Application Note AN058

Antenna Selection Guide

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Keywords

- *Antenna*
- *Radiation Pattern*
- *Bandwidth*
- *Reflection*
- *Anechoic Chamber*
- *Impedance*
- *Gain*
- *Directivity*
- *2.4 GHz*
- *868/915 MHz*

1 Introduction

This application note describes important parameters to consider when deciding what kind of antenna to use in a short range device (SRD) application.

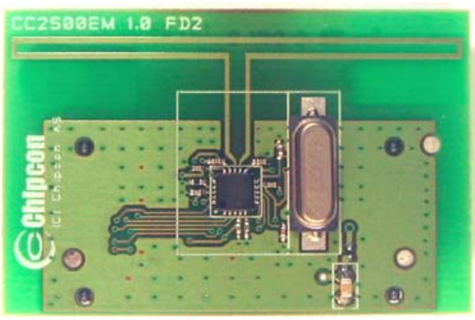
Important antenna parameters, different antenna types, design aspects and techniques for characterizing antennas are presented. Radiation pattern, gain, impedance matching, bandwidth, size and cost are some of the parameters discussed in this document.

Antenna theory and practical measurement are also covered.

In addition different antenna types are presented, with their pros and cons. All of the antenna reference designs available on www.ti.com/lpw are presented.

The last section in this document contains references to additional antenna resources such as literature, applicable EM simulation tools and a list of antenna manufacturer and consultants.

Correct choice of antenna will improve system performance and reduce the cost.



PCB Antenna

Chip Antenna

Whip Antenna

Figure 1. Different Antenna Solutions

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2 Abbreviations

AN	Application Note
CW	Carrier Wave
DB	Demonstration Board
DN	Design Note
DUT	Device Under Test
EIRP	Effective Isotropic Radiated Power
EM	Electro Magnetic
EM	Evaluation Module
IFA	Inverted F Antenna
IP	Intellectual Property
ISM	Industrial, Scientific, Medical
LOS	Line of Sight
MIFA	Meandered Inverted F Antenna
PCB	Printed Circuit Board
RF	Radio Frequency
SRD	Short Range Device
TI	Texas Instruments
TTM	Time To Market
VSWR	Voltage Standing Wave Ratio

3 Brief Antenna Theory

The antenna is a key component for reaching the maximum distance in a wireless communication system. The purpose of an antenna is to provide transmission of data electromagnetically in free space:

- Transform electrical signals into RF electromagnetic waves, propagating into free space (transmit mode)

- Transform RF electromagnetic waves into electrical signals (receive mode)

3.1 Wavelength Calculations for Dipole in Free Space

For the same output power, sensitivity and antenna gain; reducing the frequency by a factor of two doubles the range (line of sight). Lowering the operating frequency also means that the antenna increases in size. When choosing the operating frequency for a radio design, the available board space must also accommodate the antenna. So the choice of antenna, and size available should be considered at an early stage in the design.

$$\lambda \text{ meters} = \frac{2.99792458\text{E8 m/sec}}{f\ (\text{GHz})}$$

Table 1. Wavelength Equation

Frequency	λ / 4 (cm)	λ / 4 (inch)	λ (cm)	λ (inch)
2.4 GHz	3.05	1.204	12.236	4.81
915 MHz	8.19	3.22	32.76	12.89
868 MHz	8.63	3.39	34.5	13.59
433 MHz	17.3	6.77	69.2	27.1
27 MHz	277.58	109.2	1110.3	437.1

Table 2. Various Wavelengths for Several Frequency Ranges

3.2 Antenna Considerations

There are a numerous issues to consider when selecting the antenna:

- PCB materials and antenna placement
- Multi-path returns between in TX and RX
- Ground planes for ¼ wavelength antennas
- Undesired magnetic fields on PCB
- Mismatch from device to antenna
- Objects that alter or disrupt Line of Sight (LOS)
- Antenna gain characteristics
- Antenna bandwidth and efficiency

3.3 Friis Transmission Equation

Friis equation is the primary math model to predicting point to point communication links. This is the very elementary equation and has been expanded to include height of antenna above ground and difference in TX and RX antennas. The formula is very accurate once all the constants have been entered. Please refer to [36] for further information concerning "Range Measurements in an Open Field Environment".

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi R} \right)^2$$

Equation 1. Friis Transmission Equation

λ = Wavelength in Meters
P_r = Received Power in dBm
P_t = Transmit Power in dBm
G_t = Transmit Antenna Gain in dBi
G_r = Receive Antenna Gain in dBi
R = Distance between Antennas in Meters

Friis equation is the primary math model to predicting point to point communication links. This is the very elementary equation and has been expanded to include height of antenna above ground and difference in TX and RX antennas.

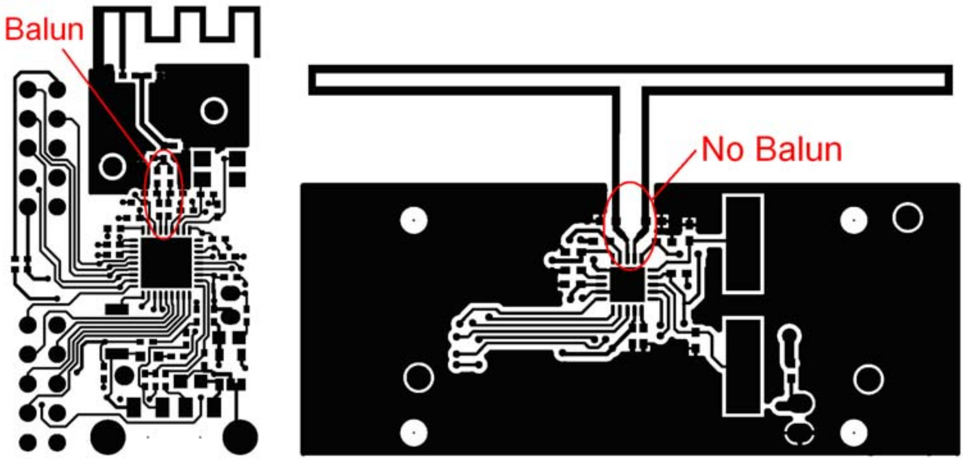
4 Antenna Types

There are several antenna types to choose from when deciding what kind of antenna to use in an RF product. Size, cost and performance are the most important factors when choosing an antenna. The three most commonly used antenna types for short range devices are PCB antennas, chip antennas and whip antennas with a connector. There are also PCB antennas that are patented and Wire antennas. Table 3 shows the pros and cons for these antenna types.

Antenna types	Pros	Cons
PCB antenna (non – IP based)	• Low cost • Good performance • Small size at high frequencies • Standard design antennas widely available that are not patented protected	• Difficult to design small and efficient PCB antennas • Potentially large size at low frequencies
Chip antenna	• Small size • Short TTM since purchasing antenna solution	• Medium performance • Medium cost
Whip antenna	• Good performance • Short TTM since purchasing antenna solution	• High cost • Difficult to fit in many applications
PCB antenna (IP based)	• Large support from IP company • Short TTM since purchasing antenna solution	• High cost compared to non-IP PCB antenna. • Similar cost to Chip antenna
Wire antenna	• Very cheap	• Larger variance of mechanical positioning which could alter antenna performance

Table 3. Pros and Cons for Different Antenna Solutions

It is also common to divide antennas into single ended antennas and differential antennas. Single ended antennas are also called unbalanced antennas, while differential antennas are often called balanced antennas. Single ended antennas are fed by a signal which is referred to ground and the characteristic impedance for these antennas is usually 50 ohms. Most RF measurement equipments are also referenced to 50 ohms. Therefore, it is easy to measure the characteristic of a 50 ohm antenna with such equipment. However many RF IC's have differential RF ports and a transformation network is required to use a single ended antenna with these IC's. Such a network is called a balun since it transforms the signal from balanced to unbalanced configuration. Figure 2 shows a single ended antenna and a differential antenna. The figure shows the differential antenna connected directly to the RF pins and a balun needed by the single ended antenna.



Single Ended Antenna **Differential Antenna**

Figure 2. Single Ended and Differential Antenna

You can take a dipole and use techniques like meandering to decrease the overall board size. Here the feed line (smaller line provides an impedance change. The first line intersects the main antenna trace the impedance changes by sqt root of Za and Zt1. The smaller trace width between the pad and feed line increases the input impedance by sqt root of Zt1 and Zt2. The larger line at far right connects the ground plane or the other half of the antenna. There are several fine tuning done that is not discussed to increase efficiency and other 2nd order specs.

The antennas presented in this document are mainly intended for the license free 2.4 GHz - 2.4835 GHz band, the 863-870 MHz band in Europe, the 902-928 MHz band in US and the Japanese band 955 MHz. The European band is usually referred to as the “868 MHz band” and the US band is commonly designated the “915 MHz band”. It is often possible to achieve good performance with the same antenna for both the European 868 MHz and the US 915 MHz bands by tuning the antenna length or changing the values of the matching components. Such antennas are called “868/915 MHz antennas” in this document.

4.1 PCB Antennas

Our ambition is to provide excellent design and application notes so the design-in process will be easier and quicker. With RF designs, the antenna design is a critical stage to be able to achieve the best possible link budget for a specific application. As previously mentioned in 3.2, there are many considerations to consider when choosing the type of antenna.

The antenna application notes are updated regularly and improved with new designs. The TI antenna designs that are released are free of charge and can be used directly in the final application design. In addition to these free TI antenna designs, we also have specific antennas designs that are IP based. The antenna IP company usually has a specific design profile such as directivity or compact design for example.

The antenna in the basic form, PIFA, patch, spiral etc is generally free from patent infringement because these are well known designs that have been around for many years. When the antenna is adapted from the "standard format"; then the antennas are more than likely protected through patents. It is important to keep this in mind when developing a new antenna. Many antenna patents collide with each other and which company had the original IP, and if the IP is valid can be a long discussion.

It is advisable to keep the standard text book antenna designs when developing an antenna to avoid any legal discussions.

4.1.1 TI Antenna Reference Designs

Designing a PCB antenna is not straight forward and usually a simulation tool must be used to obtain an acceptable solution. In addition to deriving an optimum design, configuring such a tool to perform accurate simulations can also be difficult and time consuming. It is therefore recommended to make an exact copy of one of the reference designs available at www.ti.com/lpw, if the available board space permits such a solution. See section 7 for a description of the available reference designs. If the application requires a special type of antenna and none of the available reference designs fits the application, it could be advantageous to contact an antenna consultant or look for other commercially available solutions. Table 7 lists a few companies that can offer such services.

4.1.2 IP Based

There are many IP antenna design companies that sell their antenna design competence through IP. Since there is no silicon or firmware involved; the only way for the antenna IP companies to protect their antenna design is through patents. Purchasing a chip antenna or purchasing an IP for the antenna design is similar since there is an external cost for the antenna design.

Figure 3, shows an EM board with the CC2430 and a quarter wave slot antenna from Pinyon. The antennas from Pinyon are specifically designed for directional operation. Applications environments such as corridor coverage, metering surveillance, and maximum range distance between two fixed devices can be ideal applications for the Pinyon type of directivity antenna.

One advantage of using a directional antenna is the PA power can be reduced due to the higher gain in the antenna between two devices for a given distance so that current consumption can be reduced. Another advantage is that the antenna gain can be utilized to achieve a greater range distance between two devices.

However, a disadvantage of using directional antennas is that the **positioning of the transmitter and receiver unit must be known in detail**. If this information is not known then it is best to use a standard omni-directional antenna design such as described in DN007 [4].

It is important to state that the antenna gain is not similar to amplifier gain where there is more power generated. Antenna gain is just a measure of the antenna directivity and an antenna can only radiated the power that is entered into the antenna.

An alternative to the Pinyon antenna can be a standard patch antenna which will also give directivity but with no IP cost attached. The patch antenna mainly radiates in just one direction (one main lobe) whereas the Pinyon antenna has two main lobes, similar to a figure eight, as can be seen in Figure 5.

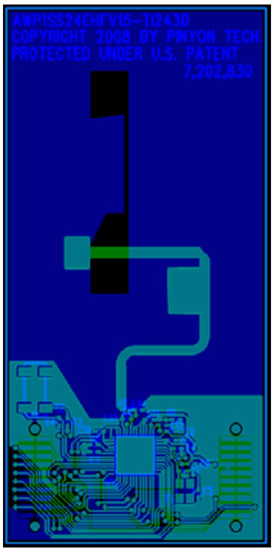


Figure 3. CC2430 EM Board with Pinyon Quarter Wave Antenna

Fractus is also an antenna IP company that TI uses. Fractus concept is to design very compact antennas in a fractal pattern. The fractal pattern is laid out so that the current flow in the antenna structure will not oppose each other and the layout size can be kept to a minimum. Fractus also sells their antenna as a chip antenna component. Figure 4 shows a selection of the standard chip antennas that are available from Fractus covering 2.4 GHz, 915 MHz & 868 MHz bands.

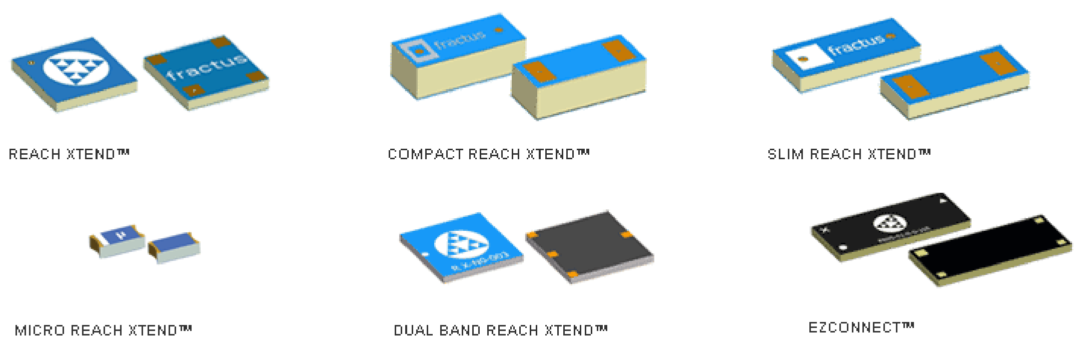


Figure 4. Standard Chip Antennas Available from Fractus.

4.2 Chip Antennas

If the available board space for the antenna is limited a chip antenna could be a good solution. This antenna type allows for small size solutions even for frequencies below 1 GHz. The trade off compared to PCB antennas is that this solution will add BOM and mounting cost. The typical cost of a chip antenna is between $0.10 and $1.00. Even if manufacturers of chip antennas state that the antenna is matched to 50 ohms for a certain frequency band, it is often required to use additional matching components to obtain proper performance. The performance numbers and recommended matching given in data sheets are often based on measurements done with a test board. The dimensions of this test board are usually documented in the data sheet. It is important to be aware that the performance and required matching might change if the chip antenna is implemented on a PCB with different size and shape of the ground plane.

4.3 Whip Antennas

If good performance is the most important factor and size and cost are not critical, an external antenna with a connector could be a good solution. These antennas are often monopoles and have an omni-directional radiation pattern. This means that the antenna has approximately the same performance for all directions in one plane. The whip antenna should be mounted normally on the ground plane to obtain best performance. Whip antennas are typically more expensive than chip antennas, and will also require a connector on the board that also increases the cost. Notice that in some cases special types of connectors must be used to comply with SRD regulations. For more information about SRD regulations please see Application Note 001 [1] and Application Note 032 [2].

4.4 Wire Antennas

For applications that operate in the lower bands of the sub 1 GHz such as 315 MHz and 433 MHz; the antenna is quite large, refer to Table 2. Even when the earth plane is utilized for half of the antenna design; the overall size can be large and difficult to put onto a PCB. What can be done for this frequency range which is practical and cheap; a wire can be used for the antenna and the wire can be formed around the mechanical housing of the application.

The pros of such a solution are the price and good performance can be obtained. The cons are the variations of the positioning of the antenna in the mechanical housing will have to be controlled so that the antenna will not vary too much during volume production.

5 Antenna Parameters

There are several parameters that should be considered when choosing an antenna for a wireless device. Some of the most important things to consider are how the radiation varies in the different directions around the antenna, how efficient the antenna is, the bandwidth which the antenna has the desired performance and the antenna matching for maximum power transfer. Sections 5.1 and 6.2 give an explanation on how these properties are defined and how they should be evaluated. Since all antennas require some space on the PCB, the choice of antenna is often a trade off between cost, size and performance. This will be discussed further in section 5.2.

5.1 Radiation Pattern and Gain

Antenna specs from the majority of suppliers will reference their designs to an ideal Isotropic antenna. This is a model where the antenna is in a perfect sphere and isolated from all external influences. Most of the measurements of power are done in units of dBi where "i" refers to the condition of isotropic antenna. Power measurements for a theoretical isotropic antenna are in dBi. Monopole Dipole Antenna Power is related to an isotropic antenna by the relationship 0 dBd = 2.14 dBi.

The radiation pattern is the graphical representation of the radiation properties of the antenna as a function of space. i.e. the antenna's pattern describes how the antenna radiates energy out into space (or how it receives energy). It is common, however, to describe this 3D pattern with two planar patterns, called the *principal plane patterns*. These principal plane patterns can be obtained by making two slices through the 3D pattern through the maximum value of the pattern or by direct measurement. It is these principal plane patterns that are commonly referred to as the antenna patterns.

Principal plane patterns or even antenna patterns, you will frequently encounter the terms *azimuth plane pattern* and *elevation plane pattern*. The term *azimuth* is commonly found in reference to the horizontal whereas the term *elevation* commonly refers to "the vertical". When used to describe antenna patterns, these terms assume that the antenna is mounted (or measured) in the orientation in which it will be used.

The azimuth plane pattern is measured when the measurement is made traversing the entire x-y plane around the antenna under test. The elevation plane is then a plane orthogonal to the x-y plane, say the y-z plane (φ = 90 deg). The elevation plane pattern is made traversing the entire y-z plane around the antenna under test.

The antenna patterns (azimuth and elevation plane patterns) are frequently shown as plots in polar coordinates.

The azimuth plane pattern is formed by slicing through the 3D pattern in the horizontal plane, the x-y plane in this case. Notice that the azimuth plane pattern is directional, the antenna does not radiate its energy equally in all directions in the azimuth plane.

The elevation plane pattern is formed by slicing the 3D pattern through an orthogonal plane (either the x-z plane or the y-z plane). The gain of the antenna pattern shown is 6 dBi; refer to DN027 for further information.

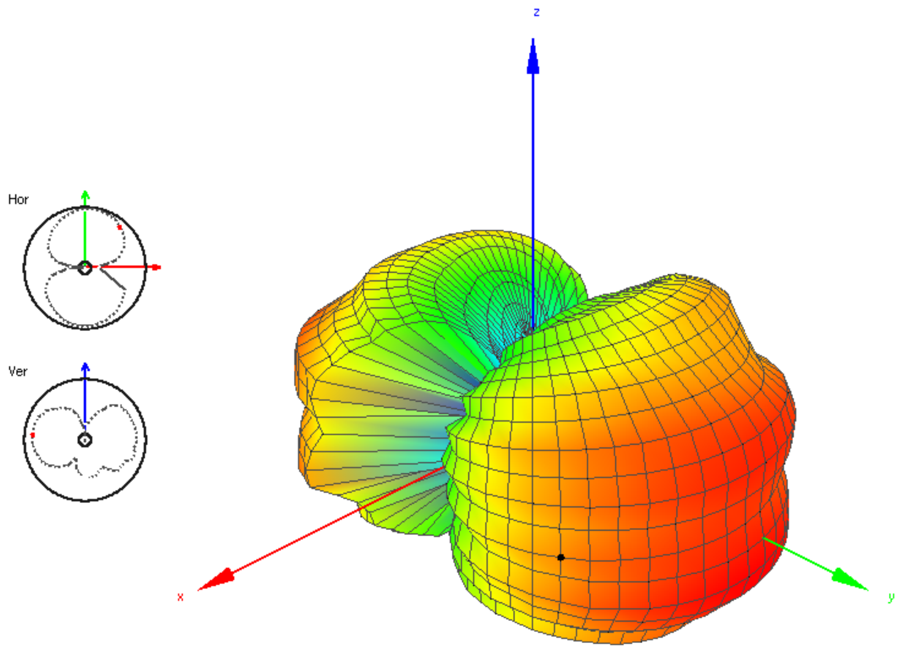


Figure 5. 3D Radiation Pattern from a Directional Antenna

It is also important to be able to relate the different directions on the radiation pattern plot to the antenna. Radiation pattern is typically measured in three orthogonal planes, x-y, x-z and y-z. It is also possible to perform full 3D pattern measurements, but this is usually not done, since it is time consuming and requires expensive equipment. Another way of defining these three planes is by using a spherical coordinate system. The planes will then typically be defined by θ = 90°, φ = 0° and φ = 90°. Figure 6 shows how to relate the spherical notation to the three planes. If no information is given on how to relate the directions on the radiation pattern plot to the positioning of the antenna, 0° is the X direction and angles increase towards Y for the x-y plane. For the x-z plane, 0° is in the Z direction and angles increase towards X, and for the y-z plane, 0° is in the Z direction and angles increase towards Y.

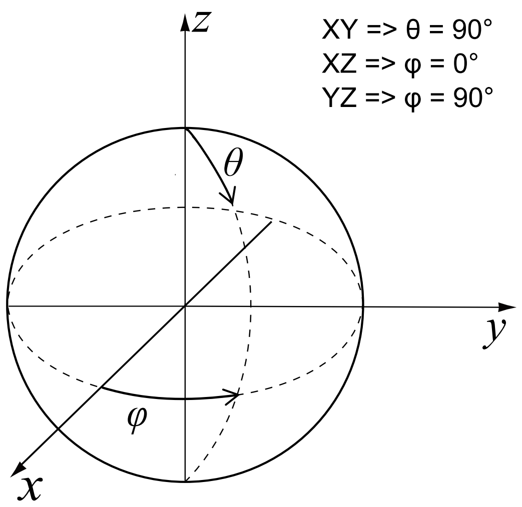


Figure 6. Spherical Coordinate System

5.1.1 Dipole Antennas

A dipole antenna most commonly refers to a half-wavelength (λ/2) dipole. The antenna is constructed of conductive elements whose combined length is about half of a wavelength at its intended frequency of operation. This is a simple antenna that radiates its energy out toward the horizon (perpendicular to the antenna).

The resulting 3D pattern looks like a donut with the antenna sitting in the hole and radiating energy outward. The strongest energy is radiated outward, perpendicular to the antenna in the x-y plane. Given these antenna patterns, you can see that a dipole antenna should be mounted so that it is vertically oriented with respect to the floor or ground. This results in the maximum amount of energy radiating out into the intended coverage area. The null in the middle of the pattern will point up and down.

For LPW we are concerned with antenna size so the antenna is further reduced to each length of a dipole to be ¼ wavelength. Then the one radiator is folded and turned into a ground plane.

Figure 7 shows how the radiation from the PCB antenna in Figure 1 varies in different directions in the plane of the PCB. Several parameters are important to know when interpreting such a plot. Some of these parameters are stated in the lower left portion of Figure 7. In addition to the information shown on the plot in Figure 7, it is important to know how to relate the radiation pattern to the positioning of the antenna.

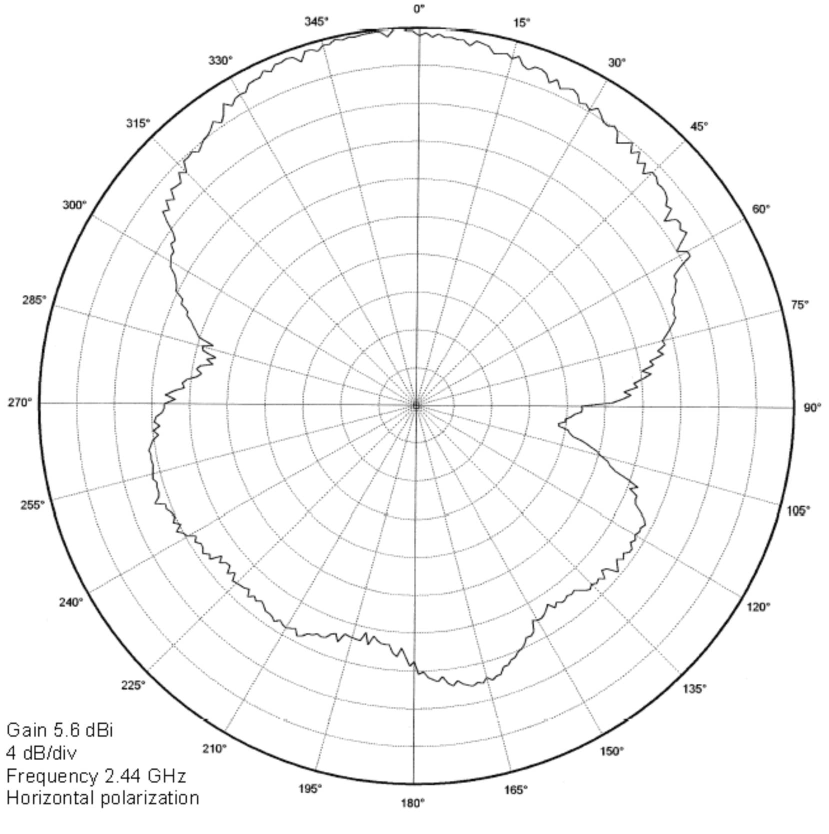


Figure 7. Radiation Pattern

The gain or the reference level is usually referred to an isotropic radiating antenna which is an ideal antenna that has the same level of radiation in all directions. When such an antenna is used as a reference, the gain is given in dBi or specified as the Effective Isotropic Radiated Power (EIRP). The outer circle in Figure 7 corresponds to 5.6 dBi. The “4 dB/div” notation in the lower left of Figure 7 means that for each of the inner circles the emission level is reduced by 4 dB. This means that compared to an isotropic antenna the PCB antenna in Figure 1 will have 5.6 dB higher radiation in the 0° direction and 6.4 dB lower radiation in the 180° direction.

$$G = e \cdot D = \frac{P_{rad}}{P_{in}} \cdot D = \frac{P_{rad}}{P_{in}} \cdot \frac{U_{\max}}{U_{avg}}$$

Equation 2. Definition of Gain

Gain (G) is defined as the ratio of maximum to average radiation intensity multiplied by the efficiency of the antenna, see Equation 2. Ohmic losses in the antenna element and reflections at the feed point of the antenna determine the efficiency. The ratio of the maximum and average radiation intensities is defined as directivity (D). High gain does not automatically mean that the antenna has good performance. Typically for a system with mobile units it is desirable to have an omni-directional radiation pattern such that the performance will be approximately the same regardless of which direction the units are pointed relative to each other. For an application where both the receiver and the transmitter have fixed positions, high gain could be desirable. If the units could be placed such that the direction of maximum gain is pointed toward each other, this will result in optimum performance with that antenna.

Polarization describes the direction of the electric field. All electromagnetic waves propagating in free space have electric and magnetic fields perpendicular to the direction of propagation. Usually, when considering polarization, the electric field vector is described and the magnetic field is ignored since it is perpendicular to the electric field and proportional to it. The receiving and transmitting antenna should have the same polarization to obtain optimum performance. Most antennas in SRD application will in practice produce a field with polarization in more than one direction. In addition reflections will change the polarization of an electric field. Polarization is therefore not as critical for indoor equipment, which experiences lots of reflections, as for equipment operating outside with Line of Sight (LOS). Some antennas produce an electrical field with a determined direction, it is therefore also important to know what kind of polarization that was used when measuring the radiation pattern. It is also important to state which frequency the measurement was done at. Generally the radiation pattern does not change rapidly across frequency. Thus it is usual to measure the radiation pattern in the middle of the frequency band in which the antenna is going to be used. For narrowband antennas the relative level could change slightly within the desired frequency band, but the shape of the radiation pattern would remain basically the same.

To make an accurate measurement of the radiation pattern, it is important to be able to measure only the direct wave from the DUT and avoid any reflecting waves affecting the result. It is therefore common to perform such measurements in an anechoic chamber. Another requirement is that the measured signal must be a plane wave in the far field of the antenna. The far field distance (R_f) is determined by the wavelength (λ) and the largest dimension (D) of the antenna, see Equation 3. Since the size of anechoic chambers is limited, it is common to measure large and low frequency antennas in outdoor ranges.

$$R_f = \frac{2\mathrm{D}^2}{\lambda}$$

Equation 3. Far Field Distance

The size and shape of the ground plane will affect the radiation pattern. Figure 8 shows an example of how the ground plane affects the radiation pattern. The radiation pattern in the upper left corner is measured with the small antenna board plugged in to the SmartRF04EB, while the pattern in the upper right corner of Figure 8 is measured with the antenna board only connected to a battery. SmartRF04EB has a solid ground plane. By plugging the antenna board into this, the effective ground plane seen by the antenna is increased. The change in size and shape of the ground plane changes the gain from -1.2 dBi to 4.6 dBi. Since many SRD applications are mobile, it is not always the peak gain that is most interesting. The average radiation for one plane gives more information about the total radiated energy and is commonly stated when antenna performance is presented.

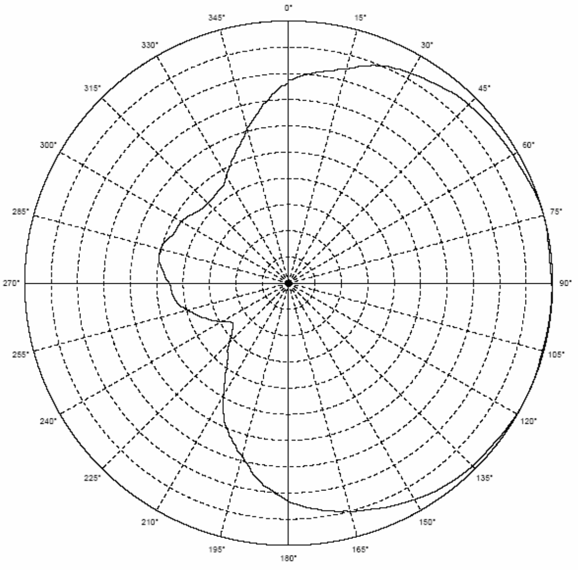
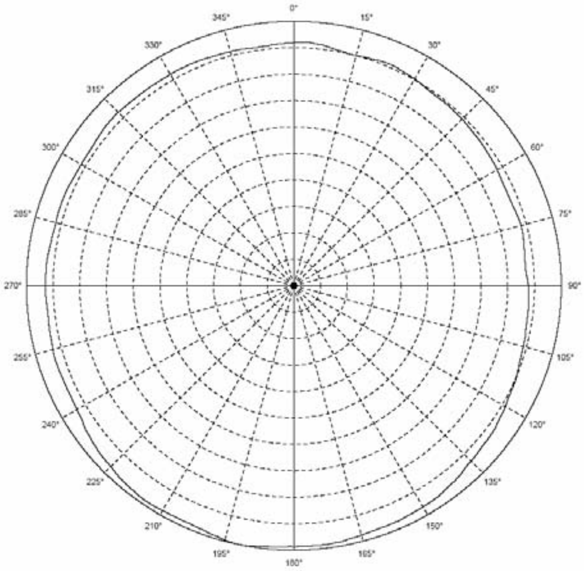
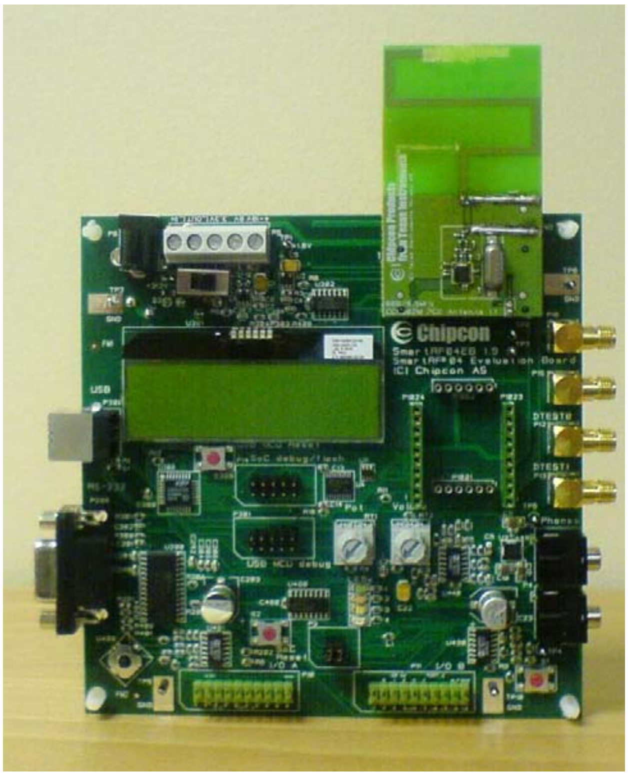
CC1100EM PCB Antenna in SmartRF04EB	**CC1100EM PCB Antenna without SmartRF04EB**
	
Vertical Polarization, YZ plane 2 dB/div 0 dBm, 868 MHz Ref Lev: 4.6 dB	Vertical Polarization, YZ plane 2 dB/div 0 dBm, 868 MHz Ref Lev: -1.2 dB
	

Figure 8. Influence on Shape and Size of the Ground Plane on Radiation Pattern

5.2 Size, Cost and Performance

The ideal antenna is infinitely small, has zero cost and has excellent performance. In real life this is not possible. Therefore a compromise between these parameters needs to be found. Reducing the operating frequency by a factor of two doubles the range. Thus one of the reasons for choosing to operate at a low frequency when designing an RF application is often the need for long range. However, most antennas need to be larger at low frequencies in order to achieve good performance. Thus in some cases where the available board space is limited, a small and efficient high frequency antenna could give the same or better range than a small an inefficient low frequency antenna. A chip antenna is good alternative when seeking a small antenna solution. Especially for frequencies below 1 GHz a chip antenna will give a much smaller solution compared to a traditional PCB antenna. The main draw backs with chip antennas are the increased cost and often narrow band performance.

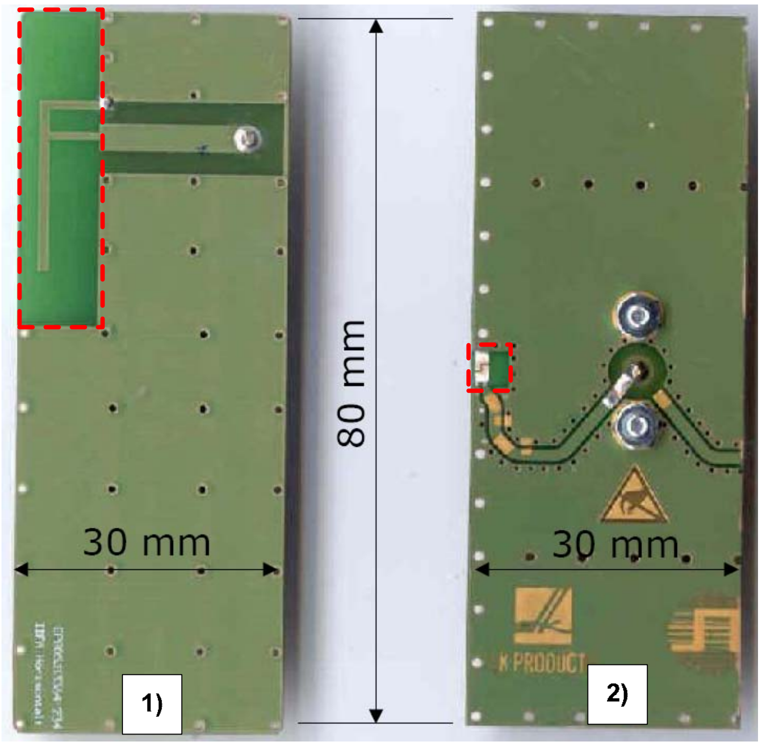


Figure 9. Layout Comparison of 1) PCB Antenna and 2) Chip Antenna

Figure 9 shows the layout of a 2.4 GHz PCB antenna and a 2.4 GHz chip antenna. The required space for the two antenna solutions are indicated with red squares. As can be seen from the picture, the chip antenna consumes much less board space than the PCB IFA antenna. The radiation efficiency of these two antenna solutions is shown in Figure 10. The graph clearly shows that the chip antenna has a narrower bandwidth than the PCB antenna, even though both antennas have the same efficiency in the middle of the 2.4 GHz band.

By using the meandering layout techniques on the IFA antenna, the total size can be reduced, refer to Figure 15.

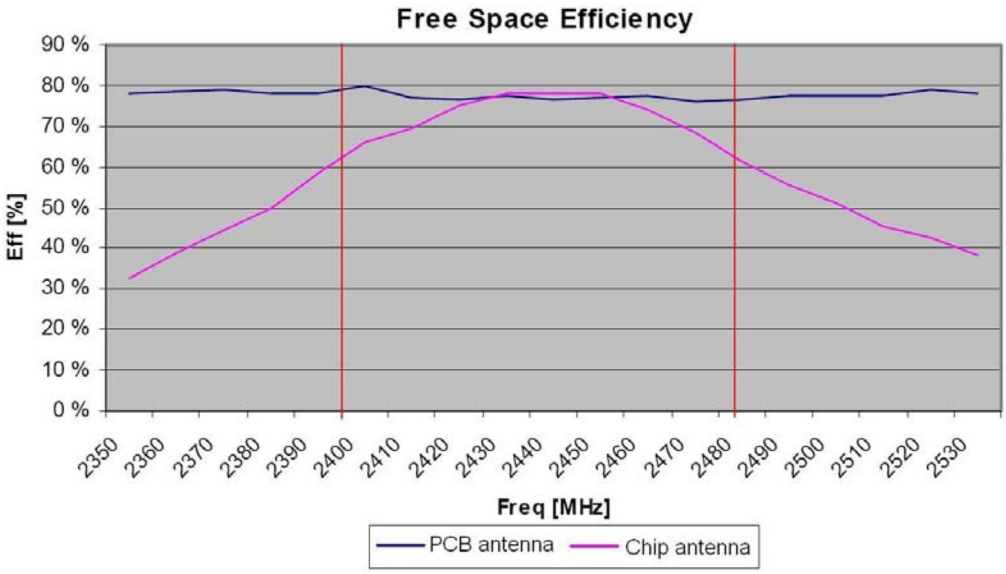


Figure 10. Comparison of a PCB Antenna and a Chip Antenna

6 Antenna Measurements

6.1 Maximum Power Transfer (VSWR)

Moritz Von Jacobi's maximum power theory states that *maximum* power transfer happens when the source resistance equals the load resistance. As impedances are mis-matched, part of the transmitted signal is reflected back into the source which is the Voltage Standing Wave Ratio (VSWR); the ratio of the reflected waveform to the transmitted waveform. With antenna design, VSWR is a measure of how well the input impedance of the antenna matches the characteristic impedance of the output from the RF network.

VSWR	Return Loss (dB)	% Power / Voltage Loss	Reflection Coefficient	Mismatch Loss (dB)
1	∞	0 / 0	0	0.000
1.15	23.1	0.49 / 7.0	0.07	.021
1.25	19.1	1.2 / 11.1	0.111	.054
1.5	14.0	4.0 / 20.0	0.200	.177
1.75	11.3	7.4 / 27.3	0.273	.336
1.9	10.0	9.6 / 31.6	0.316	.458
2.0	9.5	11.1 / 33.3	0.333	.512
2.5	7.4	18.2 / 42.9	0.429	.880
3.0	6.0	25.1 / 50.0	0.500	1.25
3.5	5.1	30.9 / 55.5	0.555	1.6
4.0	4.4	36.3 / 60.0	0.600	1.94
4.5	3.9	40.7 / 63.6	0.636	2.25
5.0	3.5	44.7 / 66.6	0.666	2.55
10	1.7	67.6 / 81.8	0.818	4.81
20	0.87	81.9 / 90.5	0.905	7.4
100	0.17	96.2 / 98.0	0.980	14.1
∞	.000	100 / 100	1.00	∞

Table 4. VSWR Chart

6.2 Bandwidth and Impedance Matching

There are two main ways of measuring the bandwidth of the antenna. Measuring the radiated power when stepping a carrier across the frequency band of interest and measuring the reflection at the feed point of the antenna with a network analyzer. Figure 11 shows a measurement of the radiated power from a 2.4 GHz antenna. The results show that the antenna has approximately 2 dB variation in output power across the 2.4 GHz frequency band and max radiation at the center of this band. This measurement was done with the radio stepping a continuous wave (CW) from 2.3 GHz to 2.8 GHz.

Such measurements should be performed in an anechoic chamber to obtain a correct absolute level. This kind of measurement can however also be very useful even if an anechoic chamber is not available. Performing such a measurement in an ordinary lab environment will give a relative result, which shows whether the antenna has optimum performance in the middle of the desired frequency band. The performance of the antenna connected to the spectrum analyzer will affect the result. Thus it is important that this antenna has approximately the same performance across the frequency band being used. This will ensure that the result gives a correct view of the relative change in performance across the measured frequency band.

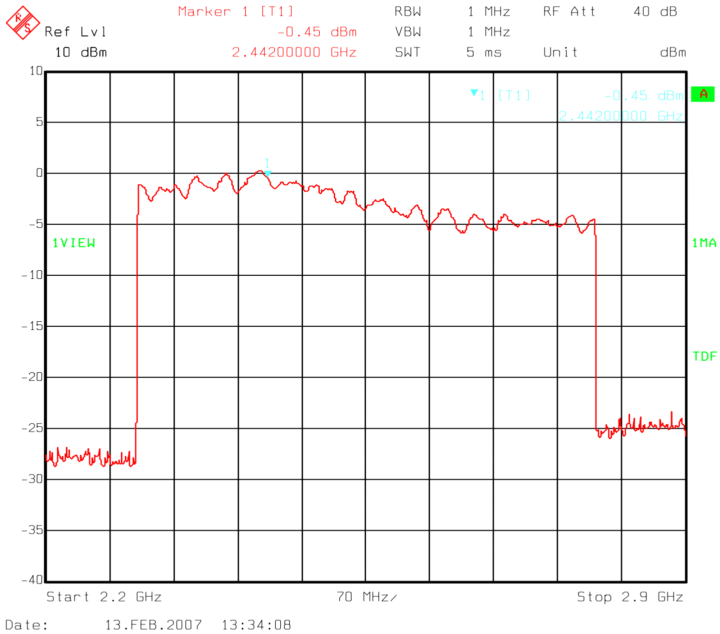


Figure 11. Bandwidth of a 2.4 GHz Antenna.

Another method to characterize the bandwidth is to measure the reflected power at the feed point of the antenna. By disconnecting the antenna and connecting a coax cable at the feed point of the antenna, such measurements could be performed with a network analyzer. The bandwidth of an antenna is typically defined as the frequency range for which the reflection is lower than -10 dB or the VSWR is less than 2; refer to Table 4. This is equal to the frequency range where less than 10 % of the available power is reflected by the antenna. More information about reflection measurements can be found in Design Note 001 [10].

Figure 12 shows plots from three reflection measurements performed on an antenna intended for a 2.4 GHz remote control. The red plot shows the reflection when the antenna is positioned in free space with no objects in its vicinity. Encapsulating the antenna in plastic affects the performance by lowering the resonance frequency. This is shown by the blue graph. By holding the encapsulated antenna in one's hand, the performance is affected even more. This shows why it is important to do characterization and tuning when the antenna is placed in the position and environment it is going to be used during normal operation.

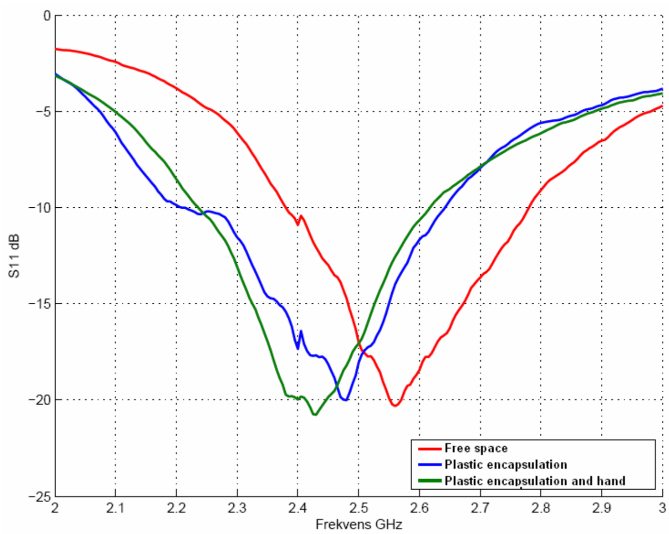


Figure 12. Reflection Influenced by the Vicinity of the Antenna

6.2.1 Mounting of cable for S11 measurements

It is invaluable to have semi-rigid cables in the lab for debugging RF. Solder first shielding onto an earth plane and then solder the 50 ohm connection. Minimize risk for ripping off tracks when connecting to the semi-rigid cable. Ready made semi-rigid cables are quite expensive but can be re-used again. A semi rigid coax cable is useful when performing measurements on prototypes. The outer of the cable should be soldered to ground while the inner conductor is soldered to the feed line of the antenna. It is important that the antenna is disconnected from the rest of the circuitry when this measurement is performed. The unshielded part of the inner conductor should be as short as possible to avoid introducing extra inductance when measuring and the outer should be soldered to ground as close as possible to the end of the cable.

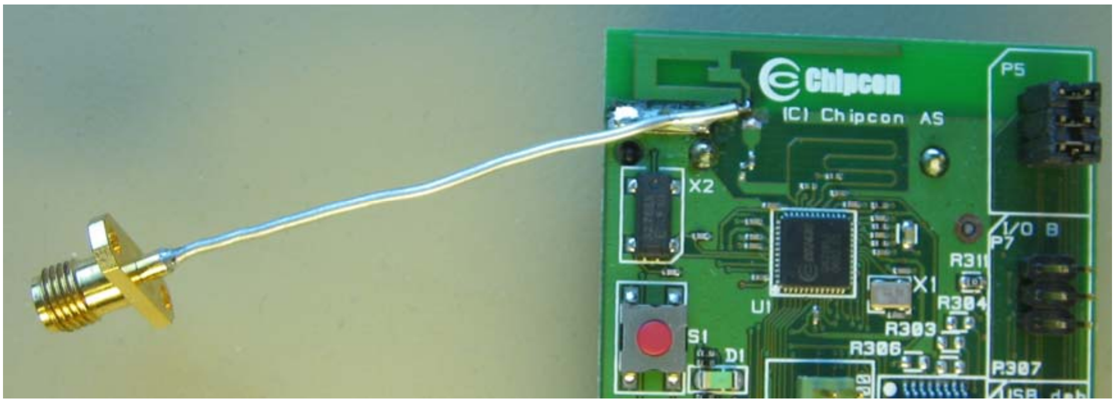


Figure 13. Mounting of Semi-Rigid Cable to Measure Antenna Characteristics

It is ideal to have dedicated boards that are specifically used just for calibration purposes. Measuring one antenna design would require four boards:

1. **Open** : end connector in air; shield connected to GND

2. **Short** : end connector to closest GND; shield connected to GND

3. **Load**: 50ohm calibration, it is useful to use two 100ohm parallel resistors assembled at the end connection point; shield connected to GND

4. **Device Under Test** Board.

By performing these steps then the semi-rigid cable is also taken care of during the calibration. By just using the network analyzer calibration kit; then the semi-rigid cables will be a part of the measurements.

Keep the cables in a constant direction and it is good practice to use cable ties to maintain cables including network analyzer cables in a fixed position. The placement of the cable can affect the measurement result, especially if there are strong currents traveling back and forth on the ground plane.

Ferrites can be used to reduce the influence from currents running at the outer of the cable. PCBs which have a ground plane with dimensions that are a fraction of a wavelength tend to have larger currents running on the ground plane. This could potentially cause more unstable results when trying to measure the reflection at the feed pint of antennas implemented on such PCBs

The placement of the ferrite along the cable will also affect the result. Thus it is important to understand that there is a certain inaccuracy when performing this kind of measurement.

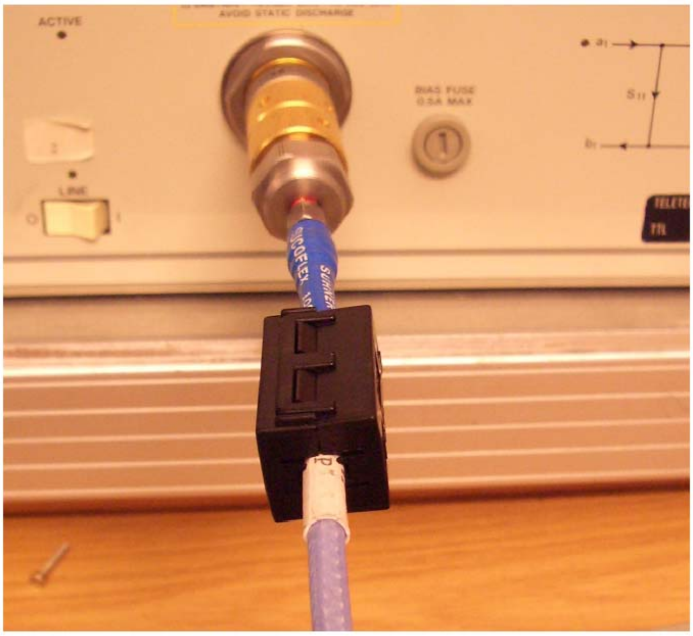


Figure 14. Usage of Ferrites during Antenna Measurements

7 Antenna Reference Designs Available on www.ti.com\lpw

Texas Instruments offers several antenna reference designs. For each reference design TI provides design files and documentation that show what kind of board the antenna was tested on and the measured performance. Common to all these designs is that the size and shape of the ground plane affects the performance of the antenna. Thus implementing the antennas on a PCB with different shape and size of the ground plane might result in slightly different results. It is important to make an exact copy of the dimensions of the antenna to obtain optimum performance. No ground plane or traces should be placed beneath the antenna. All the reference designs presented in chapter 7 and additional documentation can be downloaded from www.ti.com\lpw.

7.1 2.4GHz Antenna Reference Designs

7.1.1 Single Ended Antennas

For 2.4 GHz solutions, TI provides five different antenna reference designs. Three of these are single ended antennas matched to 50 ohms. These can be used with all 2.4 GHz products as long as a 50 ohm balun is implemented. TI provides reference designs with a balun matched to 50 ohm for all 2.4 GHz products.

The smallest antenna solution for 2.4 GHz is a Meandered Inverted F Antenna (MIFA) shown in
Figure 15. This antenna is optimum for USB dongles and other implementations with limited board space. The antenna and its performance are described in Application Note 043 [3] and design files showing the layout is included in CC2511 USB Dongle Reference Design [16].

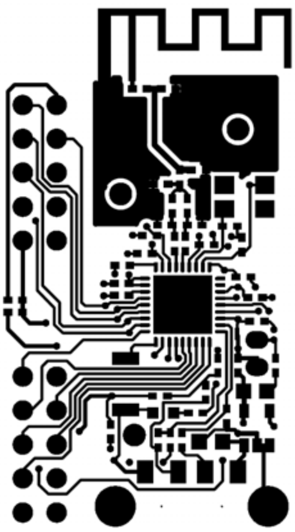


Figure 15. Meandered Inverted F Antenna

The Inverted F Antenna (IFA) shown in Figure 16 requires more board space than the MIFA, but provides a more omni-directional radiation pattern than the MIFA. This antenna can be found in the CC2400DB, CC2420DB and CC2430DB reference designs and the performance is documented in Design Note 007 [4]. The length of the IFA differs slightly between the various DB boards. The reason is that the length is tuned to compensate for the different sizes of the ground plane on the different boards.

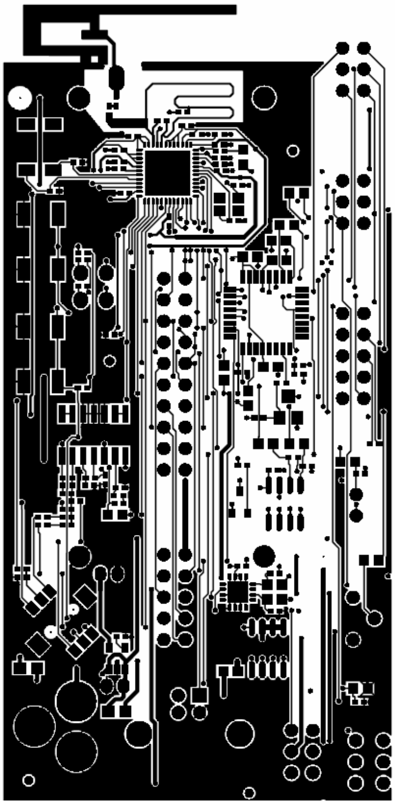
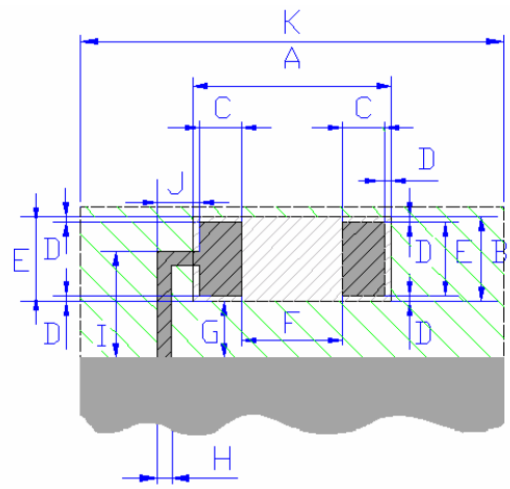


Figure 16. Inverted F Antenna

Together with Fractus [11], Texas Instruments provides an application note describing how to implement a 2.4 GHz chip antenna with 2.4 GHz radios. Application Note 048 [7] contains implementation recommendations and measurement results for a chip antenna implemented on a PCB with the size of a USB dongle. Figure 17 shows the required board space for this solution.



All dimensions listed in millimetres.

Letter	Meas.
A	7.00
B	3.00
C	1.50
D	0.20
E	2.60
F	3.60
G	2.00
H	0.50
I	3.75
J	1.50
K	15.00

Zone occupied by the antenna

Soldering pads, feed point and feeding line

PCB border (no ground-plane)

PCB ground-plane

Figure 17. 2.4 GHz Chip Antenna from Fractus

7.1.2 Differential Antennas

To reduce the number of external components required by a balun, it is possible to design a differential antenna that is matched directly to the impedance of the RF port of the radio. In some cases a few external components are required to obtain proper impedance matching or filtering.

CC2500, CC2510, CC2511 and CC2550 have all the same impedance. This makes it possible to use the antenna shown in Figure 18 with all these products. This antenna design and the measured performance are presented in Design Note 004 [5]. The only external components needed are two capacitors to ensure compliance with ETSI regulations. Thus for FCC compliance no external components are required if the proper output power and duty cycling are used.

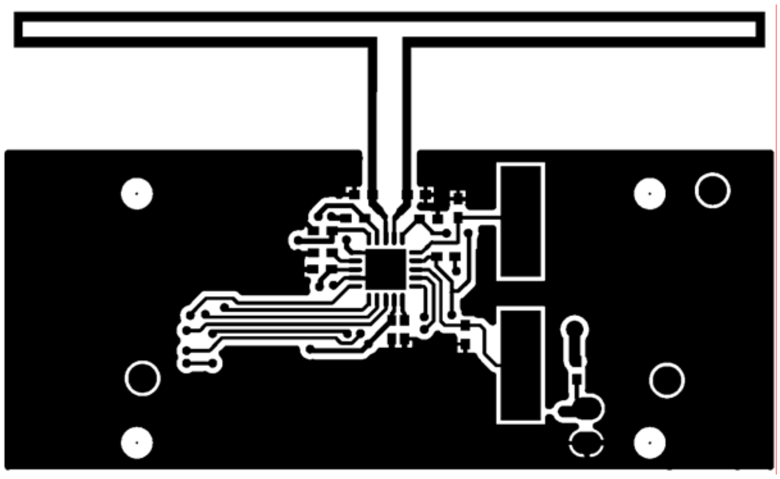


Figure 18. CC25xx Folded Dipole

CC2400, CC2420 and CC243x have all slightly different impedances. It is therefore necessary to use external components to tune the impedance so the same antenna structure can be used for all these products. The antenna presented in Application Note 040 [6] can be used with CC2400, CC2420 and CC243x if the inductor sitting between the RF pins is tuned accordingly. In addition to the tuning inductor it is recommended to use an inductor in series with the TXRX switch pin. This inductor works as a RF choke at 2.4 GHz.

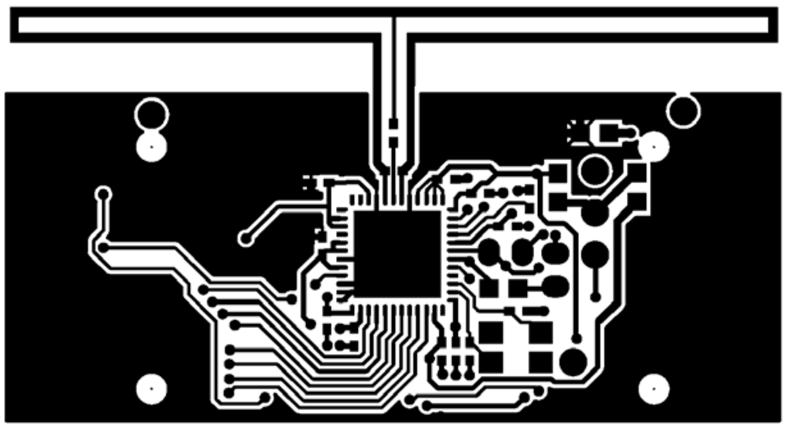


Figure 19. CC24xx Folded Dipole

7.2 Sub 1 GHz Antenna Reference Designs

7.2.1 Reference Designs for 868/915/955 MHz Antennas

For 868/915 MHz operation, TI offers four reference designs that can be used with all RF products capable of operating at these frequencies. Three designs are pure PCB antennas and the other is a chip antenna in conjunction with a special PCB trace. All designs are matched to 50 ohm. Thus a balun is needed for all products with differential output.

The first PCB antenna consists of a bent monopole and is a medium-size, low-cost solution. Figure 20 shows the bent monopole PCB antenna EM board for 868/915/955 MHz. More information about this design can be found in Design Note 008 [9] and CC1100EM PCB Antenna Reference Design [23].

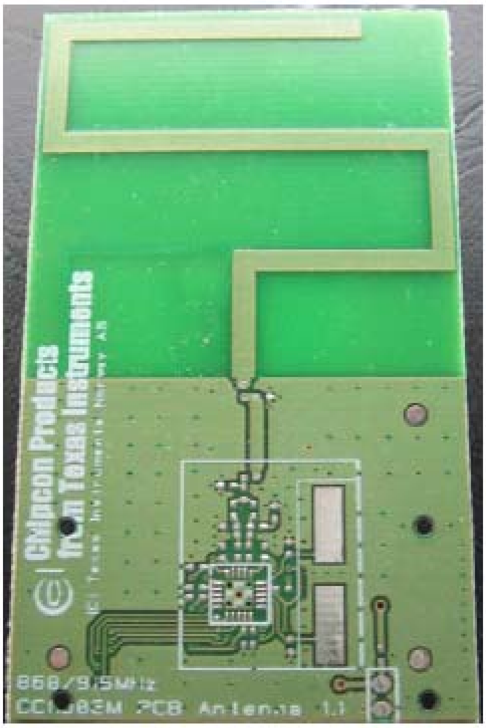


Figure 20. Bent Monopole 868/915/955 MHz

The second PCB antenna consists of an inverted F antenna and is a medium-size, low-cost solution. Figure 21 shows the inverted F antenna EM board for 868/915/955 MHz. More information about this design can be found in Design Note 023 [25] and 868/915/955 MHz PCB Inverted F Antenna Reference Design [23].

Figure 21. Inverted F Antenna EM board for 868/915/955 MHz

The third PCB antenna consists of a meandering monopole antenna and is a medium-size, low-cost solution. Figure 22 shows the meandering monopole EM board for 868/915/955 MHz. More information about this design can be found in Design Note 024 [26] and 868/915/955 MHz Meandering Monopole PCB Antenna Reference Design [27]

Figure 22. Meandering Monopole Antenna EM board for 868/915/955 MHz

The smallest antenna solution provided by TI for 868/915/955 MHz is shown in Figure 23. It consists of a chip antenna from Johanson Technology [12] in conjunction with a special PCB trace. Design recommendations and measurement results are presented in Design Note 016 [8].

Figure 23. Chip Antenna from Johanson Technology for 868/915/955 MHz

8 Additional Antenna Resources

There exists a lot of literature discussing antenna types and antenna theory. Several companies offer EM simulation tools applicable for antenna simulation. There are also many companies that manufacture antennas and also companies offering consultant services to do custom antenna design. This section lists different antenna resources.

8.1 Antenna Literature

There exist a large number of publications covering antennas. Table 5 lists some relevant literature dealing with this topic.

Title	Author
Antenna Theory and Design	Warren L. Stutzman & Garry A. Thiele
Antenna Handbook	Y. T. Lo & S. W Lee
Microwave and RF Design of Wireless Systems	David M. Pozar

Table 5. Antenna Literature

8.2 EM Simulation Tools

Table 6 lists EM simulation tools that can be used to do antenna simulations. The list is given as a reference only as TI has not evaluated all these programs.

Tool	Company
IE3D	Zeland [13]
Momentum	Agilent [14]
HFSS	Ansoft [15]

Table 6. EM Simulation Tools

8.3 Antenna Suppliers and Consultants

It is difficult to design small and effective antennas and even if a chip antenna is chosen it is often necessary to perform impedance matching to obtain optimum performance. Therefore it could be wise to contact a consultant if a special antenna solution is required. Below is a list of companies that sell different antenna solutions and offer consultant services.

Company	Web page	Expertise
Fractus	http://www.fractus.com/	Chip antennas IP Compact antennas
Johanson Technologies	http://www.johansontechnology.com/	Chip antennas
Pulse	http://www.lkproducts.com/	Chip antennas
RainSun	http://www.rainsun.com/	Chip antennas
Vishay	http://www.vishay.com/	Chip antennas
Yaego	http://www.yageo.com/	Chip antennas
Antenova	http://www.antenova.com/	Chip antennas Whip antennas
Badland	http://www.badland.co.uk/	Whip antennas
Linx Technologies	http://www.linxtechnologies.com/	Whip antennas
Antennasys	http://www.antennasys.com	Antenna consultant
LS Research	http://www.lsr.com/	Antenna consultant
Pinyon	http://www.pinyontech.com/	IP Directional antennas

Table 7. Antenna Suppliers and Consultants

9 Summary

This application note gives an overview of antenna theory, different types of antennas available, parameters to consider when implementing an antenna, and antenna measurement methods. Also, presented are the different antenna reference designs available at www.ti.com/lpw and also a list of additional antenna resources.

Table 8 lists all the antenna reference designs available at www.ti.com/lpw. This table lists which products the different antennas can be used with, the required PCB size to implement the antenna and main properties. It does also lists where to find more information on the different designs.

Reference design	Products	Size in mm	Properties	Doc. Nr.
CC2511 USB Dongle	All 2.4 GHz products	15.2 x 5.7	Meander IFA Antenna Small size & easy to tune	AN043
CC2430DB CC2420DB CC2400DB	All 2.4 GHz products	25.7 x 7.5	IFA Antenna Small size & easy to tune Omnidirectional	DN007
CC2500 Folded Dipole	CC2500 CC2550 CC2510 CC2511	46.0 x 9.0	Folded Dipole Antenna Large size & hard to tune High gain	DN004
CC2400 Folded Dipole	CC2400 CC2420 CC2430 CC2431	48.2 x 7.5	Folded Dipole Antenna Large size & hard to tune High gain	AN040
2.4 GHz chip antenna	All 2.4 GHz products	7.0 x 3.0	Chip Antenna Small size & easy to tune Medium performance	AN048
Pinyon Quarter Wave Antenna	All 2.4 GHz products	35 x 50	IP Slot Antenna Large size & hard to tune High gain & IP cost	DN026 DN028
Pinyon Half Wave Antenna	All 2.4 GHz products	35 x 80	IP Slot Antenna Very large size & hard to tune High gain & IP cost	DN027 DN029
CC1111 USB Dongle	All 868/915/955 MHz products	8.5 x 7.8	Chip Antenna Small size & easy to tune	DN016
CC1100EM PCB antenna	All 868/915/955 MHz products	39.0 x 37.0	Bent Monopole Antenna Medium size & easy to tune	DN008
868/915/955 MHz PCB Inverted F Antenna	All 868/915/955 MHz products	43.0 x 20.0	Inverted F Antenna Medium size & easy to tune	DN023
868/915/955 MHz Meandering Monopole PCB antenna	All 868/915/955 MHz products	38.0 x 24.0	Meandering Monopole Antenna Medium size & easy to tune	DN024

Table 8. Reference designs available on www.ti.com/lpw.

There is also general antenna documentation available at www.ti.com/lpw

- AN058 Antenna Selection Guide (SWRA161)
- AN003 SRD Antennas (SWRA088)
- Application Report ISM-Band and SRD Antennas (SWRA046A)

Our ambition is to provide excellent design and application notes so the design-in process will be easier and quicker. With RF designs, the antenna design is a critical stage to be able to achieve the best possible link budget for a specific application.

The antenna application notes are updated regularly and updated with new designs. The TI antenna designs that are released are free of charge and can be used directly in the final application design.

The antenna in the basic form, IFA, patch, spiral etc is generally free from patent infringement because these are well known designs that have been around for many years. When the antenna is adapted from the "standard format"; then the antennas are more than likely protected through patents. It is important to keep this in mind when developing a new antenna. Many antenna patents collide with each other and which company had the original IP, and if the IP is valid can be a long discussion. It is advisable to keep to the standard text book antenna designs when developing an antenna to avoid any legal discussions.

This document covers a large amount of various antenna design and antenna concepts. The ambition is to provide a wide spectrum of antenna designs so that the final application can choose an optimum solution for their needs. There are no general recommendations for any particular antenna supplier or antenna type.

10 References

[1] AN001 SRD Regulations for License Free Transceiver Operation (swra090.pdf)

[2] AN032 2.4 GHz Regulations (swra060.pdf)

[3] AN043 Small Size 2.4 GHz PCB antenna (swra117.pdf)

[4] DN007 2.4 GHz Inverted F Antenna (swru120.pdf)

[5] DN004 Folded Dipole Antenna for CC25xx (swra118.pdf)

[6] AN040 Folded dipole antenna for CC2400, CC2420 and CC2430/31 (swra093.pdf)

[7] AN048 2.4GHz Chip Antenna (swra092.pdf)

[8] DN016 Compact 868/915 MHz Antenna Design (swra160.pdf)

[9] DN008 868 and 915 MHz PCB antenna (swru121.pdf)

[10] DN001 Antenna Measurement with Network Analyzer (swra096.pdf)

[11] Fractus: http://www.fractus.com

[12] Johanson Technology: http://www.johansontechnology.com

[13] Zeland: http://www.zeland.com/

[14] Agilent: http://eesof.tm.agilent.com/products/momentum_main.html

[15] Ansoft: http://www.ansoft.com/products/hf/hfss/

[16] CC2511 USB-Dongle Reference Design (swrc062.zip)

[17] CC2430DB Reference Design (swrr034.zip)

[18] CC2420DB Reference Design (swrr019.zip)

[19] CC2400DB Reference Design (swrr020.zip)

[20] CC25xxEM Folded Dipole Reference Design (swrc065.zip)

[21] CC2400EM Folded Dipole Reference Design (swra093a.zip)

[22] CC1111 USB Dongle Reference Design (swrr049.zip)

[23] CC1100EM PCB Antenna Reference Design (swru122.zip)

[24] CC1110EM IIFA Reference Design (swrr058.zip)

[25] DN023 868/915 MHz PCB Inverted F Antenna Design (swra228a.pdf)

[26] DN024 868/915 MHz Meandering Monopole PCB Antenna (swra227a.pdf)

[27] CC1110EM Meander Antenna Reference Design (swra059.zip)

[28] DN026 CC2430 with ¼ wave Pinyon Antenna Design Note (swra251.pdf)

[29] DN027 CC2430 with half wave Pinyon Antenna Ref. Design Note (swra252.pdf)

[30] DN028 CC2510 with ¼ wave Pinyon Antenna Ref. Design Note (swra253.pdf)

[31] DN029 CC2510 with half wave Pinyon Antenna Ref. Design Note (swra254.pdf)

[32] CC2430 with ¼ wave Pinyon Antenna Ref. Design (swrc114.zip)

[33] CC2430 with half wave Pinyon Antenna Ref. Design (swrc113.zip)

[34] CC2510 with ¼ wave Pinyon Antenna Ref. Design (swrc116.zip)

[35] CC2510 with half wave Pinyon Antenna Ref. Design (swrc115.zip)

[36] DN018 Range Measurements in an Open Field Enviroment (swra169.pdf)

11 Appendices

11.1.1 400 - 500MHz Chip Antenna - YAGEO

Innovative Service Around the Globe **YAGEO**

MULTILAYER CERAMIC ANTENNA (LINEAR POLARIZATION MODE)
FOR 400MHz~500MHz

Product Specification[1]

QUICK REFERENCE DATA

Working Frequency*	400~500MHz
Bandwidth	20 MHz (Min)
Gain	0.5 dBi (Max)
VSWR	3.0 max
Polarization	Linear
Azimuth	Omni-directional
Impedance	50Ω
Operating Temperature	-40~125 ^{o}C
Termination	Ni/Sn (Environmentally-Friendly Leadless)
Resistance to soldering heat	260^{o}C, 10 sec.

11.1.2 325 – 916MHz Chip Antennas - Rainsun

ISM Band					
Model	AN1603-433	AN1603-868	AN1603-916	AN2004-325	AN2004-378
Image					
Size(mm)	16.0 X 3.0 X 1.7	16.0 X 3.0 X 1.7	16.0 X 3.0 X 1.7	20.0 X 4.0 X 1.5	20.0 X 4.0 X 1.36
Center Frequeney	433 MHz	868 MHz	916 MHz	325 MHz	378 MHz
Peak Gain	0.5 dBi				
Operation Temperature	-40°C ~ +85°C				
Storage Temperature	-40°C ~ +85°C				
VSWR	2.0 (Max)				
Input Impedanec	50 Ohm				
Power Handling	3W (Max)				
Bandwidth	8 MHz	10 MHz	10 MHz	4 MHz	4 MHz
Azimuth Bandwidth	Omni-directional				
Polarization	Linear				

12 General Information

12.1 Document History

Revision	Date	Description/Changes
SWRA161	2007-11-26	Initial release.
SWRA161A	2009-06-01	Updated

Following are URLs where you can obtain information on other Texas Instruments products and application solutions:

Products		**Applications**	
Amplifiers	amplifier.ti.com	Audio	www.ti.com/audio
Data Converters	dataconverter.ti.com	Automotive	www.ti.com/automotive
DLP® Products	www.dlp.com	Broadband	www.ti.com/broadband
DSP	dsp.ti.com	Digital Control	www.ti.com/digitalcontrol
Clocks and Timers	www.ti.com/clocks	Medical	www.ti.com/medical
Interface	interface.ti.com	Military	www.ti.com/military
Logic	logic.ti.com	Optical Networking	www.ti.com/opticalnetwork
Power Mgmt	power.ti.com	Security	www.ti.com/security
Microcontrollers	microcontroller.ti.com	Telephony	www.ti.com/telephony
RFID	www.ti-rfid.com	Video & Imaging	www.ti.com/video
RF/IF and ZigBee® Solutions	www.ti.com/lprf	Wireless	www.ti.com/wireless

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