# Application Note

## Antennas for Short Range Devices

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# Table of Contents

# 1 ABBREVIATIONS

| Abbreviation | Explanation |
|---|---|
| BW | Bandwidth |
| DB | Decibel |
| PCB | Printed Circuit Board |
| RF | Radio Frequency |
| SRD | Short Range Devices |
| UHF | Ultra High Frequency |
| ZM | Z-Wave Module |

# 2 INTRODUCTION

## 2.1 Purpose

This Application Note intends to provide the antenna designer with sufficient knowledge to choose, between different antenna types, the one that will best fit his Z-Wave Application.

This document starts by describing all relevant antenna terms. Then it presents all common antenna types that are relevant for SRD applications. Finally it explains how to integrate the chosen antenna in the best manner into the application.

## 2.2 Audience and prerequisites

The audience of this document is Silicon Labs and OEM customers.

# 3 ANTENNA TERMS AND USEFUL FORMULAS

As most antennas for low power wireless applications are fairly simple structures, they can be characterized and compared using some basic terms.

**Wavelength:**

The wavelength is the distance that the radio wave travels during one complete cycle of the wave. It is important for the calculation of the antenna length.

$\lambda := \frac{c}{f}$ where "c" is the velocity of light in free space and "f" is the RF frequency.

Note that the velocity of a wave along an antenna is slower than that in free space (about 95% of “c”)

**Antenna gain:**

The gain of an antenna in a given direction is the amount of energy radiated in that direction compared to the energy an isotropic antenna would radiate in the same direction when driven with the same input power. An isotropic antenna is an ideal reference antenna that radiates energy equally in all directions. Since an antenna cannot create energy, the total power radiated by a real antenna is the same as an isotropic antenna but in some directions it radiates more energy than an isotropic, so in other directions it must radiate less energy. The antenna gain can be expressed as:

$G = D \times \eta \times m$ where D is the antenna directivity, $\eta$ is the efficiency and m the mismatch loss.

The gain is usually calculated in the direction of maximum radiation and is expressed in dBi (compare to an isotropic antenna) or dBd (compare to a dipole antenna). A dipole antenna can also be used as a reference antenna. It has a gain of 2.14dBi when compared to an isotropic antenna.

**Directivity:**

Closely related to this is the gain of the antenna. The directivity is a measure of the ability of an antenna to concentrate the radiated power in a given direction. In a fixed point-to-point radio link the antenna directivity can be used to concentrate the radiated wave in the wanted direction. But in systems where the transmitter and receiver placements are not fixed, an isotropic radiation is preferred.

**Radiation pattern:**

A radiation pattern is the graphical representation of an antenna radiation properties (field strength, polarization) as a function of space coordinates. The radiation pattern is determined in the far-field region.

**Far field region:**

The region where the angular field distribution is essentially independent of the distance from the source. This distance (Rayleigh distance) is usually defined as being greater than $2 * d^2 / \lambda$ from the source, where d is the maximum dimension (in meters) of the antenna.

**Polarization:**

All electromagnetic waves, traveling in free space, has an electric field component, E, and a magnetic field component, H, which are perpendicular to each other and to the direction of propagation. The orientation of the E vector is used to define the polarization of the wave. If the E field is orientated vertically the wave is said “vertically polarized”. Sometimes the E field rotates with time and the wave is then said “circularly polarized”.

Two antennas, whose orientations are such that the lobe maximums face one another, are optimally aligned. The system designer should try to improve the orientation characteristic as much as possible but packaging constraints or remote capability sometimes makes it impossible.

**Reciprocity**

An antenna will perform equally as a transmitting antenna as well as a receiving antenna.

**Efficiency**

The most important term when talking about small antennas is the “efficiency”. The efficiency expresses the ratio of the total radiated power in all directions to the total input power.

**BandWidth**

The antenna BandWidth (BW) represents its ability to radiate a specific frequency range. The BW of a small antenna is closely related to its Q-factor and its selectivity. A narrow BW means a high Q-factor and a good selectivity.

**Q-factor**

The concept of Q-factor (or *Quality* factor) is used to describe the antenna as a resonator. A high Q-factor means a sharp resonance and narrow bandwidth. The Q-factor can be expressed as:

Q = (antenna reactance) / (antenna resistance)

The concept of Q-value is very useful when considering small antennas. The Q-value of the small antenna is high due to the low radiation resistance and the high reactance. The smaller the antenna is, the higher the Q-value is. Hence, the bandwidth of a small antenna will be small, more difficult to match and more susceptible to de-tuning by surrounding objects.

**Return Loss:**

The Return Loss is the reflection coefficient of a mismatch between the transmitter and antenna impedances. It is expressed in decibels.

**VSWR:**

The Voltage Standing Wave Ratio of a component such as an antenna is referred to the characteristic impedance of the transmission line being used. As for the “Return loss”, the VSWR is an expression of the matching quality between the transmitter and the antenna.

**Antenna Resonance:**

Any tuned circuit is in resonance when both the inductor and the capacitor reactances are equal. At resonance the reactances completely cancel, leaving only the resistive part of the impedance. Since the antenna impedance equals the radiation resistance at resonance, it can be said that the antenna is operating at maximum radiating (or receiving) efficiency. This impedance needs to be matched to the transceiver impedance to get the best performances. As a 50ohm SAW filter is used on the Z-Wave Modules, the antenna has to be matched to 50ohms.

**Friis transmission formula**

The Friis transmission formula describes the power received by an antenna in terms of power transmitted by another antenna.

$$Pr := \frac{Pt \cdot Gt \cdot Gr \cdot \lambda^2}{(4 \cdot \pi \cdot r)^2}$$

Pr = Power received (W)   Gt = Receiver antenna gain

Pt = Transmitted Power (W)   Gr = Transmitting antenna gain

r = Distance between antennas (m)

$\lambda$ = Wavelength (m)

It takes 6 dB to double or halve the radiating distance, due to the inverse square law.

**Electric field vs. Power transmitted (Far field)**

The electric field strength at a distance from a transmitting antenna is given by:

$$E_{V \cdot m^{-1}} := \frac{\sqrt{30 \cdot Pt \cdot Gt}}{r}$$

Pt = Transmitted Power (W)

Gt = Transmitting antenna gain

r = Distance between antennas (m)

**Multipath fading**

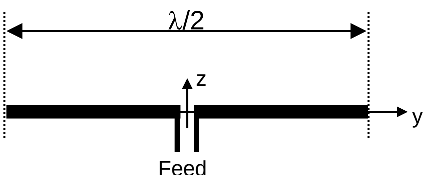
Multipath fading is caused by signals arriving at the receive antenna with differing phases. This is because signals from the transmitter may follow different paths when traveling to the receiver. Portions of the original signal may travel in a direct path, while others may arrive at the receiver by reflecting on ground or other objects present in the room. These differences in phase result in constructive and destructive interferences at the receiving antenna, that affects the amplitude of the signal developed at the antenna. This can occur even if there is line-of-sight between the transmitter and receiver locations.

# 4 ANTENNA TYPES

Z-Wave Modules transmit in the 800-900 MHz range. The communication range that can be achieved with these modules depends not only on the output power and receiver sensitivity but also on the antenna solution. It is therefore important to understand the different antenna characteristics and the tradeoffs that need to be made in order to select the most appropriate one for a specific application.

In all low power applications like the SRD, key elements for an antenna choice are size requirements, radiation performance, ease of design, manufacturability and cost. All of these elements are discussed for each of the antenna types described in the following.

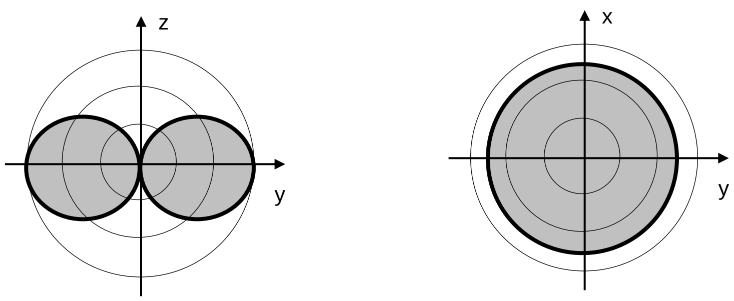
## 4.1 Dipole antenna




A dipole antenna is a differential structure measuring ½ wavelength from end to end. In order to interface with the single ended output of the Z-Wave Single Chip, a balun must be inserted in the system at the point where the feed line joins the antenna. A balun is a RF transformer that offers the flexibility to transform a balanced signal to an unbalance signal.

The dipole may actually be shorter or longer than ½ wavelength, but this fraction provides the best antenna efficiency. The antenna should be kept away from the ground plane and any metallic or conductive objects. Its impedance of about 73ohm makes it very easy to be matched to 50ohm.

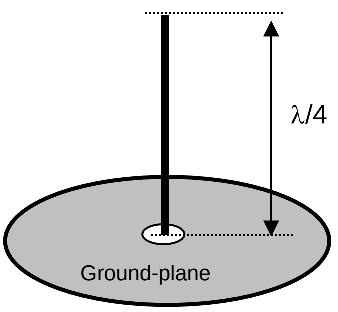
The gain of the dipole is 2.14 dBi. The polarization of the electromagnetic field corresponds to the orientation of the element. It can either be horizontally or vertically polarized




Example of the radiation pattern of a dipole antenna

A dipole antenna is typically not used in mobile communications because it is twice as big as a 1/4 wave monopole antenna. Its performance is however very good and it is very easy to implement in an application if there is enough place. It is a cheap solution as its cost is limited to the matching network and the balun.

## 4.2 Monopole antenna




A monopole antenna, also called a whip antenna, is basically a 1/4 wavelength wire that stands above a ground-plane. It needs the ground plane to operate properly, but the "far" open end should be kept away from it.

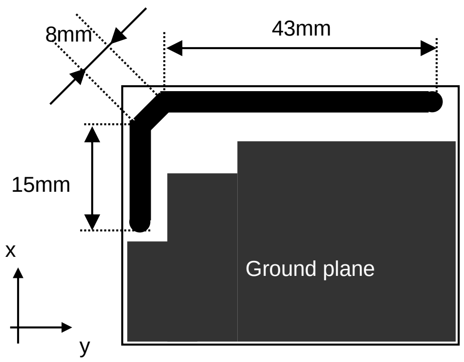
A monopole antenna is fed single-ended and has an impedance of 37 Ohms at the resonance frequency. That makes it easy to be matched to 50ohm.

Monopole antennas are very easy to design and their resonance frequency can be adjusted by slight changes of the antenna length. As for the dipole antenna, the polarization of the monopole antenna can either be horizontal or vertical, depending on its orientation. Its radiation pattern is also similar to the dipole and its gain is in theory 3dB higher than the dipole antenna because its power is only radiated in the upper half plane due to the ground plane.

A monopole antenna is the best solution when the physical size is acceptable and a ground plane is present. Having a smaller ground plane will affect the performance of the antenna and tilt the radiation pattern upwards.

Implementing a monopole antenna with a piece of wire requires some additional manufacturing costs because it usually has to be hand-assembled and may require few adjustments.

An alternative to the external wire solution is to implement the monopole antenna as a track on the PCB.



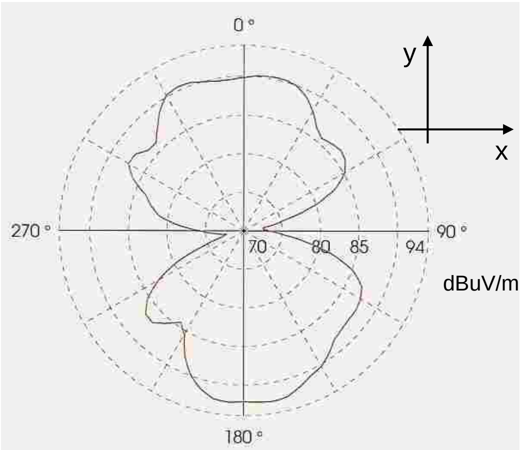
PCB antenna layout

Note that the length of this type of antenna is 10 to 20% shorter than the calculated 1/4 wavelength depending on the dielectric constant and the thickness of the board. The designer should avoid making 90º angles in the antenna trace.

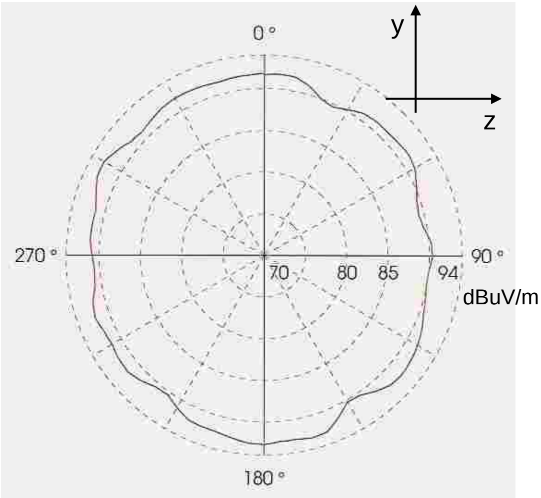
The antenna trace should be kept away (6mm or more) from other circuitry and ground. The overall size of the board and ground is not critical. As the trace runs parallel to the ground-plane, the impedance is much lower (approximately 10 Ohms) than for the first monopole antenna but still can easily be matched to 50ohms. Tuning is not critical as small variations in inductor value or antenna length will not have a great effect on performances.

Integrated PCB monopole antenna generally do not perform as well as externally mounted types, however they result in physically compact equipment and are the preferred choice for portable applications.

As seen from the following radiation pattern, the vertical polarization of the antenna is fairly omni-directional and its gain is about 4dBi.




Radiation pattern in horizontal polarization when the module is placed horizontally.

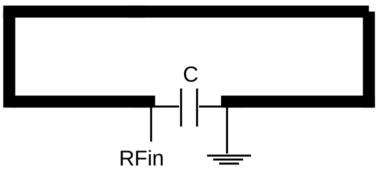



Radiation pattern in vertical polarization when the module is placed vertically.

This kind of monopole antenna has the advantages of being a cheap solution with good performance.

If the module size is still critical, a simple alternative to the whip antenna is to cut it shorter and add an inductor near the base of the whip to compensate for the high capacitive reactance. This type of antenna can have performance nearly equal to that of a full size whip.

### 4.3 Loop antenna




A loop antenna is different from a whip antenna, in the sense that both ends of the antenna are terminated. A loop antenna can be single ended or differential ended. If it is single ended, the far end of the loop must be connected to ground through a capacitor.

There are two sizes of loop antennas: electrically small and electrically large. For Short Range Devices, only small loop antennas are being considered as a large loop has a typical circumference approaching one wavelength.

The loop can be considered as a big coil and is typically tuned to parallel resonance at the desired frequency by adding a parallel capacitor. In this case, the input impedance of the loop antenna will be very high (kohms). A small loop will have a very narrow bandwidth (high Q). This is an advantage for the selectivity of the device but can makes the tuning extremely critical. Once it is tuned, the loop antenna is however not easily detuned by hand effects.

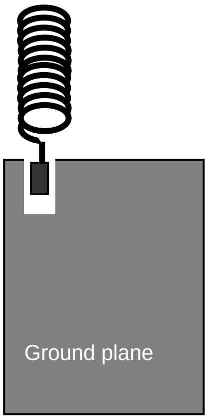
Furthermore, loop antenna radiates magnetic field. Its performance is therefore improved when close to the body. It makes it a good solution for remote or on-body applications like pagers.

Polarization is on the same surface as the loop, with an omni-directional radiation pattern.

The biggest disadvantage of loop antennas is that they have a poor efficiency when compared to the two previous considered antenna types. This is because its radiation resistor is much lower than its loss resistor. Its gain depends on the loop size but a realistic gain that in practice can be expected is about –8dBi.

Like the PCB whip antenna, the loop antenna can be low cost when it is completely integrated into the PCB. The antenna tuning is often done with a variable capacitor, which adds to the cost. It may be however practical to use a non-variable capacitor but this requires careful adjustment in engineering stages, to ensure that it is properly tuned with a standard value capacitor.

## 4.4 Helical antenna




Helical antennas may be constructed of any conductive material like copper, steel, or brass. They can be characterized as either small helicals, which operate in normal mode (right angle to the helix axis), or large helicals, which operate in axial mode (along the axis of the helix). A helical antenna is small if its diameter and length are both much smaller than one wavelength, that is usually the case for SRD applications.

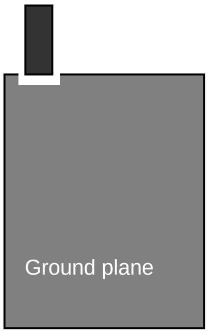
The impedance of a helical antenna depends on numerous parameters: coil diameter, coil loop pitch, coil length (or number of turns), and frequency. Variations in any of these parameters, nearby objects or human body can “detune” the antenna away from resonance. That makes them much more difficult to optimize than monopole antennas and theirs optimization is usually done empirically. They can be trimmed by spreading or compressing the length of the coil and the required dimensional tolerances can be difficult to achieve in production. The antenna can be glued on the PCB but be aware that it might change significantly the dielectric constant in which the field is generated, hence de-tuning the antenna

The efficiency of an helical antenna can be higher than a non helical antenna having the same dimension. However, its gain is usually about 5 dB lower than the gain of a full size monopole antenna. Furthermore, if for size purpose the helical is placed in proximity of the ground plane, it will make its gain even lower.

Helical antennas are circularly polarized, that is, the radiated electromagnetic wave contains both vertical and horizontal components. This is unlike the dipole, which only radiates normal to its axis.

From a size point of view, the helical antenna is quite attractive, as its length can be much shorter than a full size monopole antenna. If the coil is wounded tightly enough, it may be shorter than one-tenth of a wavelength

### 4.5 Chip antenna




Chip antennas are surface mounted devices. They are the smallest antennas available and are designed for frequencies from 300MHz to 2.5GHz. These devices have a very narrow bandwidth and must be made at the exact frequency. They are ground-plane dependent and are therefore easily detuned by hand effects. Chip antennas are usually tuned at the manufacturer's site.
They have a good gain considering their size but still lower than a monopole antenna. The polarization is parallel to the long axis of the chip, so maximum radiation is perpendicular to the long axis.

A chip antenna is probably the most expensive solution as it is usually a customized product.

### 4.6 Antenna type summary

To summarize, monopole antennas are physically larger structures, intended for applications that demand the best range. Monopole antennas are also by far the easiest antennas to design and apply and they also give a good range. Helical antennas and small loop antennas are a good compromise if the application size is the most critical parameter. The resulting assembly generally can be completely enclosed and made quite compact. They are more difficult to set up and optimize than whip antennas, since the antenna's characteristics are strongly influenced by nearby objects. Loop antennas provide the poorest range of the antennas considered.

The following table gives a summary of the key elements for all the antenna types presented in this application note.

| ANTENNA TYPES | PERFORMANCES | | | Size | Design simplicity | Cost | Manufact urability | Immunity to proximity effects |
|---|---|---|---|---|---|---|---|---|
| | Gain | Radiation pattern | Selectivity | | | | | |
| **Dipole** | *** | *** | ** | * | *** | *** | ** | ** |
| **Monopole** | *** | *** | ** | ** | *** | *** | ** | ** |
| **Helical** | ** | ** | *** | *** | ** | ** | * | * |
| **Loop** | * | ** | *** | *** | * | ** | * | *** |
| **Chip** | * | ** | ** | *** | *** | * | *** | * |

*** Best relative performance.

* Worst relative performance.

# 5 ANTENNA PLACEMENT GUIDELINES

Now that the antenna type is chosen, the next step is to integrate it into the application.

## 5.1 Antenna placement:

Antenna choice and location is crucial for the success of a low-power wireless application. Here are several key points to be considered when implementing an antenna in a specific application:

- Where possible, the antenna should be placed on the outside of the product. In that case, the connection between the Z-Wave Module and the antenna must go through a 50ohm microstrip line, a coaxial cable or a combination of both.

- Try to place the antenna as far away as possible from the human body. Indeed, the human body absorbs RF radiation in the UHF frequency range, especially above 750MHZ. The RF signal can be attenuated up to 20dB when passing through the user's body.

- The antenna must not be placed inside a metal case, as the case will shield it. Also, some plastics can significantly attenuate RF signals and these materials should not be used for product cases, if the antenna is going to be inside the case. Care should be taken to keep the antenna away from metal. If the conductive area is large in terms of wavelength (one half wave or more), it could act as a reflector and cause the antenna to not radiate in some directions.

- Regulatory agencies prefer antennas that are permanently fixed to the product. In some cases, antennas can be supplied with a non-standard connector that is used to prevent antenna substitution.

- The RF circuitry should be implemented on a PCB with a ground plane at the secondary layer ensuring proper grounding of all ground connections. This ground plane should not extend into the region where the antenna is to be implemented as it would alter the antenna terminal impedance due to parasitic capacitance from antenna to ground plane.

- The RF transceiver and its antenna should be located as far from any noise source as possible: Microprocessors and micro-controllers tend to radiate significant amounts of radio frequency, which can cause desensitization of the receiver if the antenna is in close proximity. This becomes worse as logic speed increases, because fast logic edges are capable of generating harmonics across the UHF range which are then radiated effectively by the PCB tracking. To minimize any adverse effects, the antenna and the module should be situated as far as possible from any such circuitry and keep PCB track lengths to the minimum possible. If you have the option, choose a microprocessor with the slowest rise and fall time you can use for the application to minimize the generation of harmonics in the UHF band.

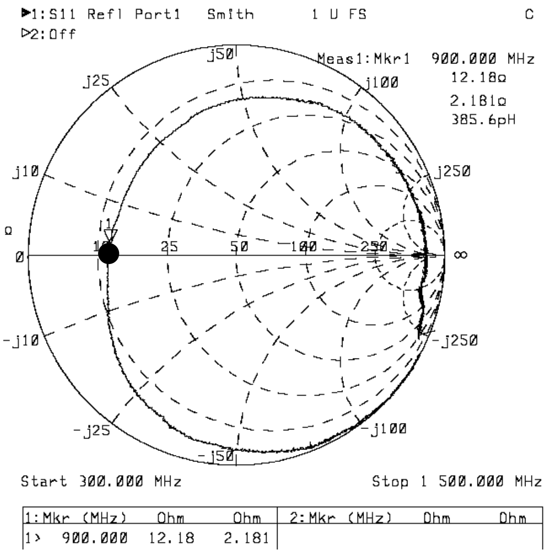
### 5.2 Antenna matching

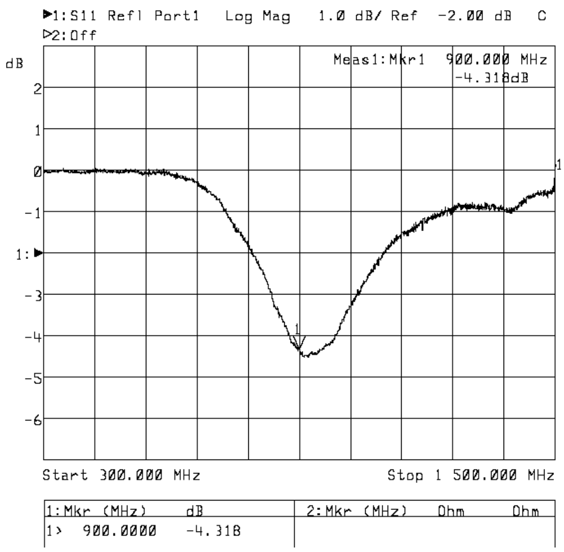
Many suitable antenna designs are possible, but efficient antenna development requires access to antenna test equipment such as a network analyzer, calibrated test antennas, screened room, etc. Unless you have access to this equipment, the use of a standard antenna design or a consultant is recommended.

The matching of a Z-Wave Single chip requires a network analyzer (Agilent 8714ES or equivalent). This analyzer is used to measure the antenna impedance and return loss. As the impedance of the SAW filter is around 50ohm at the transmitting frequency, the antenna impedance has to be matched to 50ohm. The “return loss” is another way to look at the antenna resonance frequency. It represents the attenuation of the signal reflected back by the antenna to the generator.

**Matching procedure:**

- The antenna size is adjusted to have resonance (reactance=0) at the desired frequency. The following antenna is resonant at around 900MHz where it has a return loss of about –4.5dB. This return loss can be improved by adding only two matching components

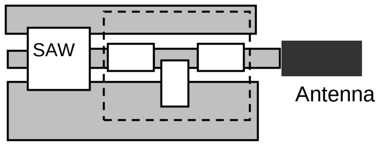


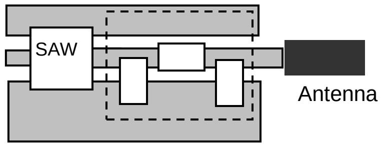

- The component values of the matching network are adjusted until the impedance seen from the SAW filter output is about 50ohm or the return loss is <-9dB. The closer to 50ohm the impedance is, the lower the return loss will be.

The matching network can either be a “T”, a “π” structure or only two components.

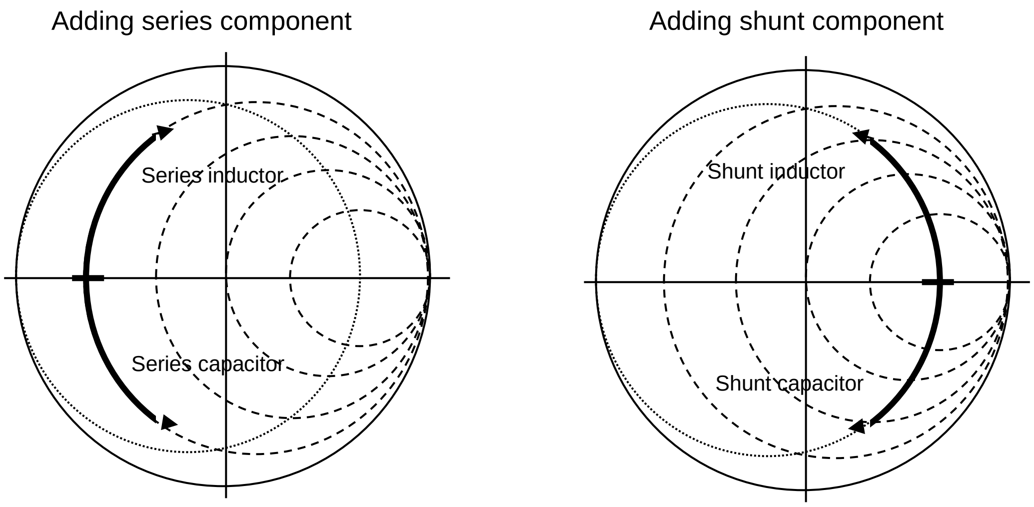
“T” structure



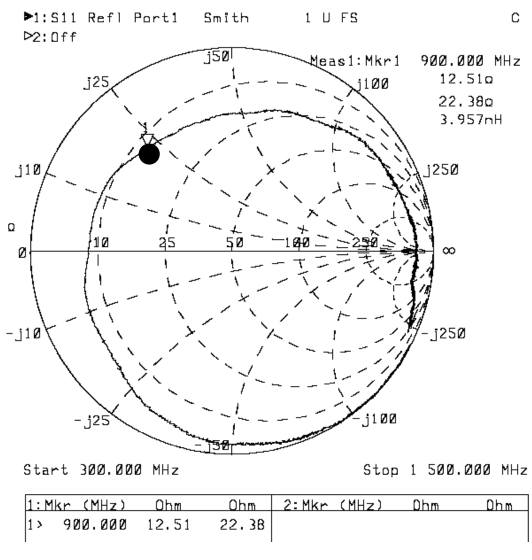

“π” structure



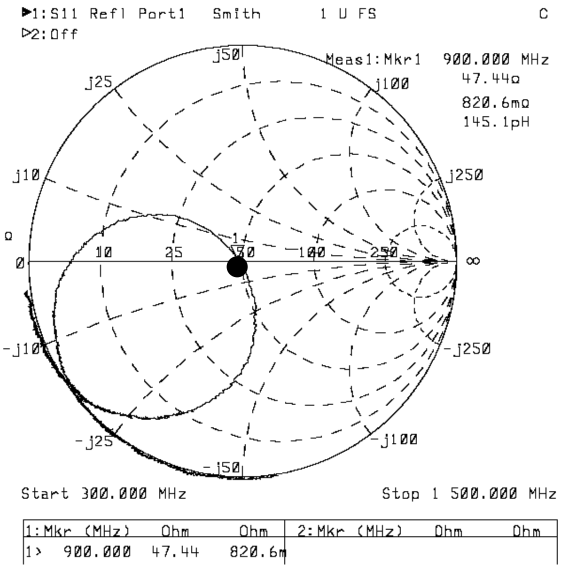
By introducing matching components, the antenna impedance is changing as shown in the following drawing

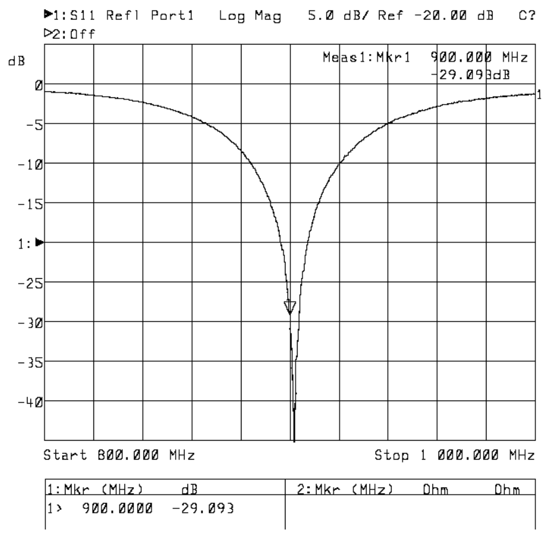



- By adding a 3.9nH series inductor with the antenna, the impedance is moved as followed:



- Finally, by adding a 5.6pF shunt capacitor, the impedance moves to the 50ohm point and the return loss becomes better than –25dB at 900MHz

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- Once the matching is completed, the radiation pattern and the antenna gain can be measured in an anechoic screened room.

The major difficulty with small antennas is the validity of the measurement performed: proximity of the hands, connectors, and environment may completely modify the measurement. It is recommended to perform measurements as close as possible from the final configuration.

# APPENDIX A ELECTRICALLY SMALL LOOP ANTENNAE

This appendix will discuss about the implementation of a small loop antenna for the Z-Wave modules family.

Loop antennas despite their poor gain are interesting because they also radiate magnetic power, which make them a good choice for handheld product such as remote controls.

## Appendix A.1 Equivalent circuit of the small loop antenna

**Figure 1** Equivalent schematics to the small loop antenna

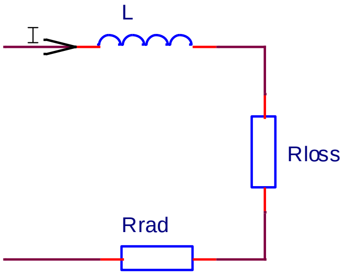



Figure 1 shows the equivalent circuit of a small loop antenna. L is the inductance of the loop. Rrad is the radiation resistance that represents the energy Prad actually radiated by the antenna.

$$\boxed{Prad = Rrad.I^2} \quad (1)$$

Rloss is the resistance due to loss in the material. The energy Ploss will be dissipated in heat.

$$\boxed{Ploss = Rloss.I^2} \quad (2)$$

It is possible to calculate an approximate value for the three components of the equivalent circuit.

According to 0 the radiation resistance may be approximated by

$$\boxed{Rrad = 320.\pi^4.\left(\frac{A^2}{\lambda^4}\right)} \quad (3)$$

Where A is the area of the loop (in square meters) and λ is the wavelength of the signal (in meters).

In order to easier the approximation of the loss resistance, two assumptions need to be made. Recalling that the skin depth in the copper is approximately 2.25µm at 900MHz, it is only a small fraction of the thickness of the PCB (6.4% for a 35µm thick trace). In the same way, the thickness of the loop is a small fraction of its length (several centimeters).

Assuming that the two conditions are fulfilled, one gets

$$\boxed{Rloss = \frac{l}{2.w}.\sqrt{\pi.f.\rho.\mu_0}} \quad (4)$$

Where l is the length of the loop in meters, f is the frequency in Hertz, $\rho$ the resistivity of copper in $\Omega$.m (= 18E-9), $\mu_0$ the permeability of air in H/m (= 1.26E-6), and w is the width in meters of the PCB trace constituting the loop.

The last component in the model of the Figure 1 is the loop inductance. Its value can be approximated by: $\boxed{L = \frac{\mu_0 . l}{2.\pi} . \left[ \ln\left(\frac{4.l}{w}\right) - 2 \right]}$ (5)

## Appendix A.2 Resonance and matching

Because the input resistance of the loop is very low and its reactance very high, a way to match it to 50$\Omega$ (output of the SAW filter) is to cancel the inductance of the loop with a capacitor (see Figure 2) in order to reach the resonance and then to tap the capacitor in order to set the input impedance to 50$\Omega$ as it is shown in Figure 3(b).

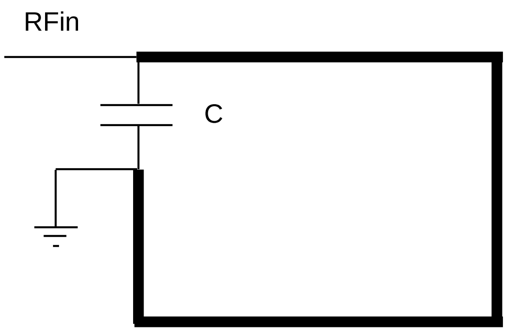



**Figure 2** Loop antenna and Capacitor

At resonance, the impedance of the inductor is the opposite of the impedance of the capacitor therefore one gets the following expression for C:

$$\boxed{C = \frac{1}{L.\omega^2} = \frac{1}{4.L..\pi^2.f^2}}. \quad (6)$$

In Figure 3 (a), Rser is the total serial resistance, which is the sum of the loss resistance Rloss, the radiated resistance Rrad as well as the ESR of the capacitor. One can then calculate the serial quality factor of the loop.

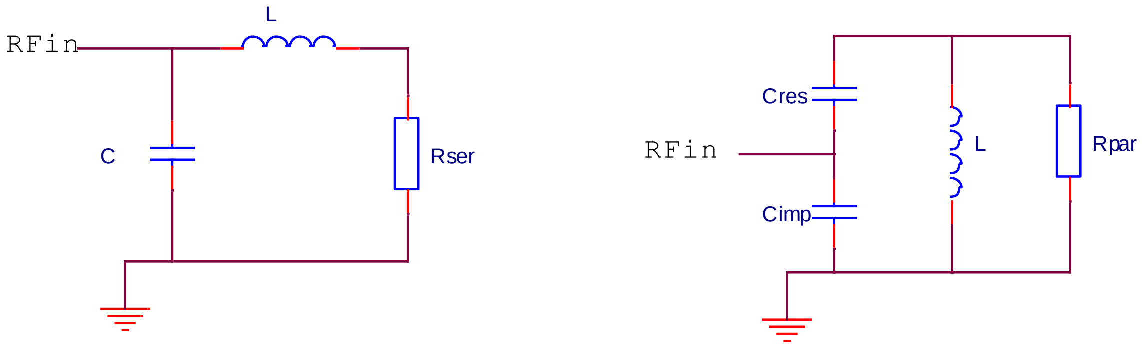



**Figure 3 (a)Loop and matching C model (b) with tapped capacitor**

$$\boxed{Qser = \frac{L.\omega}{Rser} = \frac{2.\pi.f.L}{Rser}} \quad (7)$$

Now, it is possible to convert the serial resistance Rser in a parallel resistance Rpar with the formula:

$$\boxed{Rpar = Rser.\left(1 + Qser^2\right)} \quad (8)$$

Because Rser is small, Qser is large and Rpar is also large. Cres is used to tune the resonance frequency and Cimp is used to adjust the input impedance.

By having now two capacitors it is possible to control the input impedance of the loop antenna. At the resonance one gets:

$$\boxed{Zin = Rpar.\left(\frac{1}{1 + \frac{Cimp}{Cres}}\right)^2} \quad (9)$$

Recalling that Cimp and Cres are in series, one gets from (6)

$$\boxed{\frac{Cimp + Cres}{Cimp.Cres} = \frac{1}{C}} \quad (10)$$

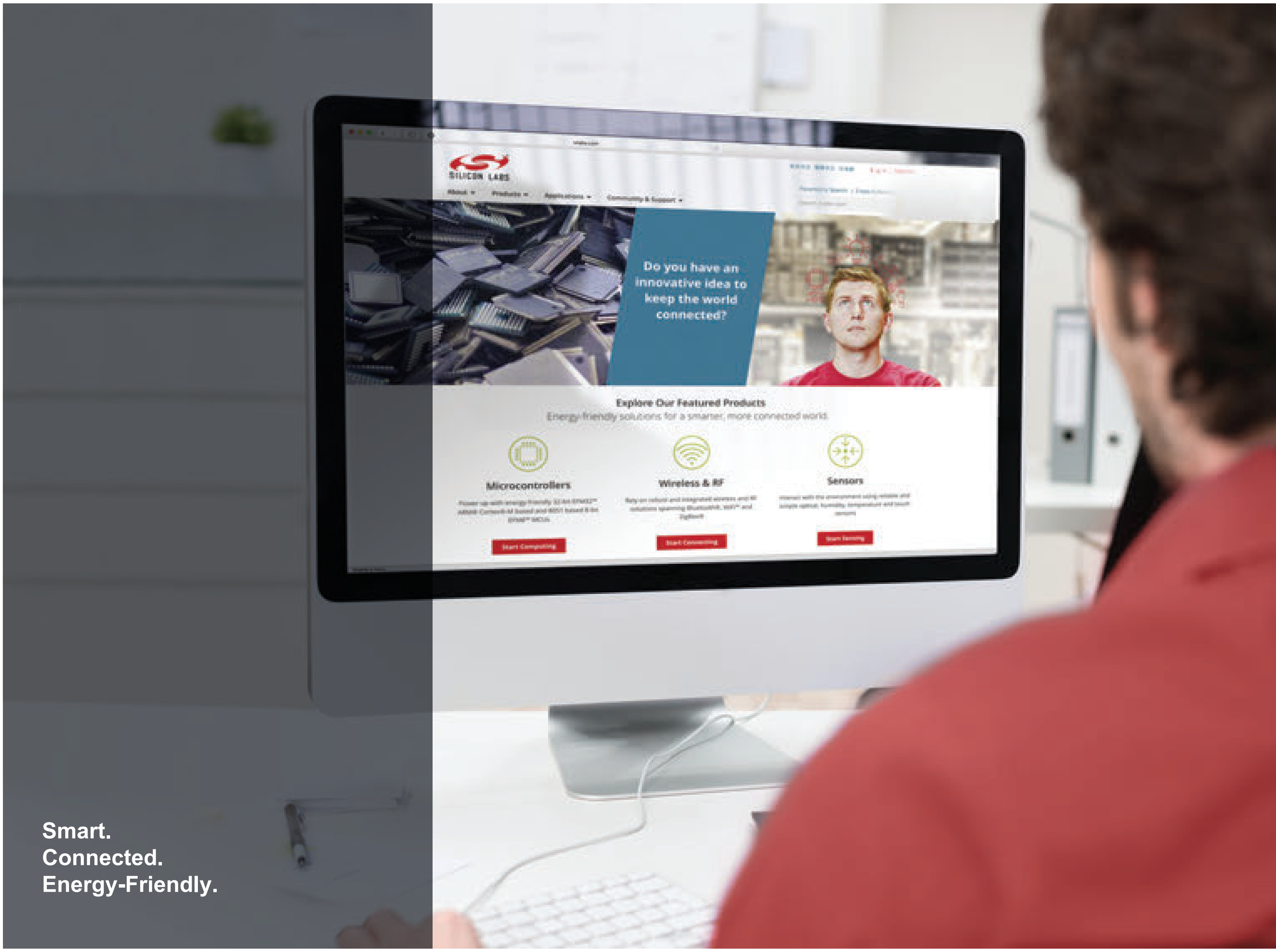
By combining (7), (8), (9) and (10) one gets the following expressions for Cres and Cimp.

$$\boxed{Cimp = \frac{1}{2.\pi.f.\sqrt{Rser.Zin}}} \qquad (11)$$

$$\boxed{Cres = \frac{1}{L.(2.\pi.f)^2 - 2.\pi.f.\sqrt{Rser.Zin}}} \qquad (12)$$

# 6 REFERENCES

C.A. Balanis ,Antenna theory, ISBN 0-471-59268-4

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**Silicon Laboratories Inc.**
**400 West Cesar Chavez**
**Austin, TX 78701**
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