AN003
SRD Antennas

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Keywords

- *Antenna theory*
- *Small antennas*
- *PCB antenna design*
- *Body-worn and handheld antennas*

Introduction

This application note addresses one of the most important issues faced by a designer of short-range radio systems; the antenna design. Key elements are the antenna size requirements and radiation performance, ease of design and manufacturability. In particular the theoretical background and practical aspects of *small* antennas will be addressed.

Chipcon is a world-wide distributor of integrated transceiver chips designed to be used in all kinds of SRDs and with different antenna solutions.

Overview

The communication range that can be achieved in a radio system depends very much on the antenna solution. It is important to understand the difference between different antennas, and the trade-offs to be made, in order to select the right antenna solution for a particular application.

In many SRDs (Short Range Devices) the physical size is restricted, and hence the antenna ought to be small as well. The important aspects of small antenna design are presented in this application note. Several PCB integrated antenna solutions are shown, and a practical design example with measurement results is given. The design example is based on the CC400DB Demonstration Board design.

For long-range systems requiring high efficiency antennas, external resonant antennas must be used. An overview of these kinds of antennas is also given.

Applications involving body-worn or handheld devices represent a special challenge for the antenna design. In the end of this note these problems are addressed.

Antenna fundamentals

Antenna gain

The antenna gain describes the antenna's ability to radiate power in a certain direction when connected to a source. Usually we calculate the gain in the direction of maximum radiation.

$$G = D\mu m$$

where D is directivity, μ is efficiency and m is mismatch loss.

The gain is usually expressed in dBi or dBd. Here *dBi* means that the directivity D is measured compared to an isotropic radiator (equal radiation in all directions). *dBd* is used when the directivity is referring to the directivity of a dipole antenna.

A dipole antenna itself has a gain above that of an isotropic radiator, which we can express as dBd = 2.15 dBi.

Directivity

The *directivity* of the antenna describes the radiation pattern. The antenna can "see" and radiate better in some directions than others. In a fixed point-to-point radio link antenna directivity can be used to concentrate the radiation beam in the wanted direction. But in systems where the transmitter and receiver placements are not fixed, we want the radiation to be equal in all directions. That is, we want the antenna to be *omni-directional*.

EIRP

Effective Isotropic Radiated Power (EIRP) is a term used to describe the effective radiated power from an antenna taking the gain of the antenna into account. Regulative specifications often refer to EIRP for maximum output power measurements.

EIRP = G P

where G is the antenna gain and P is the output power from transmitter.

Efficiency

The most important term when talking about small antennas is the *efficiency*. The efficiency express the ratio of power radiated from the antenna and the power dissipated in the antenna structure (heat).

The efficiency is

$$\eta = \frac{R_r}{R_d + R_r}$$

where R_r is radiation resistance (wanted) and R_d is dissipation resistance (unwanted).

When the radiation resistance is low, as for small antennas, any circuit loss (resistance) will give a significant reduction in efficiency. This is especially the case for small magnetic loop antennas.

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.

Usually in circuit design we want elements to have a high Q-factor in order to reduce the circuit loss. However, talking about antennas we want a low Q-factor because the “loss” involved is the radiation we really want. A low-Q antenna is easier to match and tune, and have a wider bandwidth.

McLean [3] has described the fundamental theoretical limit for the minimum Q-value of a small antenna. If the antenna can be placed inside a sphere of radius a, the minimum Q-value for a loss-less antenna is

$$Q_{\min} = \frac{1}{(ka)^3}$$

where

$$k = \frac{2\pi}{\lambda}$$

This expresses the absolute minimum Q value the antenna can take. Unfortunately, the theory does not tell us *how* to implement a minimum Q antenna.

The antenna Q can of cause be reduced by introducing loss (a resistor) in addition to the radiation resistance, but this would reduce the antenna efficiency, see below.

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, the higher Q-value we expect. Hence, the bandwidth of a small antenna will be small, more difficult to match and more susceptible to de-tuning by surrounding objects.

Bandwidth

The bandwidth of a small antenna is closely related to the Q-factor and the efficiency. It can be shown that the maximum bandwidth is given by [4]:

$$BW = \frac{16(\pi r)^3}{\eta \lambda^3}$$

Where the antenna is confined within a sphere of radius r, λ is the wavelength and η is the radiation efficiency.

We see there is an inverse proportional relationship between bandwidth and efficiency; a large bandwidth means low efficiency for a given antenna size.

Reciprocity

An antenna will operate equally as well as a transmitting antenna, or as a receiving antenna. This is called *reciprocity*.

Polarisation

An electric antenna mounted vertically is said to be vertically *polarised* because the radiating electric wave field component is vertically oriented. A receiving antenna should also be oriented to have the same polarisation direction in order to receive the strongest possible signal. If not, we will experience a *polarisation loss*.

Resonant antennas and small non-resonant antennas

Electric and magnetic antennas

In general we classify antennas as electrical or magnetic antennas. The difference between the two is the primary field they set up close to the antenna. This is termed the *near field*. The electrical antenna sets up a predominantly electric field; that is, the electric field component is much stronger than the magnetic component. For the magnetic antenna the magnetic field dominates in the near antenna region.

The far field, the electromagnetic field far away from the radiation antenna, is the same no matter if the antenna operates as a magnetic or electric field source. In the far field the relationship between the electric field component and the magnetic field component is given by the free space radiation impedance that is $120\pi\ \Omega$ ($377\ \Omega$).

The far field extends approximately from one wavelength and outwards.

Dipoles, monopoles and stub antennas are common electric antennas. Loop antennas are magnetic. Helix antennas are generally a combination of the two.

Resonant antennas

Antennas are usually resonant structures, resonating at the frequency of operation. Therefore their physical size (length or perimeter) is integer fractions or multiples of the wavelengths they are designed for. The antenna impedance (the input impedance looking into the antenna) in resonance is then purely resistive (no reactive component).

A dipole antenna is an example of a resonant antenna. Each “leg” is one quarter of the wavelength. The monopole is another example where the antenna is one quarter of the wavelength place above a ground plane.

The normal mode helical antenna (NMHA) exhibits self-resonance even when the antenna length in the axial direction is considerably shorter than the resonant monopole. This antenna can be viewed as a quarter-wave monopole winded up like a coil.

Small antennas

In many designs involving short-range devices, the physical size of the product is restricted. Implementing antennas with a restricted physical size involves several important problems. A small antenna is defined as an antenna where the maximum physical dimensions are a fraction of the wavelength of interest, usually $< \lambda/10$. Moreover, these antennas are usually not self-resonant, but made resonant by some sort of loading, commonly by using lumped elements.

A small antenna will have a low radiation resistance and a large reactance by itself. Usually a matching network cancels the reactance, and the resistance is transformed to a higher resistance by a transformation network. The antenna reactance itself may very well be a part of the transformation network.

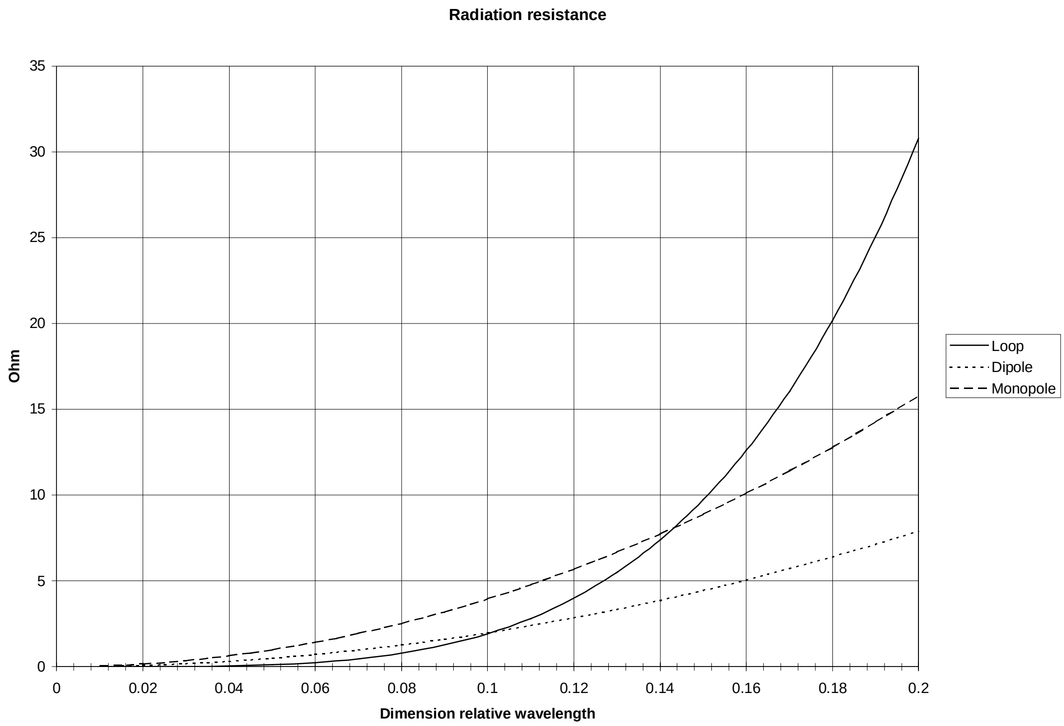
Because the radiation resistance is low, any loss in the antenna structure itself, or in the matching network will give reduced antenna efficiency (see definition below). Tuning out a very high reactance will also involve high reactance elements in the matching network. These high reactance elements tends to have significant losses, thereby giving reduced efficiency in the antenna.

To compare the small loop antenna, the short dipole and the short stub (monopole) we can compare the radiation resistance when the diameter of the loop and the length of the dipole and monopole are equal. The radiation resistance in terms of (d/λ) is given by:

$$R_{r,loop} = 20\pi^6 \frac{d^4}{\lambda^4}$$

$$R_{r,dipole} = 20\pi^2 \frac{d^2}{\lambda^2}$$

$$R_{r,monopole} = 40\pi^2 \frac{d^2}{\lambda^2}$$

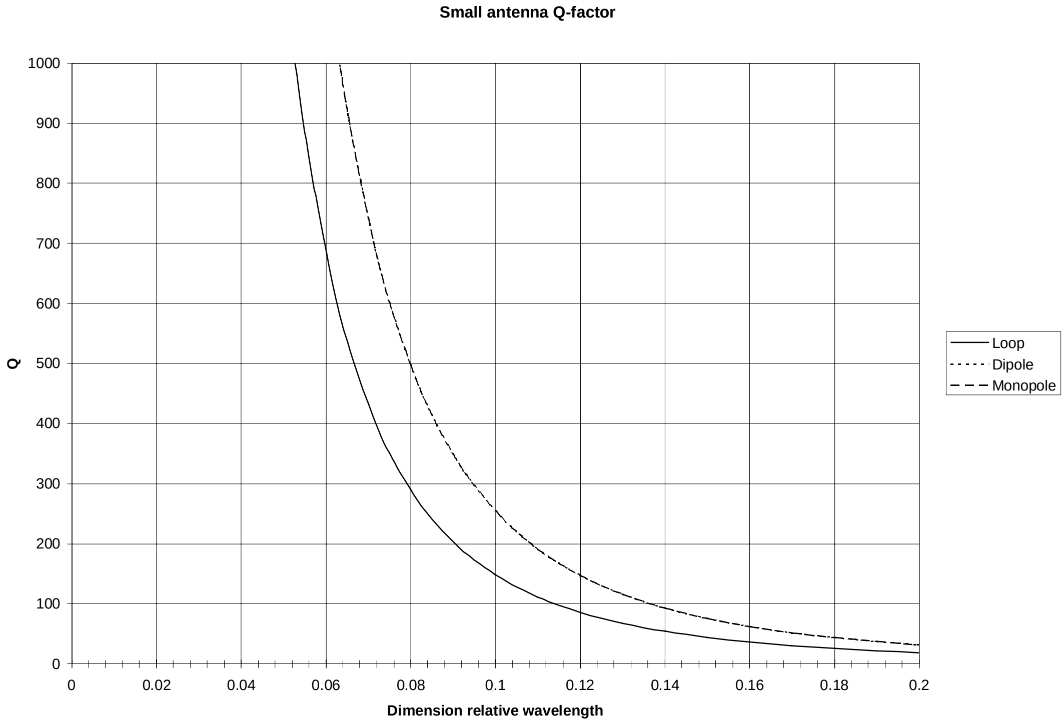


We can in the same way plot the Q-factor for the three antenna structures. The Q-factors are given by:

$$Q_{loop} = \frac{4.6}{\pi^3 \left(\frac{d}{\lambda}\right)^3}$$

$$Q_{dipole} = Q_{monopole} = \frac{7.9}{\pi^3 \left(\frac{d}{\lambda}\right)^3}$$

The Q-figure curves are plotted below:



We see that the Q-factor for the loop is half of that the dipole and monopole have. In this respect the loop utilises the physical dimensions more efficiently than the dipole and monopole. This can be explained by the two-dimensional structure of the loop, while the monopole and dipole are one-dimensional structures only (a string).

But, we did also see that the radiation resistance for the loop is less than for the dipole and monopole. In a practical implementation this has to be taken into account, giving a larger transformation ratio for the impedance matching network, which is more difficult to achieve without additional loss. Also taking the loss in the antenna structure itself into account (radiation resistance is calculated assuming a loss-less structure), the efficiency of the loop antenna will be less than for the dipole and monopole.

For small high-Q antennas, the dissipation loss in the antenna structure and loss in the matching network will dominate the overall Q. Therefore, in practice, the Q of the loop and the monopole will not be much different. However, the efficiency of the monopole will be larger because the radiation resistance is larger compared to the dissipation resistance.

If we compare an antenna for 433 MHz to be implemented in a 5 x 5 cm of PCB area, d/λ = 5 cm / 69 cm = 0.07. The loss-less Q of the loop is 433 compared to 743 for the dipole / monopole. The radiation resistance is 0.46, 0.96 and 1.93 Ohm for the loop, dipole and monopole respectively. That is, the radiation resistance for the loop is four times less than for the monopole. The low radiation resistance of the loop is expected to be smaller than the dissipation resistance giving low antenna efficiency. By bending the monopole antenna inside the area available, the length of the monopole could be even longer than the 0.07λ. Exploiting the area better, getting a monopole structure of twice the length (0.14λ), would give a radiation resistance of 7.7 Ohm, over 16 times higher than for the loop.

Design equations for small antennas

This is a summary of the design equations for *small* antennas for a given radio wavelength λ, mainly based on [4].

Short dipole
For a dipole of length 2 h the impedance is given by:

$$Z_{dipole} = 80\pi^2 \frac{h^2}{\lambda^2} - j\frac{60}{\pi}\frac{\left[\ln\left(\frac{h}{r_0}\right)-1\right]}{\frac{h}{\lambda}}$$

where r_0 is the conductor radius.

The radiation resistance is the real part of the impedance:

$$R_{r,dipole} = 80\pi^2 \frac{h^2}{\lambda^2}$$

The dissipation resistance is given by:

$$R_{d,dipole} = \frac{l}{3\pi r_0 \delta\sigma}$$

where r_0 is the conductor radius, δ is the skin depth, and σ is the metal conductivity.

The Q-factor is expressed by:

$$Q_{dipole} = \frac{\mathrm{Im}\{Z_{dipole}\}}{\mathrm{Re}\{Z_{dipole}\}} = 3\frac{\left[\ln\left(\frac{h}{r_0}\right)-1\right]}{4\pi^3\left(\frac{h}{\lambda}\right)^3}$$

For a ratio of $h/r_0 = 10$, the Q-factor is given by:

$$Q_{dipole} = \frac{0.0315}{\left(\frac{r_r}{\lambda}\right)^3}$$

Short whip or monopole
For a short whip or monopole of length h the impedance will be half the dipole impedance:

$$R_{r,monopole} = 40\pi^2 \frac{h^2}{\lambda^2}$$

$$R_{d,monopole} = \frac{l}{6\pi r_0 \delta\sigma}$$

where r_0 is the conductor radius, δ is the skin depth, and σ is the metal conductivity.

The Q-factor will be the same as for the dipole.

Small loop
The impedance of a small loop is given by:

$$Z_{loop} = 320\pi^6 \frac{r_r^{\ 4}}{\lambda^4} + j240\pi^2 \frac{r_r}{\lambda}\left[\ln\left(\frac{r_r}{r_0}\right) + 0.0966\right]$$

where r_0 is the conductor radius, r_r is the loop radius.

The Q-factor is expressed by:

$$Q_{loop} = \frac{\mathrm{Im}\{Z_{loop}\}}{\mathrm{Re}\{Z_{loop}\}} = 3\frac{\left[\ln\left(\frac{r_r}{r_0}\right) + 0.0966\right]}{4\pi^4\left(\frac{r_r}{\lambda}\right)^3}$$

For a ratio of $r_r/r_0 = 10$, the Q-factor is given by:

$$Q_{loop} = \frac{0.0185}{\left(\frac{r_r}{\lambda}\right)^3}$$

We can also express the radiation resistance for a small loop with respect to loop area A:

$$R_{r,loop} = 320\pi^4 \frac{A^2}{\lambda^4}$$

The dissipation resistance in the antenna structure is given by

$$R_{d,loop} = \frac{r_r}{r_0\delta\sigma}$$

where r_0 is the conductor radius, r_r is the loop radius, δ is the skin depth, and σ is the metal conductivity.

For small high-Q antennas the Q will be dominated by antenna losses R_d, and losses in the matching network.

Helical dipole
For a helical dipole of length 2 h, reference [2]:

$$R_{r,helical,dipole} = 1280\ \frac{h^2}{\lambda^2}$$

Helical monopole
For a helical monopole of length h the impedance will be half the helical dipole impedance [2]:

$$R_{r,helical\,monopole} = 640\ \frac{h^2}{\lambda^2}$$

General formulas
The equivalent circular radius r_0 of a rectangular conductor is

$$r_0 = 0.35t + 0.24w$$

where t is metal thickness, w is the conductor width.

The free space wavelength can be found using:

$$\lambda = \frac{c_0}{f}$$

where c_0 is the speed of light in vacuum ($3\ 10^8$ m/s). Expressing the frequency in MHz, the wavelength in meters can be found by:

$$\lambda[m] = \frac{300}{f[MHz]}$$

PCB integrated antennas

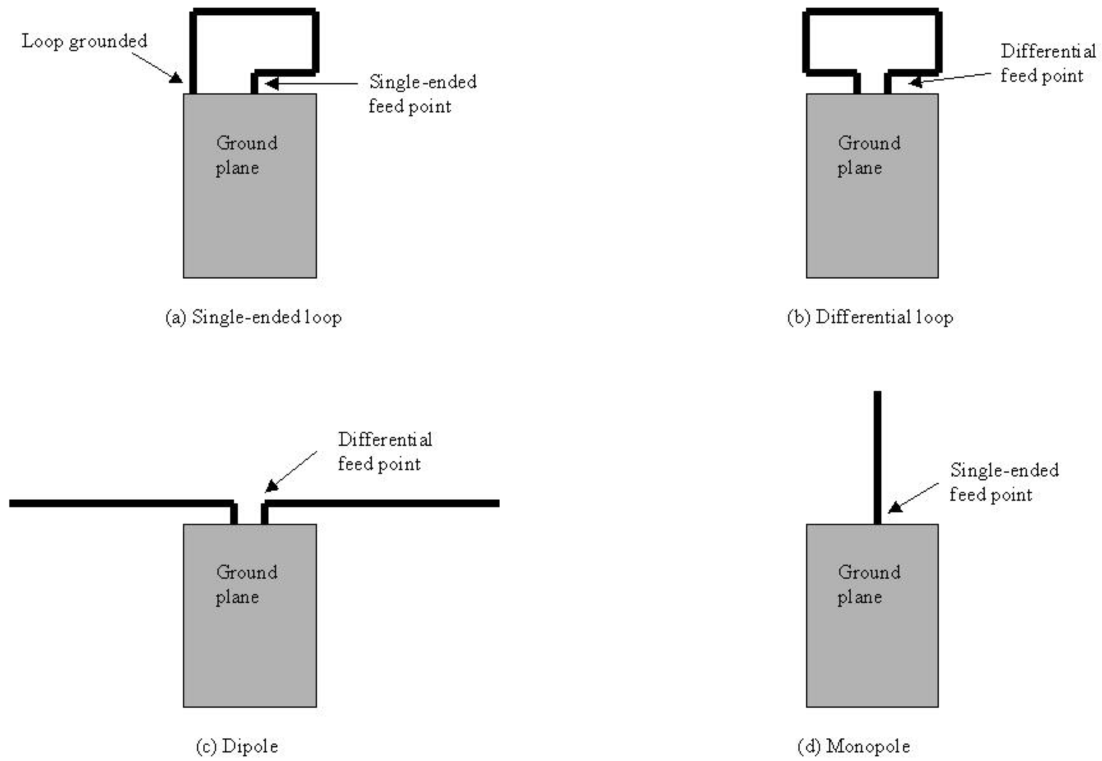
Feeding and ground plane interaction
In a previous section we looked at small antennas; loops, dipoles and monopoles, discussed their limitations and compared their expected performance. In this section we will first give some general guidelines, then look at a specific design case.

The RF circuitry should be implemented on a PCB with a ground plane at the secondary side ensuring proper grounding of all ground connections. This ground plane should <u>not</u> extend into the region where the antenna is to be implemented. This holds for all the antenna types discussed so far.

The loop antenna could be fed single-ended or differentially. If it is fed single-ended, the “far” end of the loop must be grounded. This is shown in the figure (a). A differential output could feed a “floating” loop, figure (b). The loop antenna is not very much influenced by the adjacent ground plane, but a ground plane or components inside the loop should be avoided.

The dipole antenna is a differential structure needing a differential drive. To interface a single-ended amplifier output, a balun is needed. A balun is usually implemented as a small transformer realising the balanced to un-balansed transformation. The antenna itself should be kept away from the ground plane and any metallic or conductive objects, see figure (c).

The monopole antenna must be fed single-ended. This kind of antenna needs the ground plane to operate properly, but the “far” open end should be kept away from the ground plane. Se figure (d).



(a) Single-ended loop (b) Differential loop

(c) Dipole (d) Monopole

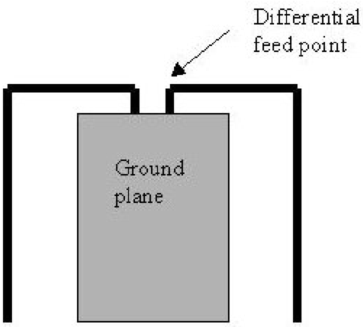
Polarisation and radiation pattern
Care should be taken to get an optimum orientation of the antenna with respect to polarisation and radiation pattern. Usually we are interested in communication in the horizontal plane, having a uniform radiation in all directions in this plane.

The loop will have a radiation pattern being omnidirectional in the plane of the loop, while having a null along its normal. To get an omni-directional coverage, the loop antenna should be placed horizontally.

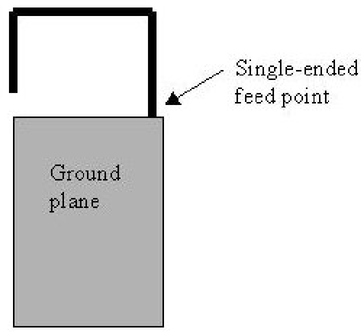
The dipole and monopole radiates in the plane normal to the antenna axis, and will have a null along the axis. To be omni-directional, these antennas should be placed vertically.

However, if the circuit board can not be oriented in an upright position, the antenna could be bent to exhibit a more uniform radiation in the horizontal plane. The figure below shows an example. By bending the antenna we also see that the antenna gets more area efficient. The antenna can be made longer without a larger geometry. We have seen that this increases the radiation resistance substantially and thus also increases the radiation efficiency.

The monopole antenna will also effectively be longer than the dipole antenna (for the same area), because the monopole exploits the ground plane as one “arm” of the antenna. For a cell phone antenna, the monopole antenna at the top of the case, use the case itself as a ground plane, and acts in a way like a dipole, because the dimensions of the case is similar to the length of the antenna.



(a) Dipole with bend

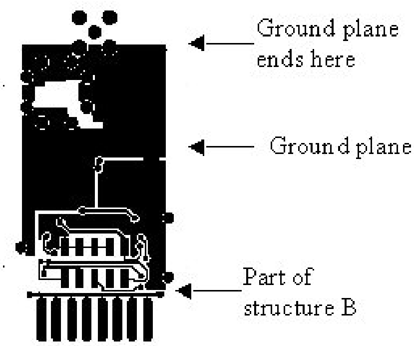


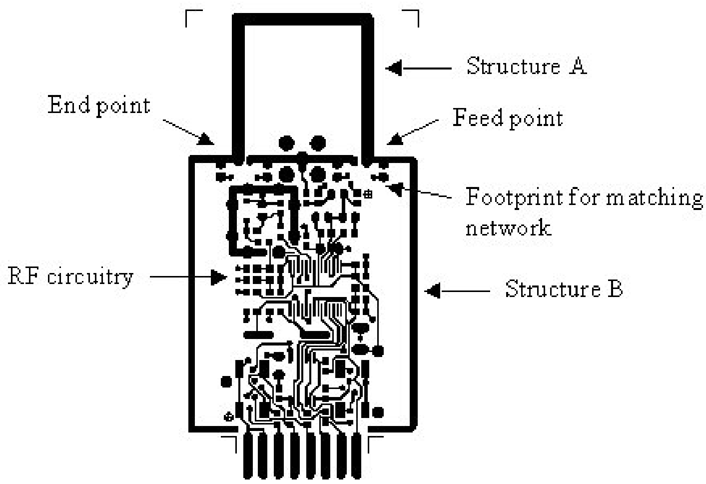
(b) Monopole with bend

A design case
The CC400DB Demonstration Board is a battery operated short-range RF device where an integrated antenna is used. The module serves as a reference design for the CC400 single-chip RF transceiver at 434 MHz. The module demonstrates a two-way radio link with a simple acknowledge protocol by sending a “message” from one unit to the other, followed by an automatic reply as acknowledgement. The “message” is a blinking sequence shown on a LED. A thorough description of the module is found in the *CC400DB User Manual*.

During the prototyping of this device several antennas were tested and performance compared. Both loops and stubs were tested. The board and antenna layout is shown in the figure below. Two structures were made (see the figure below); one enclosing the circuitry and the ground plane (B), and one at the end of the board outside the ground plane (A). Both structures could be configured as a loop or as a stub (monopole) by terminating the end point to ground, or leaving it open. Footprints for matching network were also made the feed point.

The antennas were measured with a network analyser and matched to 50 Ohms. During the measurement the circuit board was held in the hand as it would be under normal use.





These 4 antennas was tested:
1) Stub A. Structure A with end point open. The matching network consists of 56 nH series inductor and 18 nH shunt inductor.
2) Loop A. Structure A with end point connected to ground. The matching network was a series trimming capacitor (3-10 pF) and a 10 pF shunt capacitor.

3) Stub B. Structure B with end point open. The matching network consists of 7 pF series capacitor and 12pF chunt capacitor.
4) Loop B. Structure B with end point connected to ground. This antenna was in resonance without further matching.

The performance of the antennas was measured using two devices, one device set up as a transmitter and the other one as a receiver antenna connected to a spectrum analyser. Both units were held in the hand, as they would be during normal operation. For every pair of antennas, the received signal strength was measured for all six orientations (pointing left, right, up, down, backward and forward). The results are given in the table below where the average values from all tests are shown:

Antenna	**Relative performance [dB]**
Stub A	0
Loop A	-2.2
Stub B	-12.2
Loop B	-15

Stub A showed the best results, being 2.2 dB better than loop A. Using structure B showed that both loop and stub performance is low due to the presence of the ground plane close to the antenna.

The measurement results are in agreement with what we expect from theory as discussed earlier. As long as the antenna is not held within the hand, the stub antenna works better than the loop antenna even for a handheld device.

External antennas

Considering external antennas the size is usually not that critical. External antennas must be used if the electronic enclosure is conductive. External antennas should be used in “base stations” and when communication range is of great importance.

Dipole antenna
A dipole antenna has impedance 73 Ohms and need a differential feed. The directivity of the dipole is 2.15 dBi.

The dipole can be mounted horizontally as a “T” giving horizontal polarization, or it can be mounted vertically. A practical implementation of a vertically mounted dipole is to use a coaxial feed-line where the center conductor is extended as one leg, and the screen is bent back over the feed-line as the other leg. The antenna will then be fed at the centre point.

Quarter wave monopole (whip) antenna
A vertically mounted monopole is 37 Ohms, thus easy to match in 50 Ohm systems. Theoretically the directivity is 3 dBd (over that of a dipole) because the radiated power is radiated only in the upper half plane due to the ground plane. In practice the gain is lowered because of the conductive loss and finite size of the ground plane.

Vertical mounting gives a vertical polarisation with omni-directional radiation pattern in the horizontal plane. This antenna is the best solution when the physical size is acceptable and a ground plane is present. Most often the case of the equipment is used as ground plane. If the ground plane is small it will affect the performance of the antenna and tilt the radiation pattern upwards. In hand-held portables the long thin case can work as the second arm making up a dipole antenna.

5/8-wavelength monopole antenna
The 5/8 wavelength monopole has a comparatively large directivity in the horizontal direction and is used as a *high gain* antenna above a ground plane. The theoretical directivity is 8.2dBi = 6 dBd, which is 3 dB more than the quarter-wave monopole. The rise of the radiation beam due to the finite ground plane is less compared to the quarter-wave monopole.

Usually a series coil is used in the feeding point with an effective length of 1/8 wavelength, giving nearly 50 Ohm input impedance.

Normal mode helical antenna
The normal mode helical antenna radiates in the direction normal to the helical axis. Thus, the radiation pattern is as for the monopole. It can be seen as a monopole antenna shorted by coiling up the whip itself. This makes the dimensions of the helix much smaller than a wavelength, and resonance can be achieved for an antenna length much shorter than that of a full-length monopole.

The efficiency of the helix can be higher than that of a non-helical structure of the same dimensions. But the gain decrease by 3-5 dB compared to a full size monopole.

General notes on hand-held and body-worn antennas

In discussing the problem of body-worn antennas there are two problems of interest. First, the influence the human body has on the field strength of a body-worn receiver or transmitter. Second is the problem of electromagnetic energy coupled into the body tissue. In this brief note we will only discuss the influence of human body on the radiation pattern from an antenna.

The body can have a great influence on the antenna. Hence, an antenna optimised for hand-held or body-worn use can show a gain increase of 3-10 dB when used as intended compared to operated in free space [1]. This is important when designing and testing antenna solutions for such use. During measurements and optimisation the antenna should be mounted in the original equipment and held or worn as in real use.

To understand the effect the body has on the antenna, we have to look at the wave impedance close to an antenna. A small electric dipole (or monopole) antenna set up primarily an electric field, leading to high wave impedance close to the antenna, rolling off towards the far-field wave impedance of 377 Ohm. A small magnetic loop sets up a primarily magnetic field and therefore leads to low wave impedance close to the antenna. This is shown in the graph below where the wave impedance (E/H field ratio) is shown as a function of distance *kr* for a dipole antenna and a loop antenna. k is the wave number $2\pi/\lambda$.

From the same figure we can see that the near-field reach out to approximately kr = 6, or one wavelength. Antennas used in SRDs are often closer to the body than 2 cm, that is, closer than 0.07 wavelengths at 1 GHz. That means they are in the near field of the antenna.

The intrinsic impedance of the body is found to be 38 – 57 Ohm in the range of radio frequencies 30 – 3000 MHz. The high wave impedance of the dipole parallel and close to the body is therefore effectively short-circuited by the body. On the other hand, the loop antenna exhibiting low wave impedance in the near field is less affected by the body, and is hence often the preferred choice for body-worn applications [4].

However, the picture is not complete until also the practical implementation is taken into account. As discussed above, the efficiency of a small loop antenna tend to be very low, so all in all, a general conclusion can not be drawn without evaluating the actual design and use. In quite a few hand-held applications the monopole is preferred due to the higher efficiency, and thus better performance totally.


Wave impedance
10000
1000
100
10
Impedance [Ohm]
0.01
0.1
1
10
Distance in wave numbers (kr)
Dipole
Loop

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