
Antenna selection guide for ISM bands

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1. Introduction

A key component in any wireless design is the antenna. It is the most critical component to achieve maximum range, it has an influence on the mechanical design and it requires special engineering skills to design an optimal antenna.

The purpose of this document is to give the reader an easy-to-use path to making a good antenna selection/design with minimal effort and without extensive RF knowledge.

To keep this document usable for non-RF engineers, it intentionally avoids any antenna or RF-theory. The document rather focus on the practical guidance to getting the antenna design done.

2. Antenna design at start of product design

A key to achieving a good antenna design is to think of the antenna early in the development project. Often the antenna design is postponed to the end of the project and then many elements like housing, screws, etc. have fixed position. This often prevents the design of a good antenna solution.

3. Antenna selection criteria

Before discussing and recommending the various antenna types, the criteria for selecting the antenna is discussed. Projects and products are never 100% identical and therefore each new project must find the best solution based on the requirements for that specific project.

Normally the selection is a trade-off between the different criteria below.

The criteria discussed in this chapter are the following:

- Size
- Operating frequency
- Performance/range
- Cost
- Ease of use/knowledge/risk
- Certification reuse

3.1 Size

Wireless products differ in size and shape. Therefore, the available space for antenna is also different between the various projects. A wearable device needs a small antenna while a vending machine gives a lot of space for the antenna. Due to this, the physical space limitation for the antenna will vary. The industry designers will often push for the smallest antenna, while the performance criteria below will demand a larger antenna.

3.2 Operating frequency

Wireless ISM band solutions can operate from 169 MHz up to 2.4 GHz. The frequency chosen for a project is often guided by local regulation where it will operate and the specific application.

However, the operating frequency will also affect the antenna. A high frequency gives a smaller antenna than a low frequency. It scales in such a way that doubling the frequency will give half the size of the antenna.

3.3 Performance

A key parameter for a wireless solution is the range that can be achieved while maintaining good wireless connection. If your project requires maximum range possible for a given radio technology, then the antenna must be chosen among the best performing antennas.

The range performance of an antenna is given by the antenna gain. Sometimes the reference design or the antenna supplier will state the directional gain.

Directional gain does not include efficiency loss for the antenna. If your solution should need to be omnidirectional, then the directional gain should be close to 0dBi. This indicates that the antenna radiates equally well in all directions.

$\text{Gain[dB]} = \text{directional gain[dB]} - \text{efficiency loss[dB]}$

3.4 Cost

Cost is always an important criterion, but sometimes has to be traded vs. other more critical criteria. An antenna is never free of charge, but can vary from a few cents to several dollars.

The cost of the antenna is not only the price of the device, but also includes the cost of additional complex operations during assembly due to the antenna.

3.5 Ease of use/knowledge/risk

Without the knowledge of RF and without the time to fail, it is often a criterion to have low risk in the antenna design. Choosing a very complex antenna with the ultimate performance might not be desirable if there is a high risk that the antenna can easily be detuned due to small design errors, resulting in a much lower performance than the theoretical performance.

4. Certification reuse

RF modules can have certifications, which is linked to specific antennas. An example is our 2.4 GHz module, which is FCC certified with a monopole whip antenna with specified gain. Choosing the same antenna type as used in the certification can reduce the development time and certification cost, and that is often important in a project.

5. Antenna types

There are many different antenna types, but this document focuses on the most common categories

- Wire antenna
- Whip antenna
- PCB antenna
- Chip antenna

5.1 Wire antenna

A wire antenna is simply a conductive wire soldered to the RF signal trace on the PCB.

- Wire can be flexible or rigid.
- Wire can be insulated or bare
- Wire can be straight, bent or even made as a helical.

A wire antenna can have very low purchasing cost, but the manufacturing costs might be higher.

The most common way to use a wire antenna is to make it a quarter-wave monopole. That means the antenna wire length is a quarter of a wavelength long.

Frequency [MHz]	$\lambda/4$ - quarter of a wavelength [cm]
169	44.3
433	17.3
868	8.6
915	8.2
2450	3.1

Ideally, the wire is perpendicular on a PCB with a ground plane covering entire PCB. (See Figure 1). However, due to practical product design and mechanical support to keep antenna positioned during lifetime, such antennas are rarely used.

Normally the antenna needs to be bent/folded towards the PCB to save space and it needs to be fixed to some mechanical elements to keep the antenna position stable. Both these factors will detune the antenna slightly (degrade the performance). A wire antenna can normally be compensated by adjusting the length of the wire making it shorter.

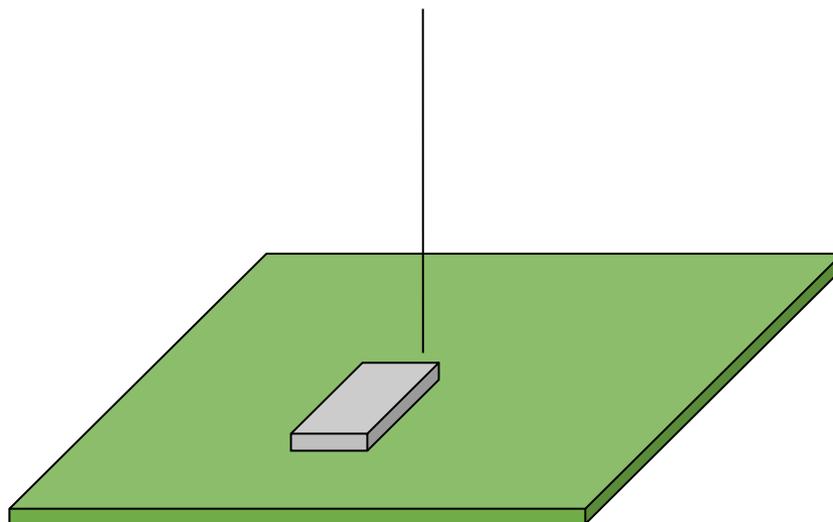


Figure 1. Ideal wire antenna.

Another challenge at lower frequencies is the length of the wire. For 169 MHz the wire should be 44 cm long which is impractical for most products.

The most common way to handle minimization is to make a helical antenna. This is a task, which requires in-depth RF knowledge.

Therefore, the least risky options are either to buy a helical antenna from a company that could also assist in tuning it to your design or alternatively to get specialist RF-assistance in another form (consultant etc.).

5.2 Whip antenna

A whip antenna is a wire antenna that has been extended with a connector and molded in plastic. This internal wire is often formed as a helical.

The advantage is that the antenna is commercially available off the shelf (COTS).

Whip antenna are classified as monopole or dipole.

A monopole antenna must be mounted directly on a conductive ground plan, while dipole antennas can be connected through an RF coaxial cable to the board. In this way a dipole antenna can be fixed in the product's plastic enclosure and connected via a cable to the PCB.



5.3 PCB antenna

PCB antennas are considered the lowest cost antenna solution available. It requires a larger PCB and increase product cost in that way, but other than that the antenna is free of charge.

A PCB antenna is a PCB route without any routing/copper in the same area of the PCB. All PCB layers needs to be free from routing/copper in the area of the antenna, not to degrade the antenna.

A PCB antenna can have many shapes. In this document we will focus on very commonly used shapes:

- Quarter wave monopole
- PIFA
- Meander

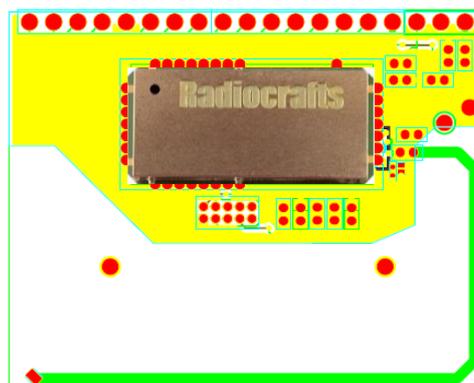


Figure 2. Radiocrafts module with PCB antenna (Yellow area is ground on layer 2).

The simplest form of a PCB antenna is a **quarter wave monopole**. It has clear resemblance with a quarter-wave monopole wire antenna. A PCB trace is simply used instead of a wire. To get the best performance the PCB trace should have maximum clearance from other traces/ground plane on the PCB. This is easiest done by routing the PCB trace on the edge of the board. See Figure 2 as an example of how this can be done.

The length of the trace is shorter than the comparable wire antenna due to the electrical properties of the PCB. The PCB have a different dielectric constant than air. The difference

depends on the PCB layout, but as a starting estimate, antenna trace length = $0.75 \times \text{length-in-air}$ can be used.

Frequency [MHz]	$\lambda/4$ - quarter of a wavelength on PCB [cm]
169	33
433	13
868	6.5
915	6.1
2450	2.3

A commonly used PCB antenna is also an inverted F antenna. The performance vs size is very good, but the reference designs must be followed in all details. If you are not able to follow the clearance requirement for the antenna very closely, you should not use it.

In addition, a PIFA antenna is quite easily detuned. So there is a risk that tuning must be done on the matching network. For those choosing to design a PIFA antenna, a lot of templates can be found on the web, in particular the 2.4 GHz.

A meander PCB antenna is a PCB antenna made smaller by winding/snake shape. Making a meander PCB antenna requires RF knowledge as matching is required.



Figure 3. Meander PCB antenna concept.

5.4 Chip antenna

Chip antennas are normally the smallest antennas that are available. The size is reduced by using ceramic with favourable electrical properties, or by special geometrical shapes.

Chip antennas have better performance and are more commonly used at higher frequencies. Due to this they are often used at 2.4 GHz and sometimes used at 868/915 MHz.

Chip antennas have very high Q (narrowband) and therefore easily detuned. The ground plane size is critical, and often these antennas require tuning by a matching network.

Examples of different chip antennas are given in the different frequency chapters at the end of the document.

5.5 Special antenna

Even though the most common antenna types are discussed above, there are some antennas that do not fit within these categories.

Some of these antennas are listed below for information:

<p>Stamped metal. E.g. 440 from Proant</p> 	<p>Ceramic patch E.g. SWLP-12 from Taoglas</p> 
<p>Flat patch dipole with cable and U.FI connector. E.g. FX73.07.0100A from Taoglas</p> 	<p>Molded helical e.g. WM4893CT-ND from Molex</p> 
<p>PCB based with cable E.g. Acara from EAD</p> 	<p>Dome with cable E.g. Linx</p> 

The antennas with cable can be evaluated for solution where ground plane is small or antenna must be placed on enclosure.

The PCB mount has close resemblance with chip antennas must be evaluated concerning cost and performance vs. other chip antennas.

6. Positioning of the antenna

Positioning of the antenna inside the product is a key to achieve the maximum performance.

As products are very different, it is hard to make exact guidelines. However, some general rules can be applied.

- If using a reference design, check the clearance requirements and follow those carefully
- The more free space around the antenna, the better
- Imagine the antenna as an eye. The more visibility the antenna has to the outside of the product, the better it radiates.
- The outer tip of the antenna is the most sensitive part, which must be in the clear.

Note that monopole antennas must be mounted on a ground plane, while dipole antenna can be fixed in a plastic enclosure and fed through an RF cable.

7. Matching of antennas

In antenna reference designs and application notes, the concept of matching the antenna is often described.

Matching the antenna is the process of adjusting the impedance of the antenna to maximize the power fed to the antenna and minimize reflection loss.

The matching network normally consist of a network of capacitors/inductors in close proximity of the antenna. Two or three passive components are typically used.

Normally, a matching circuit for commercial antennas are given in the datasheet/ref designs.

If the reference design must be altered for an application board, or if an antenna is designed from scratch, the matching might need to be tuned or designed.

To be able to perform any matching, a matching network must be included in the final PCB. A 'Pi' network with 0402 components are normally recommended. See Figure 4 (use 0603 for 169 MHz)

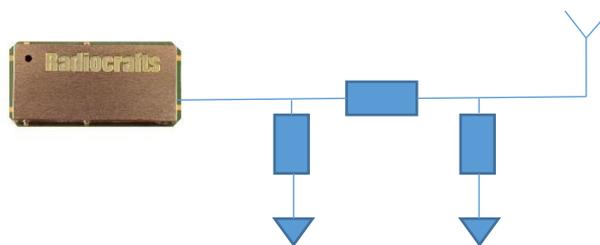


Figure 4. General matching circuitry.

There are two fundamentally different approaches to matching the antenna.

One option is the theoretical engineering approach that includes measuring the antenna impedance with a network analyser and adjust the matching according to Smith chart in order to accomplish acceptable VSWR/S11. This work required good RF understanding, knowhow and instrumentation. The method is described in detail here: [Chapter 6 in Texas Instruments Antenna Selection Guide](#)

The other option is an empirical “cut and try” method.

- Create a test setup with application DUT (Device Under Test) and a well-known receiver. (e.g. a Radiocrafts Development Board)
- Then send packets (e.g. 100 and measure average RSSI)
- Now try to adjust one matching component or antenna length and redo test.
- Did RSSI increase or decrease? Try different variation and get an overview of what makes RSSI increase or decrease.

To do this work, special precaution must be applied

- The test environment must be carefully controlled and not changed between measurements and preferably do all the measurements at the same time.
- Product position must be the same in every test.
- One recommendation is to keep one unmodified product as a reference and include it in every test run in order to “calibrate” the test environment.

8. De-tuning of antennas due to close objects

Two different effects can detune the antenna.

- Material with ϵ different from air (>1) is close to antenna. (ϵ = dielectric constant.) This is true for most plastics and other materials typically used in product housing.
- Ground or other metal parts are too close to the antenna

8.1 Material with $\epsilon > 1$ is close to the antenna

The wavelength of the antenna is given as a function of the dielectric constant ϵ and ϵ is always larger than one.

Material	ϵ
Air	1
Polypropylene	2.2-2.36
Polystyrene	2.4-2.7
FR4	3.5-5
Silicon	11.68
Rubber	7

**source Wikipedia*

All such material close to the antenna will make the wavelength shorter and the physical length of the conductor in the antenna must be shortened in order to compensate.

This explains why a PCB antenna need a shorter trace on a PCB compared to a wire antenna in air.

8.2 Ground is close to the antenna

The antenna reference designs are often based on unlimited space. In a real application, the antenna must often be adjusted to fit mechanically. This means that antenna cannot be perpendicular on ground plan, but must be folded back towards the ground plane.

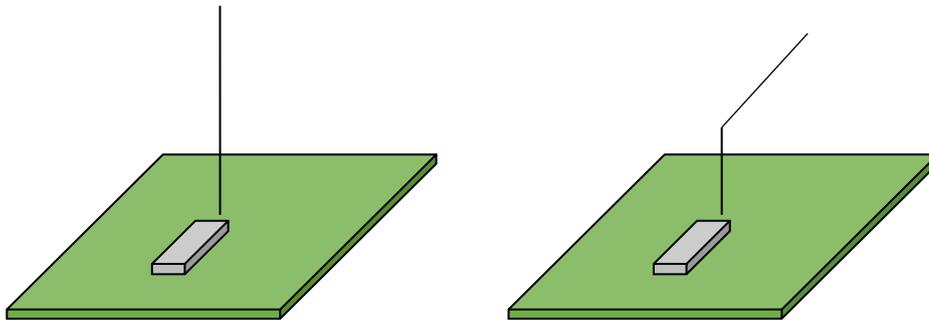


Figure 5. Ideal straight monopole vs folder monopole.

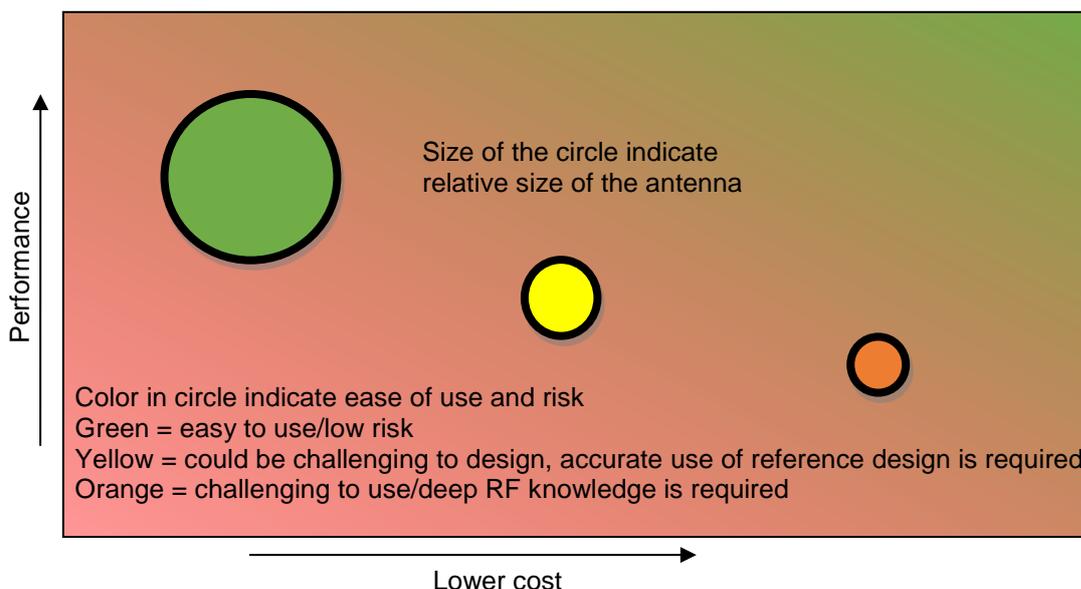
The folding of the antenna towards the ground will make the antenna have a lower optimal frequency and shortening the antenna is normally needed to get the best performance. The folding of antenna towards the ground plane is sometimes referred to as capacitive loading.

If the antenna is folded to close to the ground the antenna must be matched. This is done by adding an inductor to ground as part of the matching circuit (short inductor).

9. Antenna selection based on frequency

In the following chapters each relevant frequency is covered separately, with special consideration for each ISM band. Each chapter includes a graphical presentation showing the different antenna options in four dimensions plot. See description below.

The major axes in the drawing is cost and performance.



A set of example antenna/ref designs are given for each frequency as well.

9.1 169 MHz

At 169 MHz the antenna design is challenging, as there are only a few good options. Quarter of a wavelength is 44 cm and therefore a full-length PCB or wire antenna are impractically large.

A chip antenna gives very low performance and poor efficiency at 169 MHz and are rarely used.

Due to these circumstances, a helical antenna is normally recommended for 169MHz. Helical antennas are not straight forward to design, so RF expertise is recommended, either through buying a COTS antenna or using skilled help. COTS whip antennas at this frequency are almost all helical designs internally.

Even though using a helical antenna is the recommended antenna type, the size of the antenna is still a variable. A long helical e.g. of 15 cm give good performance (typ. -5 dBi) and is easier to design with, while a 5 cm helical gives medium performance (typ. -7 dBi) and is more demanding to design. A helical design at 169 MHz, centered at the correct frequency, still needs to be tuned by a matching network.

Example chip antenna (not recommended)

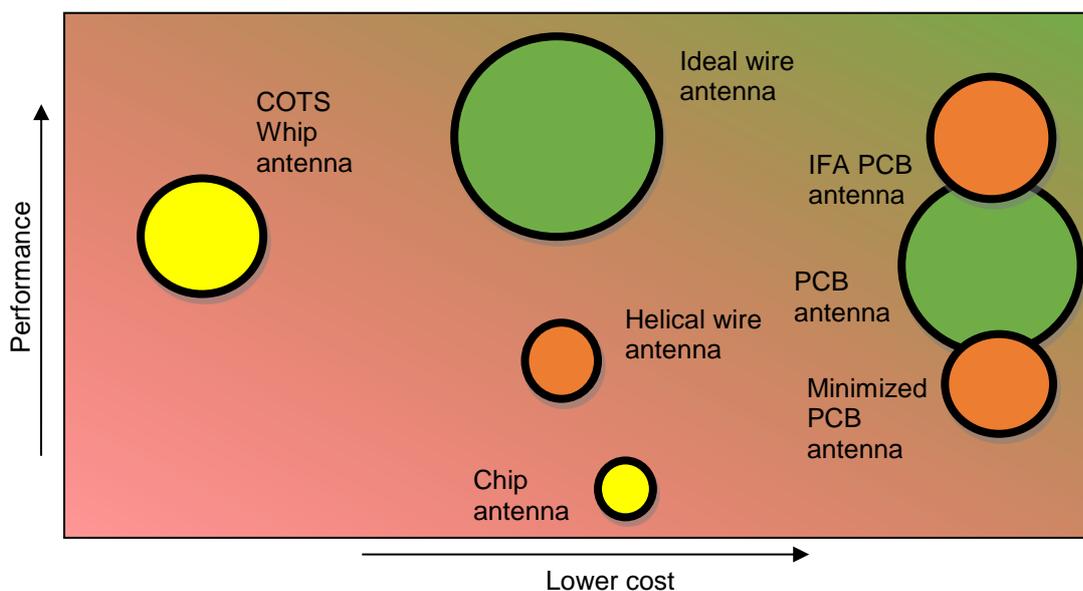
Yageo [ANT2405F001R0169A](#)
Johanson Technology [0169AT62A0010](#)

Example COTS whip antenna

EAD [H169-SMA](#) Used in Radiocrafts Dev. Kits
Siretta Ltd [DELTA12/X/SMAM/S/S/17](#)
2J [2J0819-C708N](#) Compact size

Example helical (COTS)

Taoglas [HA10.A](#)



9.2 433 MHz

At 433 MHz it is more tricky to choose the correct antenna type as there are more options. Helical designs are still a very widespread type, but PCB antenna and chip antenna can also be used. COTS antenna or wire antenna at full length (17 cm) are rarely used due to size, but they can be used in projects with no/little size restrictions.

Example COTS whip antenna

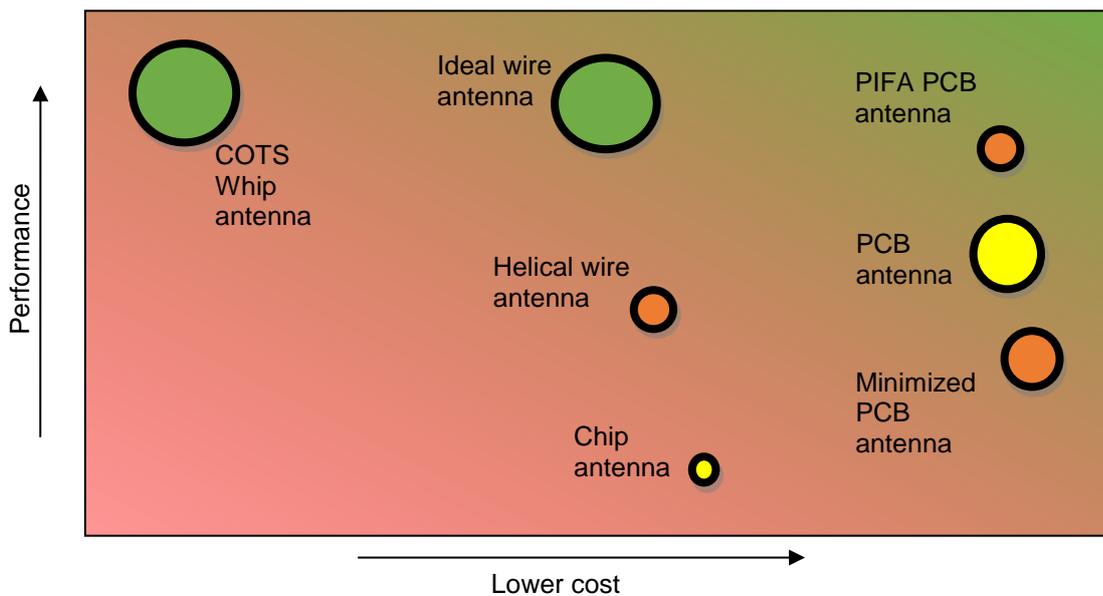
EAD	MW433	Used in Radiocrafts Dev. Kits
Linx Technologies Inc	ANT-433-CW-HD-SMA	
Taoglas	TI.10.0111.HT	Compact size

Example COTS helical

Linx Technologies Inc	ANT-433-HESM
Pulse Electronics	W3127

Example chip antenna

Mitsubishi	AMD11DP-ST01	Used on Radiocrafts USB stick
Linx Technologies Inc	ANT-433-USP	



9.3 868 MHz/915 MHz

At 868 MHz/915 MHz the $\lambda/4$ length is short and PCB antenna and wire antenna are often used. A 8-9 cm wire or a 6-7 cm PCB trace is easy to implement, test and tune. Tuning can be done by test based “cut-and-try” method.

Wire antenna

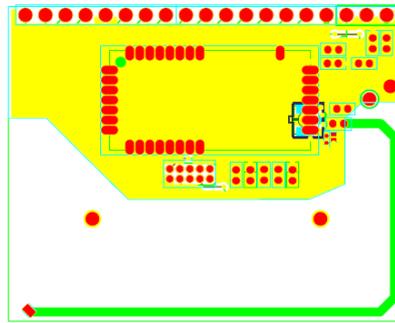
Basically a wire on 8.6 cm (868MHz) or 8.2 cm (915 MHz)

In real cases it will be shorter due to the effect of close objects and bent wire.

The antenna can be optimized through repeated trim and measurement operations.

Ref design PCB antenna

PCB trace on board edge



Minimized PCB antenna
Inverted F PCB antenna

<http://www.ti.com/lit/an/swra227e/swra227e.pdf>
<http://www.ti.com/lit/an/swra228c/swra228c.pdf>

Example COTS whip antenna

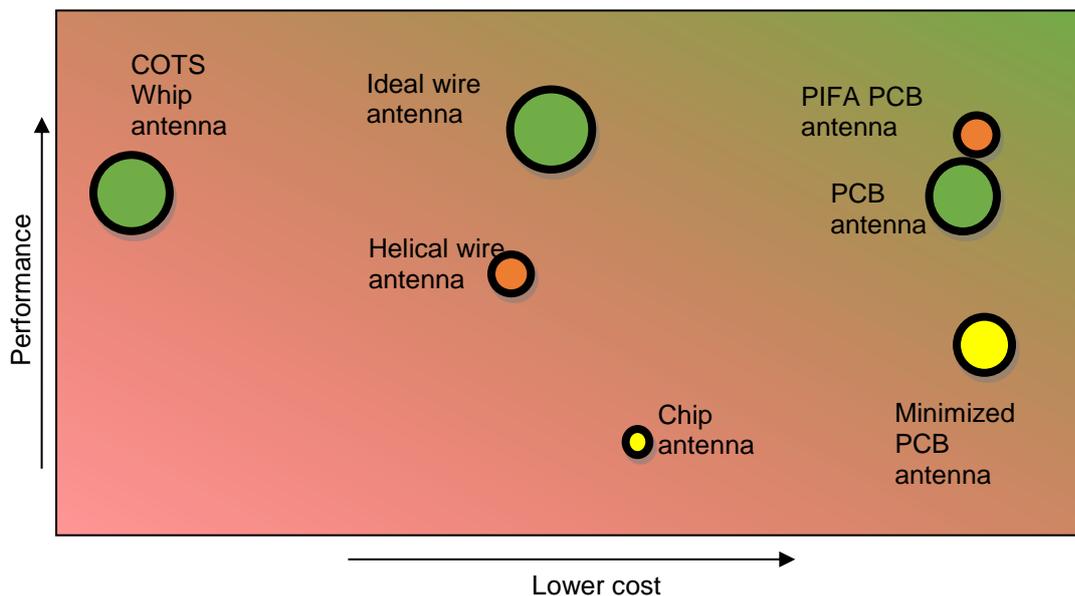
EAD
EAD

[MW868](#)
[W915-RS](#)

Used in Radiocrafts Dev. Kits
(used in FCC certifications at 915 MHz)

Example chip antenna

Mitsubishi [AM11DP-ST01](#)
Johanson Technology [0868AT43A0020E](#)
Linx Technologies [ANT-868-CHP-T](#)



9.4 2.4 GHz

At 2.4 GHz, the antennas are typically small. The difference between antenna sizes are not that large. For this band, Radiocrafts offer modules with chip antenna which can reuse certifications.

(RC241x-AT/RC241xHP-AT)

Example chip antennas:

Johanson Tech. <http://www.johansontechnology.com/antennas> several types

Fractus <http://www.fractusantennas.com/> several types

Example PCB antenna ref design:

Inverted F antenna <http://www.ti.com/lit/an/swru120b/swru120b.pdf>

Meander Inverted F antenna <http://www.ti.com/lit/an/swra117d/swra117d.pdf>

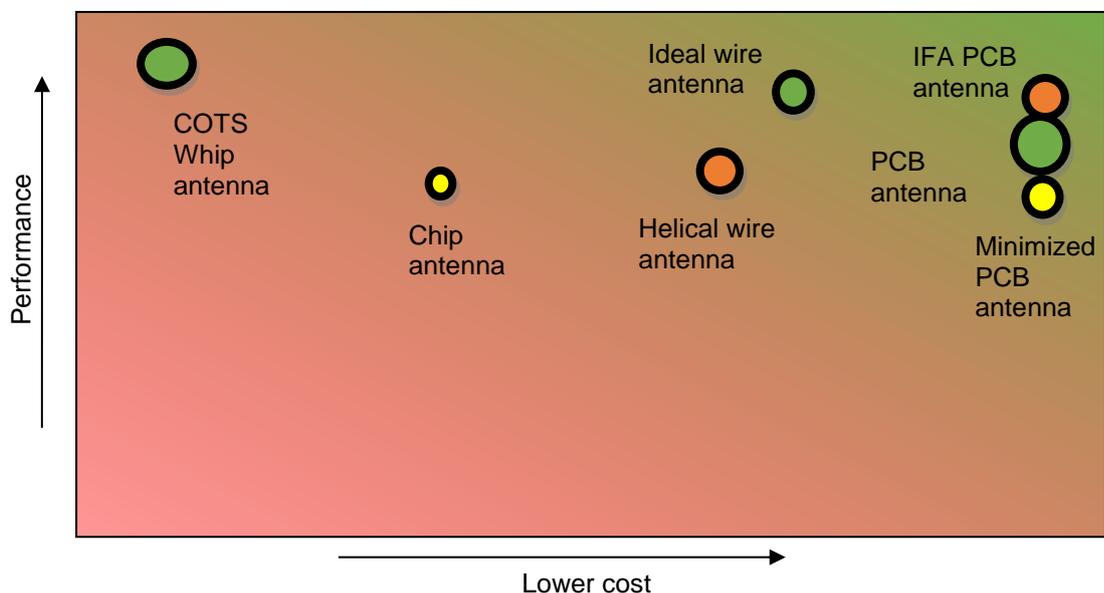
Example COTS whip antenna:

Antenova [Titanis](#) FCC certified with ZigBee modules

Linx [ANT-2.4-CW-RH-SMA](#) Very small

Pulse [W1049B050](#) Dipole with u.fl connector

In addition, most of the special antennas in chapter 5.5 can be used at 2.4 GHz



10. Document Revision History

Document Revision	Changes
1.0	First release

11. Contact Information

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