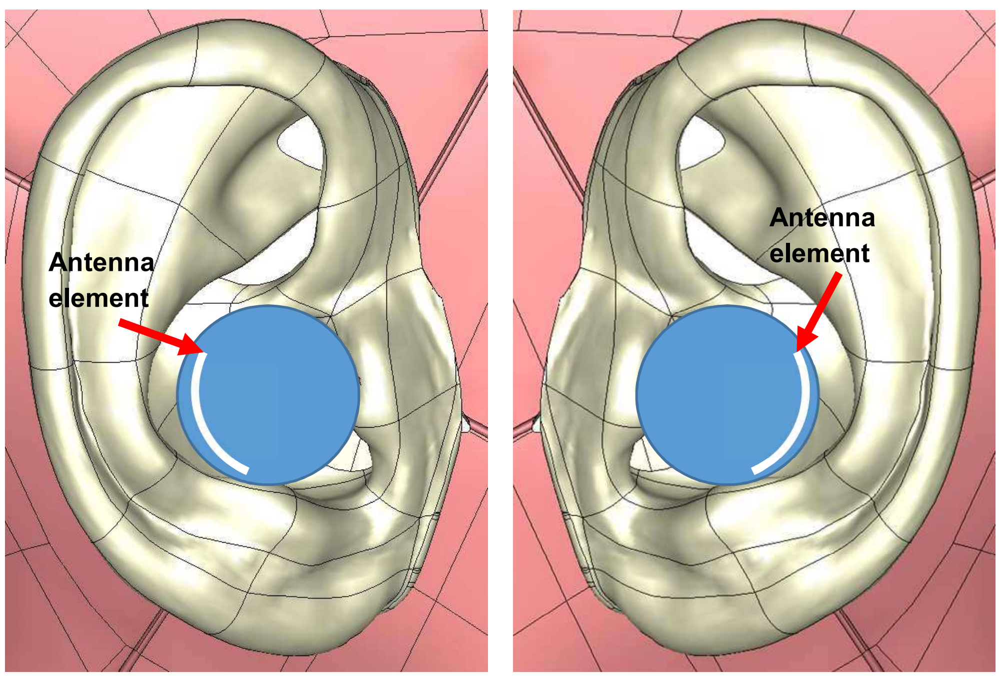

Figure 1-18 Both antennas are placed in the same position in the ear when the PCB designs are mirror image of one another

1.2.3.4 Antenna matching

Antenna matching is covered in more detail in *Integrating an Antenna into a Product*. Any antenna connected to a radio or a transmission line has to have the same characteristic impedance as the radio or transmission line.

Some antenna types can be designed to have the correct characteristic impedance (50 Ω), using an optimizer, others require a matching network.

NOTE: It is useful to include a PI matching network on the PCB close to the antenna. A PI matching network can support a number of different topologies. See Figure 1-19.

Impedance matching requires a network analyzer and manipulation of complex impedances around a Smith Chart. To maximize RF performance, it is essential that antenna matching is executed. This is particularly important for small antennas that are already bandwidth constrained, and for those designs whose impedance changes significantly when put near conductors, dielectrics and the human body.

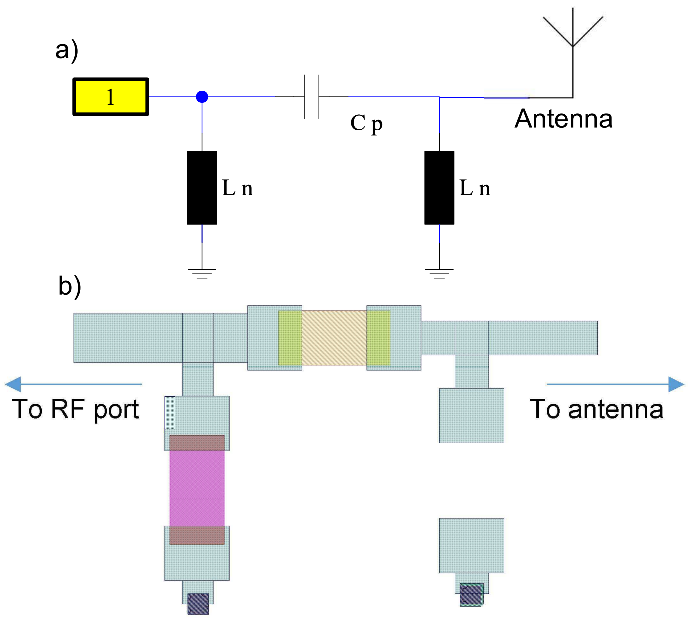

Figure 1-19 a) Schematic; b) PCB layout view of a PI matching network

To measure the antenna impedance, a network analyzer must be connected to the input of the matching network. This means temporarily disconnecting the radio from the matching network.

A short length of micro coaxial cable needs to be soldered in place. The shield of the coaxial cable must be connected to a ground point very near to the matching network.

NOTE: *Integrating an Antenna into a Product* describes this process in more detail.

There is doubt as to whether the impedance of the antenna, when measured, is the same as that when it is reconnected to the radio. This is because the currents flowing in the cable are no longer returning to the signal port that the radio sees.

The only way to confirm that the antenna has been correctly matched is to perform radiated power and radiated receiver sensitivity measurements to confirm antenna gain and frequency response flatness (a mismatched antenna often has a power slope across the band).

1.2.3.5 Radiation pattern

For an antenna within an earbud, the radiation pattern is affected by the tissues and bone within the human head. The RF currents within the antenna elements dictate the 3D field pattern. When an antenna design orients the RF currents as described in previous sections, it is expected that the resulting radiation pattern in free space will be similar to that of a monopole.

NOTE: Figure 1-20 shows that the direction of the radiated power is perpendicular to the monopole axis.

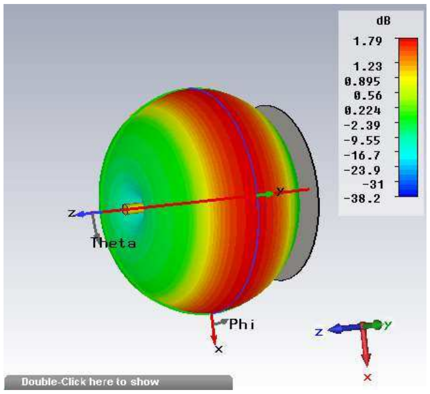

Figure 1-20 Radiation pattern of a monopole antenna in free space at 2.45 GHz

When placing an antenna with a monopole-like radiation pattern in the ear, the radiation pattern is disturbed. Figure 1-21 shows that the radiated power is distributed between the front and back of the head and a null can be observed in the direction away from the head.

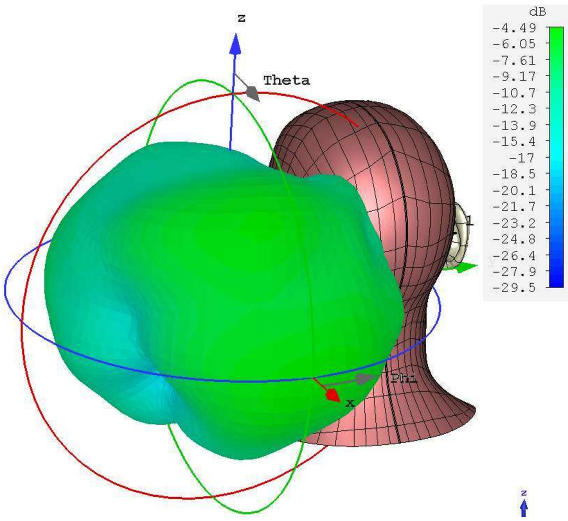

Figure 1-21 Radiation pattern of an antenna placed in the ear

It is important to note that the back of the head is the shortest path between the ears around the head. It is important to focus the radiated energy in that direction.

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