Compact Integrated Antennas

Designs and Applications for the MC1319x, MC1320x, and MC1321x

1   Introduction

Good antenna design is a critical factor in obtaining good range and stable throughput in a wireless application. This is especially true in low power and compact designs where antenna space is less than optimal. However, several compact, cost efficient, and effective options exist for implementing integrated antennas.

To obtain the desired performance, it is required that users have at least a basic knowledge about how antennas function and the design parameters involved. These parameters include selecting the correct antenna, antenna tuning, matching, gain/loss, and knowing the required radiation pattern.

This note will help users understand antenna basics, and aid in selecting the correct antenna solution for their application.

Contents

freescale™
semiconductor

2 Antenna Terms

Antenna Gain	A measure of how well the antenna radiates the RF power in a given direction compared to a reference antenna such as a dipole or an isotropic radiator. The gain is usually measured in dBs relative to a reference. A negative number means that the antenna in question radiates less than the reference antenna and a positive number means that the antenna radiates more.
Decibel (dB)	A logarithmic scale that represents power gain or loss in an RF circuit. 3 dB represents a doubling of power, -3 dB is half the power and -6 dB represents half the voltage or current, but a quarter of the power.
Radiation Resistance	The part of an antenna's impedance that produces radiated power. The measured impedance of an antenna is comprised of radiation resistance and loss.

3 Basic Antenna Theory

Every structure carrying RF current generates an electromagnetic field and can radiate RF power to some extent. Likewise, an external RF field can introduce currents in the structure. This means that theoretically, any metallic structure can be used as an antenna. However, some structures are more efficient in radiating and receiving RF power than others. The following examples explain these concepts.

Transmission lines (striplines, coaxial lines, etc.) are designed to transport RF power with as little radiation loss as possible because these structures are designed to contain the electromagnetic fields. To obtain any appreciable radiation from such a structure requires excessively high RF currents which causes low efficiency due to high losses. Likewise, the ability to introduce RF currents into the structure is of importance as described by the feed point impedance. If the feed point impedance is very high, low, and/or highly complex, it will be difficult to introduce RF current with good efficiency.

The antenna structure should be a reasonable size compared to the wavelength of the RF field. A natural size is a half wavelength. A half wavelength corresponds to approximately 6 cm (in air) in the 2.4 GHz ISM band. This size is effective because when it is fed with RF power at the center point, the structure is resonant at the half wave frequency. Reducing the size below the natural resonant length can cause low efficiency. Not all structures make an efficient antenna.

Numerous structures have been devised that provide good efficiency and a good impedance match, but most of these are derived from a few basic structures. A short description of these basic antennas and some advice on how to implement these with success is provided later in this note.

It is beyond the scope of this note to include complicated formulas concerning antenna theory. This note is intended to provide basic information about how antennas work which should allow users to achieve reasonable performance with a minimum number of attempts.

If users are interested in performing complex calculations and antenna simulations, they should consult the abundant and widely available literature concerning antenna theory and design. Simply copying an existing design does not necessarily ensure reasonable performance. A lot of external factors affect antenna tuning, gain, radiation patterns, etc. An antenna tuned for one set of environmental factors (PCB, different cases, etc.) may not perform at all if put into a new environment, and may require a lot of tuning to achieve even reasonable performance.

3.1 Basic Antenna Variations

3.1.1 3.1.1 Dipole Antenna

The dipole is one of the most basic antennas. The dipole consists of a straight piece of wire cut in the center and fed with a balanced generator or transmission line. As previously stated, this structure is resonant, or non-reactive, at the frequency where the conductor length is a half wavelength. For the ISM band, this length is approximately 6 cm or about 2 ½ inches. At this length, the dipole shows resonance, the feed impedance is resistive and close to 73 Ohms. This is also true for a thin wire in free space.

Total Length is Approximately ½ Wavelength
(At 2.4 GHz, Length is Approximately 6 cm in air)

Figure 1. Basic Dipole

A practical dipole of some thickness loaded with different dielectric materials (PCB etc.) and relatively close to ground, shows resonance at a slightly shorter length than calculated and the radiation resistance also drops. For dipoles not too close to ground, the shorting factor is typically in the range of 5-20% with the shorter being more heavily dielectric loaded with radiation resistance in the range of 35-65 Ohms.

This dipole exhibits a relatively good match to a 50 Ohm circuit, but the feed is differential (balanced). A small ceramic balun can provide a single-ended feed point. The bandwidth is typically 2-5% depending on the return loss required. The radiation pattern in free space is doughnut-shaped with pronounced dips along the direction of the wires. To fill out these dips, the outer ends of the antenna can be bent at a 45 degree angle. Several configurations are possible, including the "broken arrow" shape. Any materials close to the antenna (metal or dielectric) can distort the radiation pattern.
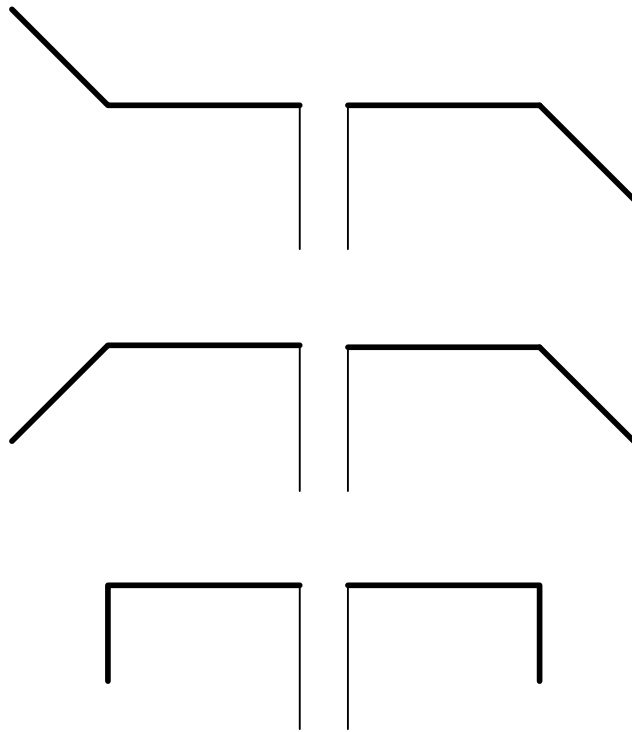
Figure 2. Dipole Shapes to Improve Omnidirectional Characteristics

To reduce the size of the dipole, several options exist:

- Replacing some of the wire length with loading coils
- Bending the dipole ends back on the dipole
- Folding the dipole into a meander pattern
- Hairpin or coil loading of the center
- Capacitive loading of the dipole ends

Folding

Inductive Loading

Meander Pattern

Hairpin Loading
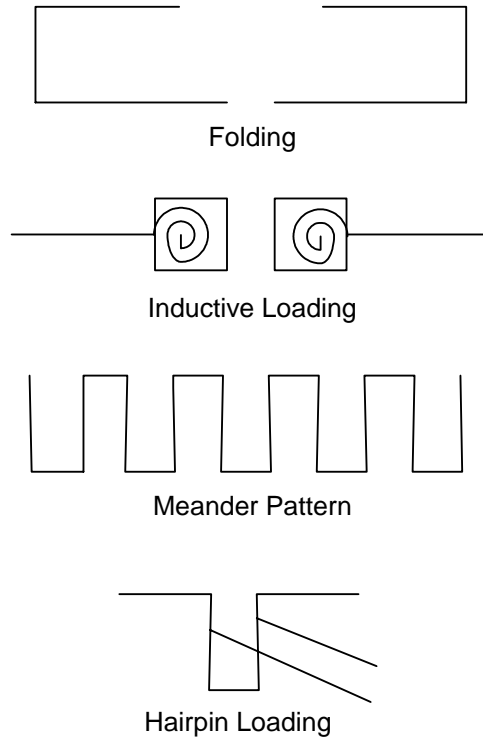
Figure 3. Dipole Loading Examples

In general, the smaller the antenna, the lower the radiation resistance and the lower the efficiency. The dipole antenna should also be removed somewhat from the ground plane, preferably at least 1/4 wavelength (3 cm) but not less than 1 cm. Sometimes a loading technique is employed where the dipole ends are bent close to the ground plane, or even loaded with small capacitors to ground. This technique shortens the dipole considerably but causes heavy RF currents to flow in the ground plane which results in low efficiency.

4 Impedance Matching

For heavily loaded antennas and antennas close to ground, the radiation resistance may deviate considerably from 50 Ohms which causes a poor match. An Inductive/Capacitive (LC) matching network may be employed, but better efficiency is possible by raising the feed impedance of the antenna itself.

These techniques may also be employed if an impedance higher than 50 Ohms is required.

The current and voltage distribution on a dipole is such that the impedance is low in the center and raises towards the ends. By tapering the dipole at some distance from the center, an appropriate match can be achieved. The tapering may take the form of Gamma, Delta, or Capacitive tapping as shown in Figure 4. This allows for matching impedances from 2 to 300 Ohms. Some loading may be required to take out the reactance introduced by the tapering or the antenna could be slightly offset tuned to compensate for the added reactive component.

Gamma Impedance Match

Delta Impedance Match

Capacitive Impedance Match
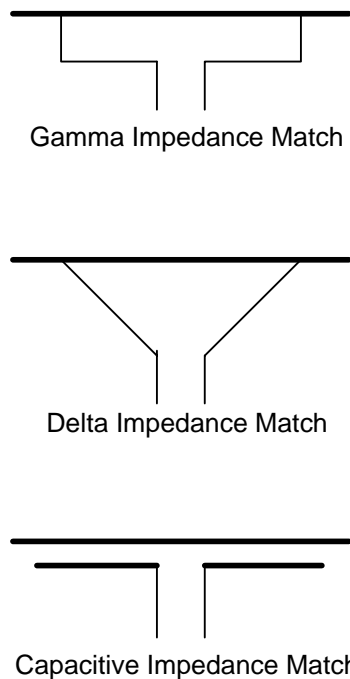
Figure 4. Impedance Matching

The folded dipole is another option. The folded dipole is where two parallel wires are placed closely together. Due to tight coupling, the current distribution is approximately proportional to the surface area of each wire. This means that in two equal wires, the current in the feeding wire is approximately half the value of the wires together. Half the current at the same power means twice the voltage or four times the impedance of 73 Ohms (292 Ohms). In practice, the impedance is somewhat lower, as in the normal dipole case. However, by changing the relative wire diameter or even introducing several wires, it is possible to tune the impedance from less than 100 Ohms up to several hundred Ohms.
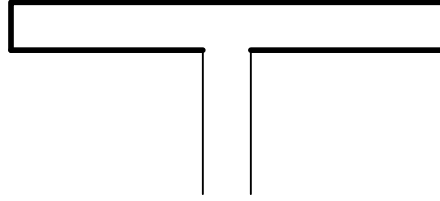
Figure 5. The Folded Dipole

All the different dipole types, loading techniques, and feeding networks total up to an enormous amount of possible combinations, each with its own advantages and disadvantages. Selection of the correct design for an application is best found using case-by-case assessment.

4.1   Monopole Antennas

If one part of a dipole antenna is removed and replaced by an infinite ground plane, the remaining half of the dipole "mirrors" itself in the ground plane. This ground plane is sometimes referred to as the counterpoise.

For all practical purposes, the monopole behaves as a "half" dipole. That is, it has the same doughnut shaped radiation pattern, the radiation resistance is half that of the dipole (37 Ohm), it can be bent or folded like the dipole, and the same loading and feeding techniques can be applied.

However, one very important difference remains in that the antenna feed point is not balanced, but single ended. Because of this, and because most RF circuits are of the unbalanced type, this antenna type is very popular and a lot of variations of the monopole theme exist, most designed to match 50 Ohms.
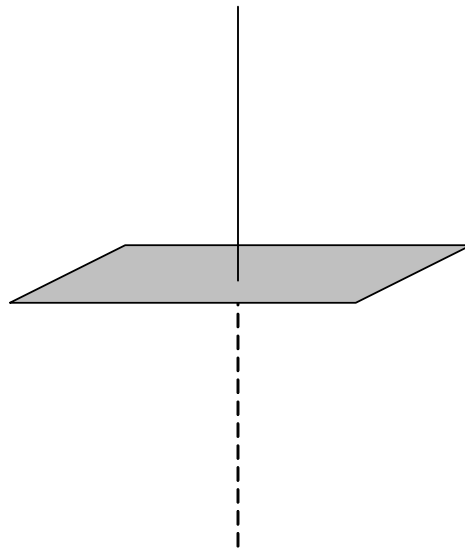
Figure 6. Monopole Above a Ground Plane, Showing the "Mirror" Antenna

It is important to note that the "whip" is only half the antenna and that the remainder is made up of the ground plane, or counter weight, as it is sometimes called. In a practical application, the ground plane is often made up of the remainder of the PCB (ground and supply planes, traces, and components) and/or the metal case of the device, if it has one.

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The ground plane should be a reasonably sized area compared to the antenna, and should be as continuous as possible. If a monopole is used on a very small PCB, perhaps even with only a small area of copper, efficiency will suffer, and the antenna will be difficult to tune. Components and PCB tracks introduce additional losses and affect the feed point impedance.

As for the dipole, resonance is typically obtained at a length slightly shorter than 1/4 wavelength. The radiation resistance is changed by bending the antenna, and like the dipole, the nulls in the theoretical radiation pattern can be reduced. By bending the antenna elements, the radiation resistance and efficiency drops, so the antenna should not be placed too close to ground. Like the dipole, the monopole can also be folded and bent around corners, if board space requires this, or it can be loaded with series coils.

Of the many variations that exist, the following sections highlight the most common.

4.1.1   PCB Whip, Quarter Wave Monopole, or Quarter Wave

If board space allows for both the element and adequate ground area, a full-size quarter wave antenna is very efficient and often provides a reasonable match to a 50 Ohm system.

4.1.2   Open Stub, Tilted Whip

If the monopole is bent and traced along the ground plane, it will be more compact and the null in the radiation pattern is partly eliminated. The antenna should not bee too close to ground, preferably not closer than 1/10 wavelength (1 cm), or efficiency suffers too much. At this close spacing, the radiation resistance is so low (in the order of 10 Ohms) that a matching network is usually needed. If the monopole is very close to ground, it will act as a transmission line instead of an antenna, with little or no radiation at all.

4.1.3   The F-Antenna

The F-antenna can be thought of as a tilted whip, where impedance matching is accomplished by tapping the antenna at the appropriate impedance point along its width. This antenna is used extensively because it is reasonably compact, has a fairly omnidirectional radiation pattern, good efficiency, and is very simple. Note that the currents in the ground leg are high and that an adequate ground plane is necessary to provide good efficiency.
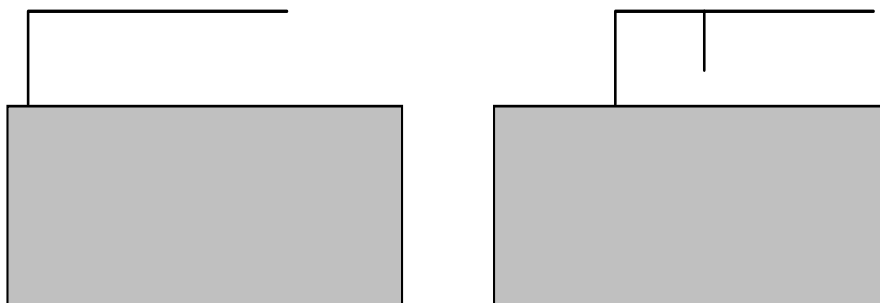

Figure 7. Tilted Whip and F-Antenna (Note the Ground Plane Area)

4.1.4 The Helix

If a 1/4 wavelength element is coiled up like a spring, a very compact antenna can be made that still has reasonable efficiency. Some experimentation may be required to find resonance, because the length of the wire is not exactly related to a 1/4 wavelength. This type of antenna is very popular at lower frequencies.

4.1.5 The Spiral

A spiral antenna, with the windings in one plane like a pancake, is well suited for implementation on a PCB. Performance is similar to the helix.

4.1.6 The Meander Antenna

The meander antenna or meander pattern, is an antenna with the wire folded back and forth where resonance is found in a much more compact structure than can otherwise be obtained.

The meander, spiral, and helix antennas are similar in that resonance is obtained in a compact space by compressing the wire in different ways. In all three cases, the radiation resistance, bandwidth, and efficiency drops off as size is decreased, and tuning becomes increasingly critical. Impedance matching can be implemented by tapping much like tapping is accomplished in the F-antenna. The meander and helix antenna, or a combination of these two, are easily implemented in a PCB and also many ceramic chip antennas are based on these types of antenna.
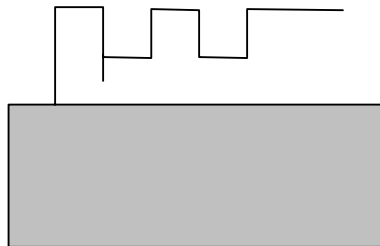
Figure 8. Meander Pattern (Tapped for Impedance Match)

4.2 Loop Antennas

Loop antennas can be divided in three groups:

1. Half-wave antennas
2. Full-wave antennas
3. Series-loaded, short loop antennas

Wave refers to the approximate circumference of the loop.

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4.2.1 Half wave Loop

The half wave loop consists of a loop approximately 1/2 wavelength in circumference with a gap cut in the ring. It is very similar to a half-wave dipole that has been folded into a ring and most of the information about the dipole applies to the half-wave loop. Because the ends are very close together, there exists some capacitive loading, and resonance is obtained at a somewhat smaller circumference than expected. The feedpoint impedance is also somewhat lower than the usual dipole, but all the usual feeding techniques can be applied to the half-wave loop. By increasing the capacitive loading across the gap, the loop can be made much smaller than 1/2 wavelength. At heavy loading, the loop closely resembles a single winding LC tuned circuit. The actual shape of the loop is not critical. Typically, the efficiency is determined by the area enclosed by the loop. The half-wave loop is popular at lower frequencies but at higher frequencies, the tuning capacitance across the gap becomes very small and critical.

4.2.2 Full wave Loop

As the name implies, the full wave loop is approximately one (1) wavelength in circumference. Resonance is obtained when the loop is slightly longer than one (1) wavelength. The full wave loop can be thought of as two end-connected dipoles. Like the half-wave loop, the shape of the full wave loop is not critical, but efficiency is determined mainly by the enclosed area. The feed impedance is somewhat higher (approximately 120 Ohms) than the half wave loop.

Loading is accomplished by inserting small coils or hairpins in the loop which reduces the size. Like the dipole and half wave loop, numerous impedance matching methods exist, including gamma matching and tapering across a loading coil or hairpin. The main advantage of the full wave loop is it does not have the air gap in the loop, which is very sensitive to load and PCB capacitance spread.

4.2.3 Loaded Loop Antennas

Loaded loop antennas are commonly used in remote control and Remote Keyless Entry (RKE) applications. The loop is placed in series with an inductor which reduces efficiency of the antenna but shortens the physical length.
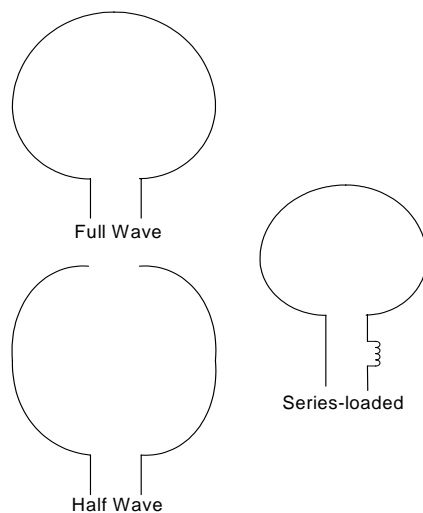
Figure 9. Loop Antennas

4.2.4   Slot Antennas

Slot antennas are used extensively in aircraft and radar applications. The basic slot antenna is a 1/2 wave slot cut in a conducting sheet of metal. The feed point is across the center of the slot and it is balanced. The feed impedance is high, typically several hundred Ohms. Because the slot antenna is the opposite of a dipole, that is, the slot antenna is a non-conducting slot in a sheet of metal as opposed to a conducting rod in free air, the slot antenna is similar to a dipole. However, it does exhibit some differences as follows:

- The feed point is across the center instead of in series, so the feed point impedance is high instead of low
- E and H fields are switched so that the polarity is opposite
- A horizontal slot is equivalent to a vertical dipole
- The slot antenna may be of interest if the RF unit must be placed in a metal enclosure where the slot antenna could be made in the enclosure itself
- If the slot antenna is cut in the center, a 1/4 wave slot antenna is created which is equivalent to the monopole
- Impedance matching is accomplished by tapping across the slot close to the shorted end

The slot antenna can be used if a metal enclosure is required or if considerable board area is available. If a slot antenna is implemented in a PCB made with FR4 material, considerable dielectric loading occurs which causes the physical length to be shorter than expected.
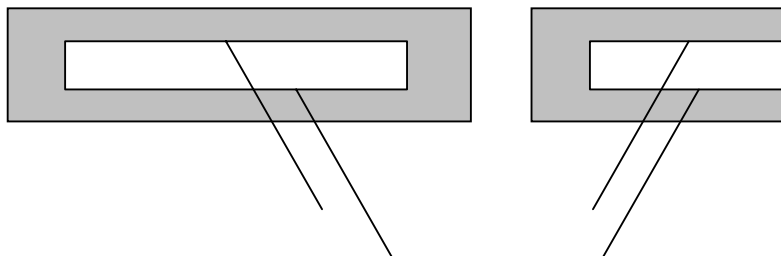
Figure 10. Half-wave and Quarter-wave Slot Antennas

4.2.5   Patch Antennas

Patch antennas are a group of antennas that have a very low profile and are capable of working very close to a ground plane. However, they require a fair amount of board space. They consist of an area of copper suspended above a ground plane.

The radiation pattern can be wide or narrow depending on the size of the patch and the ground area under the patch. Patch antennas are commonly used as GPS antennas, but are too large and too directional for most general purpose applications.

4.2.6   Chip Antennas

Numerous commercial chip antennas are available. At first glance, chip antennas appear to work for no apparent reason. However, careful investigation reveals that most of these antennas are based on a helix, meander, or patch design. To ensure proper operation, it is very important to follow the manufacturer's recommendations regarding footprint, ground areas, and mounting of the chip antenna. The "keep out"

area around the antenna is especially important. Even following the recommendations does not always guarantee good performance due to de-tuning by nearby objects. It is expected that fine tuning of the antenna and/or a matching network is required to ensure satisfactory performance. Because chip antennas normally, but not always, use a ceramic material with higher dielectric constant and lower loss than the usual FR4, it is possible to build smaller antennas with reasonable efficiency.

Efficiency is not exceptionally high and is typically in the range of 10-50%, which corresponds to 3-10 dB loss (-3 to –10 dBi). The lower number being inferior products with high inherent losses. As already stated, buying a chip antenna does not guarantee good performance. However, while they provide the smallest antenna solution possible, the size reduction comes at a cost both in performance and pricing.

If a slightly larger PCB area is available than is required by the chip antenna and the "keep out" area can be allocated to a PCB antenna, it is possible to implement a PCB antenna with the same or better performance than a chip antenna.

4.2.7   Baluns

Many of the antennas already mentioned in this note are single-ended and designed to have a feed point impedance close to 50 Ohms. A balun is required to interface these antennas to a balanced output/input. The balun converts a single ended input to a balanced output together with an optional impedance transformation. The output is differential. That is, the output voltage on each pin is of equal magnitude, but of opposite phase. The output impedance is normally stated as the differential impedance. That is, measured between the two output pins. The balun is bidirectional. The balanced port can be both input or output.

Several discrete circuits are available that perform as baluns but most of them are sensitive to input and output loading and PCB layout issues which requires cumbersome fine tuning. Also, all of these require at least two chip inductors. In the 2.4 GHz band, there are small ceramic baluns which are easy to use and are less sensitive to the PCB layout with standard output impedances of 50, 100, and 200 Ohms.

The cost of a discrete balun is comparable to the ceramic balun and the ceramic balun requires less board space. Therefore, the ceramic balun is recommended for most designs.

5   Miniaturization Trade-offs

As previously stated, reducing antenna size results in reduced performance. Some of the parameters that suffer are:

- Reduced efficiency (or gain)
- Shorter range
- Smaller useful bandwidth
- More critical tuning
- Increased sensitivity to component and PCB spread
- Increased sensitivity to external factors

Several performance factors deteriorate with miniaturization, but some antenna types tolerate miniaturization better than others. How much a given antenna can be reduced in size depends on the actual

requirements for range, bandwidth, and repeatability. In general, an antenna can be reduced to half its natural size with moderate impact on performance. However, after a 1/2 reduction, performance becomes progressively worse as the radiation resistance drops off rapidly. As loading and antenna losses often increase with reduced size, it is clear that efficiency drops off quite rapidly.

The amount of loss that can be tolerated depends on the range requirements. Bandwidth also decreases, which causes additional mismatch losses at the band ends. The bandwidth can be increased by resistive loading, but this often introduces even more loss than the mismatch loss. The low bandwidth combined with heavy loading requires a spread analysis to ensure adequate performance with variations in component values and PCB parameters. So, it is often better not to reduce antenna size too much if board space allows. Even if range requirements do not require optimum antenna performance, production problems and spread are minimized. It is also best to keep some clearance between the antenna and nearby objects. Although the antenna may be retuned to compensate for the loading introduced by the surrounding objects, tuning becomes more critical, and the radiation pattern can be heavily distorted.

6 Potential Issues

Numerous things can go wrong with an antenna design. The following list provides a few do's and don't's which may serve as a good checklist in a final design. Many of these items seem obvious to the experienced antenna designer, but many of these issues are routinely encountered in practice. This is obviously not a complete list.

- Never place ground plane or tracks underneath the antenna
- Never place the antenna very close to metallic objects
- In the final product, ensure that the wiring and components do not get too close to the antenna
- A monopole antenna will need a reasonable ground plane area to be efficient
- Do the final tuning in the end product enclosure, not in open air
- Never install a chip antenna in a vastly different layout than the reference design and expect it to work without tuning
- Do not use a metallic enclosure or metallized plastic for the antenna
- Test the plastic casing for high RF losses, preferably before production
- Never use low-Q loading components, or change manufacturer without retesting
- Do not use very narrow PCB tracks. The tracks should be relatively wide as space allows

7 Recommended Antenna Designs

Two antenna designs are employed for the Freescale, ZigBee compliant hardware:

1. Dipole (lowest cost implementation)
2. F-antenna

Freescale's family of integrated ZigBee solutions have differential RF inputs and outputs. Except for the dipole, most antenna designs have a 50 Ohm, single ended interface. A balun interface between the 50 Ohm single ended antenna and the differential RF terminals is required. While seemingly more complex, the performance advantage of a design such as Freescale's F antenna, often make this the preferred approach.

The MC13192-EVB (included in the MC13193EVK-A00), the MC13213-SRB, and MC13213-NCB, all provide an example of this setup. Users can omit the RX/TX switch and use two antennas, but in most cases the switch is less costly than another antenna. The MC1321X and MC1320X devices include an internal RX/TX switch as an option. Any other 50 Ohm, single ended antenna design can be added if required. This includes among others, the F-antenna, monopole, helical, and the usual commercially available chip antennas. The single-port, 50 Ohm solution has an added advantage in that adding a ceramic bandpass filter for improved performance is relatively easy.

Because the MC1319x has separate RX and TX ports, two antennas will eliminate RX/TX switching. The two antennas should ideally be placed at least ¼ wavelength apart to reduce coupling, but due to low board space requirements, closer spacing can be allowed. The following list shows the results from testing with dipole antennas and shows the typical isolation. The values are empirical, and depend somewhat on the surrounding layout etc., but they should provide a reasonable indication of the isolation obtainable.

- On each side of a PCB, on top of each other: – 3 to – 4 dB
- Very close, on the same side of the PCB: – 6 dB
- 15 mm apart: – 10 dB
- 25 mm apart: – 13 dB

For the MC1319x to show optimum performance, at least 6 dB of TX to RX isolation is required or the ESD protection diodes in the RX input cause some TX power loss and perhaps also increased 3rd harmonic output. However, placing the RX and TX dipoles on top of each other, with only 3 dB of isolation results in the smallest design possible, and only reduces TX power a few dB, which is entirely acceptable in most cases. The RX side works well with any isolation available. When the antennas are very close, the coupling results in some interaction in the tuning of the two antennas. With just a few attempts, users should be able to optimize performance.

8   Design Examples

The following section shows a series of design examples. Each of these has been tuned for a particular design, so a cut-and-paste approach will not necessarily ensure optimum performance. However, these designs are a good starting point for further optimization, and they indicate the approximate size of the particular antenna.

8.1   F-antennas

The following figure shows an F-antenna. Measurements are in millimetres.
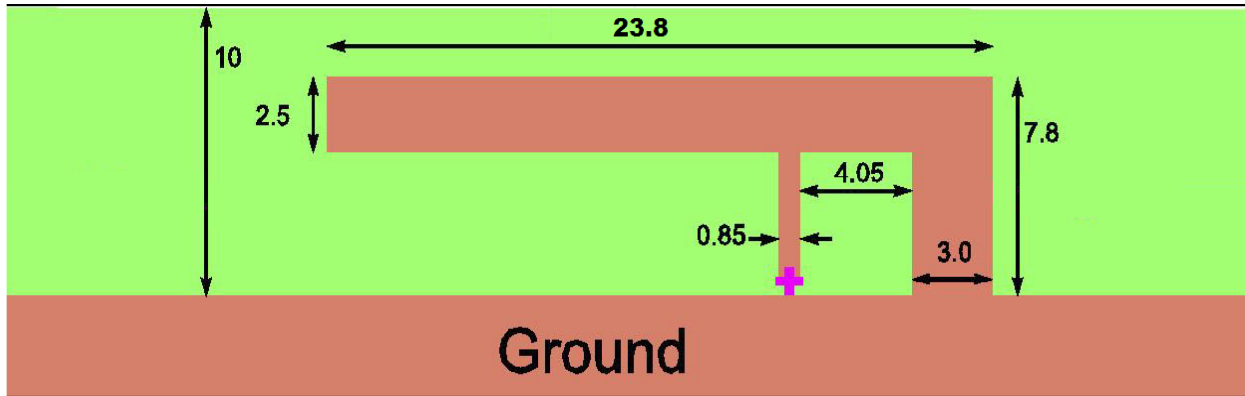
Figure 11. F Antenna

Figure 12 shows the EVK horizontal PCB radiation pattern. Red represents vertical polarization and blue represents horizontal polarization both measured in dBi.
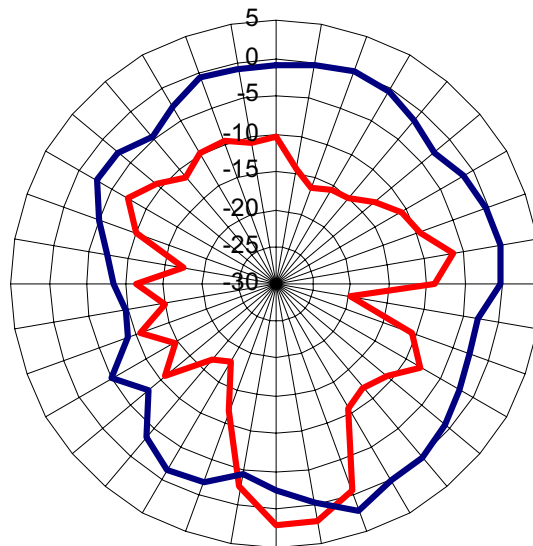
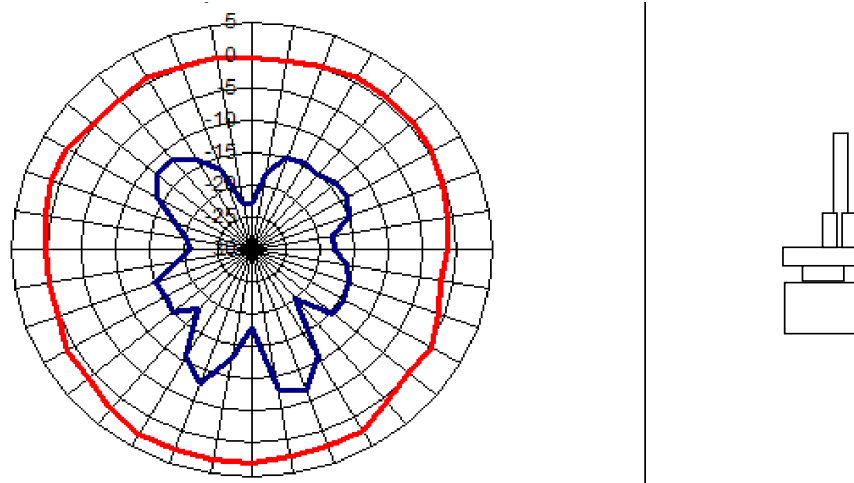**Figure 12. F-Antenna Radiation Pattern (For Antenna as Shown in Figure 11)**

Figure 13 shows a typical plot of the return loss and bandwidth obtainable with an F-antenna. A slight ripple is caused by the ground plane size.
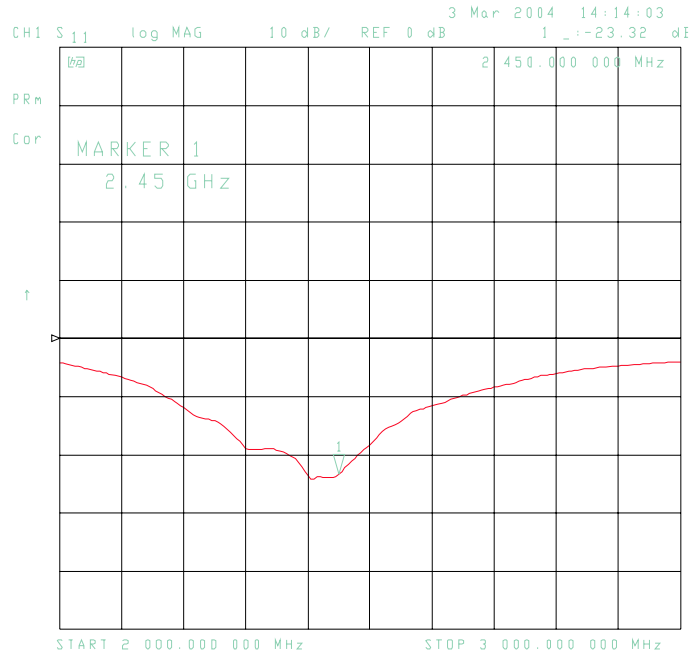
Figure 13. F Antenna Return Loss and Bandwidth

8.2 Chip Antennas

Numerous chip antenna designs exist and Freescale strongly recommends carefully following the antenna manufacturers guidance regarding ground, keep-out areas, etc.

With no tuning, chip antennas often have a resonant frequency above 2.5 GHz and the return loss at 2.45 GHz is very poor. The antenna must be tuned either by inserting a chip coil in series with the feed point, or adding a PCB track to the opposite end to lower the resonant frequency to 2.45 GHz. The antenna needs to be tuned for the PCB and enclosure that the end product will have.

8.3 Dipole Antennas

The following two full-size designs have been tested:

1. A printed balun and 50 ohm connector for use with the RF Daughter Card (13192RFC-A00).
2. A printed balun on the MC13192-SARD which is included in the Developer's Starter Kit (13192DSK-A00).

The shape assures reasonable omnidirectional coverage while feeding and matching is accomplished by the hairpin design. In one particular design, separate TX and RX antennas were placed on top of each other one on each side of the PCB. Performance in this design has been adequate, but not optimum. This approach trades off performance for reduced PCB area. This dipole has also been bent to improve the omnidirectional characteristics and reduce board width. Impedance matching is improved by using a

folded design with uneven track within the antenna. Gerber data is available for the designs shown in Figure 14 and Figure 15.

30mils/.76mm

1.2"/30.53mm

.5"/12.73mm

.33"/8.46mm

DIG5J6-2

98mils/2.5mm
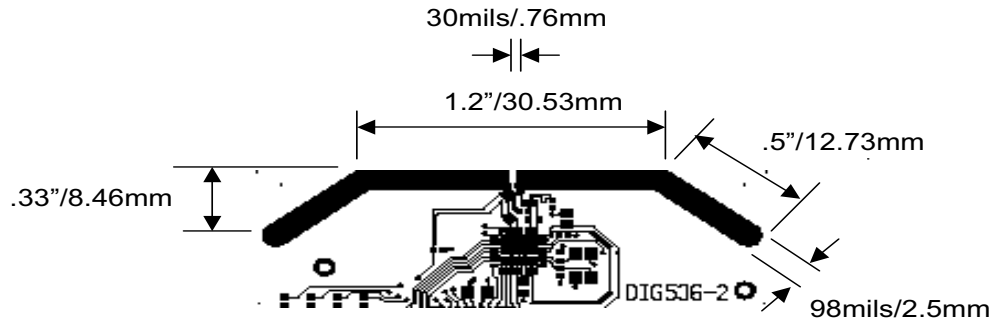
Figure 14. Single Bend Dipole (Figure not to scale)

.522"/13.27mm

1.22"/30.99mm

PCB Material: FR4
PWB Thickness: 15 mils

.375"/9.53mm

.84"/21.29mm

.582"/14.79mm
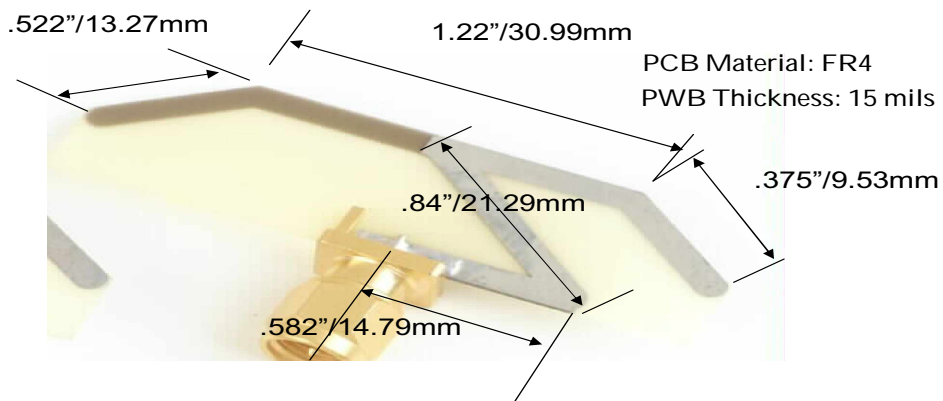
Figure 15. Dipole Antenna With Dimensions (Figure not to scale)

29 Sep 2003   13:01:29

CH1 S₁₁   log MAG   10 dB/ REF 0 dB   3:-19.657 dB

2 450.000 000 MHz

PRm

1:-19.599 dB
2.4 GHz

MARKER 3

2:-20.54 dB
2.5 GHz

2.45 GHz

CENTER 2 450.000 000 MHz   SPAN 1 000.000 000 MHz
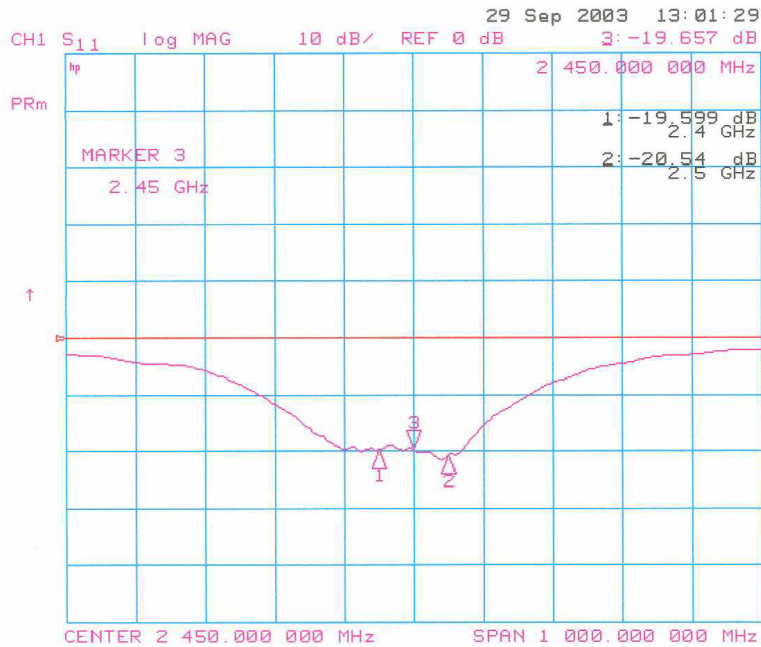
Figure 16. VSWR Plot of Dipole Antenna

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Figure 17 shows the Z-antenna horizontal PCB radiation pattern. Red represents vertical polarization and blue represents horizontal polarization both measured in dBi.
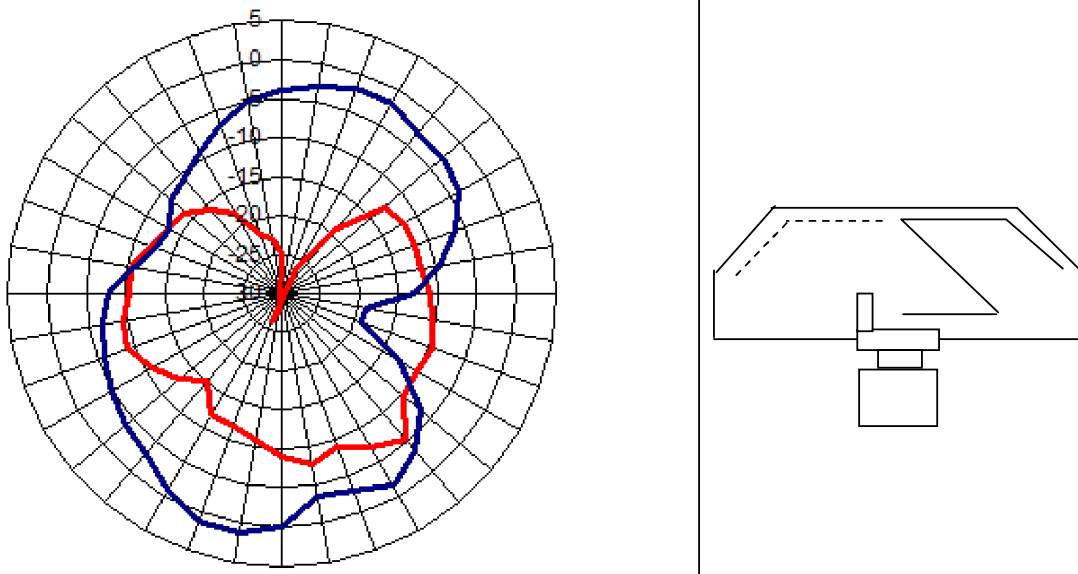
Figure 17. Antenna Pattern for Dipole Antenna in Position Shown (1 of 3)

Figure 18 shows the Z-antenna vertical PCB (long axis) radiation pattern. Red represents vertical polarization and blue represents horizontal polarization both measured in dBi.

Figure 18. Antenna Pattern for Dipole Antenna in Position Shown (2 of 3)

Figure 19 shows the Z-antenna vertical PCB (long axis) radiation pattern. Red represents vertical polarization and blue represents horizontal polarization both measured in dBi.
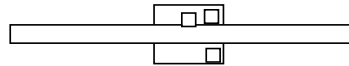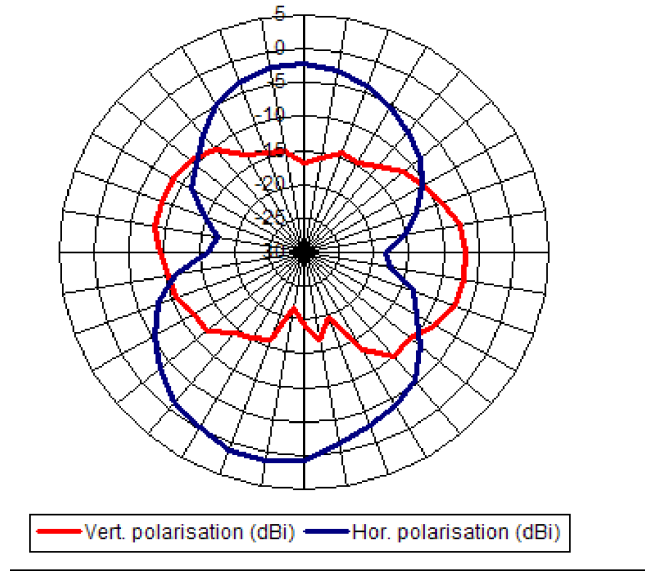
Figure 19. Antenna Pattern for Dipole Antenna in Position Shown (3 of 3)

8.4   Loop Antennas

The following figure shows an experimental full-wave loop loaded with chip inductors. The gain is approximately –3 dBm, which is much better than a chip antenna of comparable performance.

Side Length of Loop = 14 mm
Track Width   = 3x3 mm
Loading Coils   = 2 x 3.9 nH
Impedance   = 200 ohms (Symmetrical)
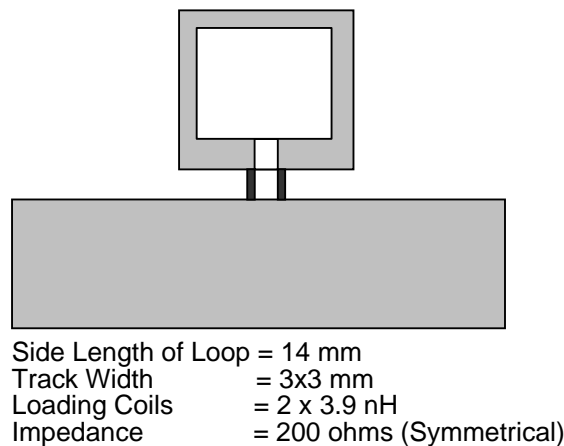
Figure 20. Experimental Full Wave Loop

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