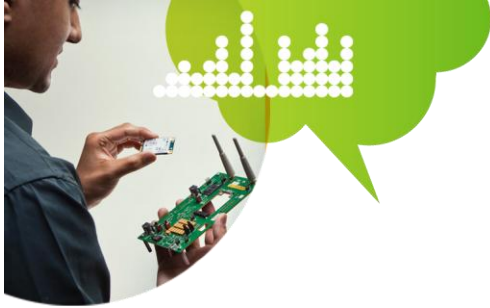




12.2.2009

Antenna Fundamentals

Technical Brief



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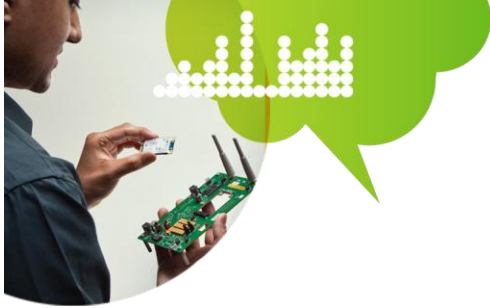


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Revision History

All marks, trademarks, and product names used in this document are the property of their respective owners.

Date	Revision	Description
January 27, 2009	1.0	First release of this paper.
December 2, 2009	1.5	Updated terminology.



1. Introduction

This white paper discusses antenna fundamentals, integrated antenna design and selection, common antenna implementation issues, and antenna measurement for emerging wireless devices.

1.1 Audience

The target audiences of this paper are OEMs and ODMs who are designing a wireless device for the first time using a pre-certified radio module and want to integrate the antenna into the device.

1.2 Contact Information

E-mail any comments or questions regarding this white paper via the [AT&T Developer Program](#). Please reference the title of this paper in the message.

1.3 AT&T Resources

AT&T Developer Program: <http://developer.att.com>

Mobile Application Development: <http://developer.att.com/mobiledevelopment>

Network Technology:

<http://developer.att.com/developer/index.jsp?page=toolsTechSection&id=7600074>

3G: <http://developer.att.com/3G>

Device Information: <http://developer.att.com/devicedetails>

Mobile Middleware: <http://developer.att.com/middleware>

Wireless Reference Architecture Material: <http://developer.att.com/WRA>

Certified Application Catalog: <http://developer.att.com/certifiedsolutionscatalog>

devCentral Resource on [Platforms and Operating Systems](#)



1.4 Terms and Acronyms

The following table defines the acronyms used in this document.

Table 1. Terms and Acronyms

Term or Acronym	Definition
dBi	Gain in dB relative to an isotropic radiator
DF	Dissipation Factor or Loss Tangent of Dielectric Material
DK	Dielectric Constant of Material
IFA	Inverted-F Antenna
ISM	Industrial, Scientific, and Medical
LOS	Line of Sight
MIMO	Multiple Input Multiple Output
PCB	Printed Circuit Board
PIFA	Planar Inverted-F Antenna
PTCRB	PCS Type Certification Review Board
OTA	Over-the-Air
RSE	Radiated Spurious Emission
RX	Receive Mode
S11	S-Parameter Associated with Return Loss and VSWR



TIS	Total Isotropic Sensitivity
TRP	Total Radiated Power
TX	Transmit Mode
VSWR	Voltage Standing Wave Ratio

2. Introduction

Every wireless product requires at least one antenna. Much of the success or failure of a wireless product depends on the performance of the wireless link – including items such as the usable range, robust and repeatable connectivity, and connectivity speed. Wireless performance is completely dependent on a high-performance antenna design and implementation. The benefits of a high performance, and likely expensive, radio module can easily be lost with a poorly designed antenna, or even a well-designed antenna that has been improperly implemented. An improperly designed or poorly implemented antenna is often the cause of performance issues found during the PCS Type Certification Review Board (PTCRB) Certification process.

More than any other component, integration of the antenna into the product is a critical part of the design process. Too often, the antenna is simply “added on” to a product design that has been essentially completed, resulting in serious implementation compromises.

Each different type of antenna has its relative merits and disadvantages in performance, manufacturability, and cost. This paper discusses the various trade-offs involved in the antenna selection and design process for mobile devices.

In general, all of the following discussion is focused on the 850 and 1900 MHz frequency bands. Where absolute dimensions are given, these dimensions are scaled for the 850/1900 MHz bands.

3. Antenna Fundamentals



Antennas for wireless devices are as varied as the devices themselves. Possibilities include external versus embedded, printed on flex printed-circuit boards (PCBs), formed from thin sheet metal, created on the product housing using sprayed-on conductive paint, embedded in materials with a high-dielectric constant for size reduction, and so forth.

Regardless of the type and configuration of the antenna, performance can be characterized by the same metrics:

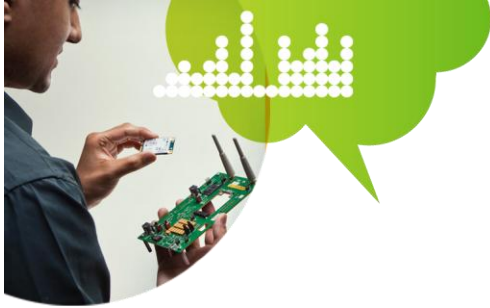
- **Impedance Bandwidth**
- **Efficiency**
- **Directive Gain**
- **Polarization**
- **Radiation Pattern**

The following discussion of antenna performance parameters uses a transmit (Tx) perspective, but exactly the same parameters can be applied to the antenna for receive (Rx) operation. The impedance, efficiency, gain, and radiation patterns of the antenna will likely be different for receive and transmit modes because the two modes are separated in frequency, but the interpretation of the performance parameters is exactly the same.

3.1 Antenna Impedance and Bandwidth

The antenna is essentially a transducer between the characteristic impedance of the radio system (nominally 50 ohms) and the impedance of free space. As such, the antenna impedance and the radio frequencies over which that impedance is maintained are critical. It is essential that the antenna present an acceptable impedance match over the frequency band(s) of operation.

Antenna impedance and the quality of the impedance match are most commonly characterized by either return loss (represented by the scattering parameter S_{11}) or Voltage Standing Wave Ratio (VSWR) – these two parameters are simply different formats of exactly the same impedance data. As shown in 2, S_{11} is typically measured on a logarithmic (dB) scale. VSWR is a unit-less ratio. (Return



loss, S11, and VSWR are used interchangeably in this paper). These impedance parameters measure how much of the power supplied to the antenna reflects back from the antenna terminals. Ideally, but impossible to achieve, all of the power supplied to the antenna is radiated with no reflection.

It is important to note that the return loss measured at the antenna terminals is relevant for both receive and transmit operation. In transmit mode, compromised S11 will reflect power back into the final output amplifier, while in receive mode the power is reflected back into the antenna.

Table 2. Return Loss (S11) and VSWR Relationship

S11 (dB)	VSWR	Reflection Loss (dB)	Comment
-6.0	3:1	1.2	Marginal
-9.5	2:1	0.5	Acceptable (and typical Antenna Specification)
-15.0	1.4:1	0.15	Good
-20.0	1.2:1	0.04	Very Good

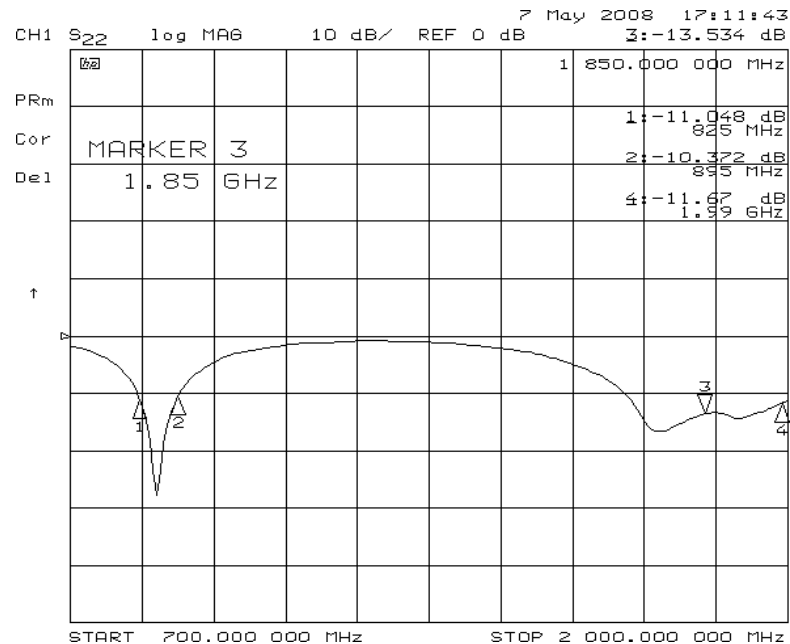
1 below shows the return loss of a typical dual-band embedded cell phone antenna. The horizontal scale is swept frequency from 700 MHz to 2 GHz; the vertical scale is S11 in dB (10 dB/div); and the markers identify the two operating bands.

The worst-case S11 is about -10.3 dB (a VSWR of 1.9:1). While the return loss data in 1 is acceptable, note that the response in the low band is just wide enough to cover the desired frequency range. In high-volume production, the frequency response will likely shift a small amount, resulting in degraded return loss at one of the band edges. The amount (and direction) of the shift depends on the type of



antenna and the repeatability of the device assembly, but some shifting is inevitable. Some shifting of the frequency response will also occur during normal use when the device is near other objects, a secondary or temporary enclosure, the user's hand or head and so forth. Therefore, excess bandwidth should be designed in from the beginning of the product design.

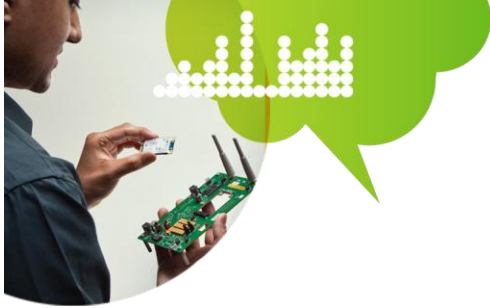
Figure 1. Typical Return Loss of an Embedded Dual-Band PCB Antenna



The bandwidth of an antenna over which the return loss is acceptable is directly proportional to the volume the antenna occupies, so very small antennas can produce inadequate bandwidth, especially in the 850 MHz band where the effective volume is smallest relative to the frequency of operation.

3.2 Antenna Efficiency

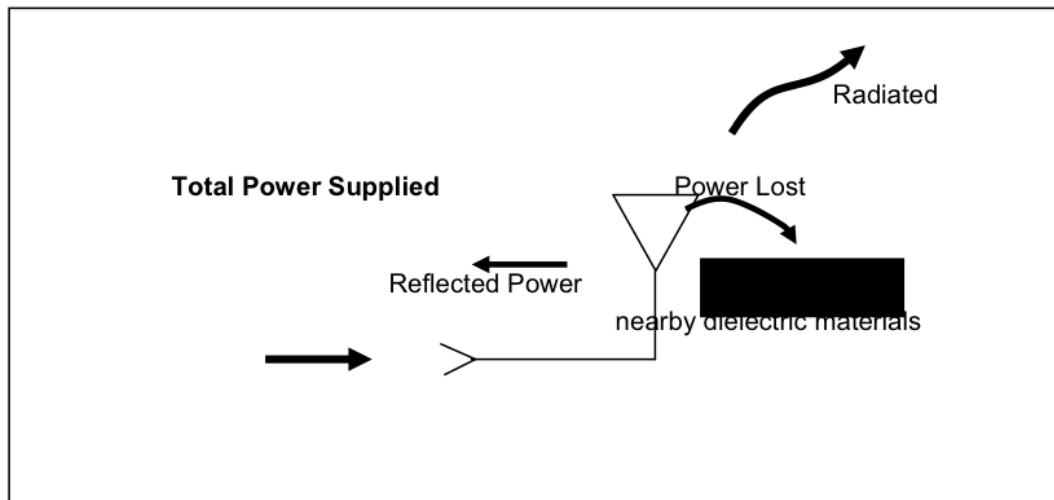
For most antennas, but especially for an embedded antenna (or an external antenna mounted on a small device), efficiency is arguably the most important performance parameter, assuming the antenna produces an acceptable return loss



over the band of interest. Efficiency is simply a measure of what portion of the power supplied to the antenna, including any reflection loss, is actually radiated by the antenna.

The efficiency of small antennas that are tightly integrated into a small product can be affected substantially. Nearby grounded conductors and dielectric materials (like a typical plastic housing) will constrain and absorb the near-fields of the antenna and cause significant losses. 2 below illustrates the efficiency concept.

Figure 2. Efficiency Concept



Common plastic materials, like polycarbonate or ABS (Acrylonitrile Butadiene Styrene), can become significant absorbers of RF energy when very close to an antenna. Energy loss will occur during both receive and transmit operation. Efficiency is typically expressed as a percentage, but it is helpful to translate efficiency into the same logarithmic scale used in other antenna performance parameters, as shown in 3.



Table 3. Efficiency and Loss (dB)

Efficiency (%)	Efficiency (dB)
90	-0.5
75	-1.2
50	-3.0
25	-6.0

As shown in the table above, antenna efficiency in percentage can be converted to a dB scale by a $10 \log (\%)$ function.

The efficiency of a typical embedded antenna can range from about 40 to 75%. Greater than 75% efficiency is challenging to obtain from a fully embedded antenna and lower than 40% efficiency will typically cause certification failures. In most cases, the efficiency goal should be 60%, with 40% as an absolute minimum. It is important to understand that good return-loss performance can be inadvertently achieved at the expense of efficiency. An extreme example of this concept is a 50 ohm resistor: the resistor has an excellent return loss but has virtually 0% efficiency, and is obviously not an antenna. Therefore, an understanding of the return loss and efficiency concepts is critical to good antenna design.



3.3 Antenna Radiation Pattern and Polarization

An antenna is a physical device that radiates energy, almost always with some directional dependence. Even an omni-directional antenna will have one or two narrow directions where there is a reduction or a null in the radiated energy. The energy leaving an antenna is also polarized – meaning that the electric field is in a particular orientation.

Theoretically, for efficient transfer of energy between two antennas, their respective radiation patterns must be optimized in the correct direction and the antennas must be polarized with the same orientation. However, in the real world, where line of sight (LOS) between two antennas rarely exists, and at frequencies above about 500 MHz, objects in the path between the antennas (walls, structures, people, terrain, etc.) can substantially alter both the effective radiation patterns and the polarization. These scattering effects on the radiation pattern and polarization are random, uncontrollable, and typically change continuously with time, relative antenna position and orientation. Even if a device is located in a fixed position, polarization will typically change with time due to movement of nearby objects. As a result, while some general attention must be paid to radiation pattern shape and antenna polarization, these parameters can be optimized for a particular situation in only a general way.

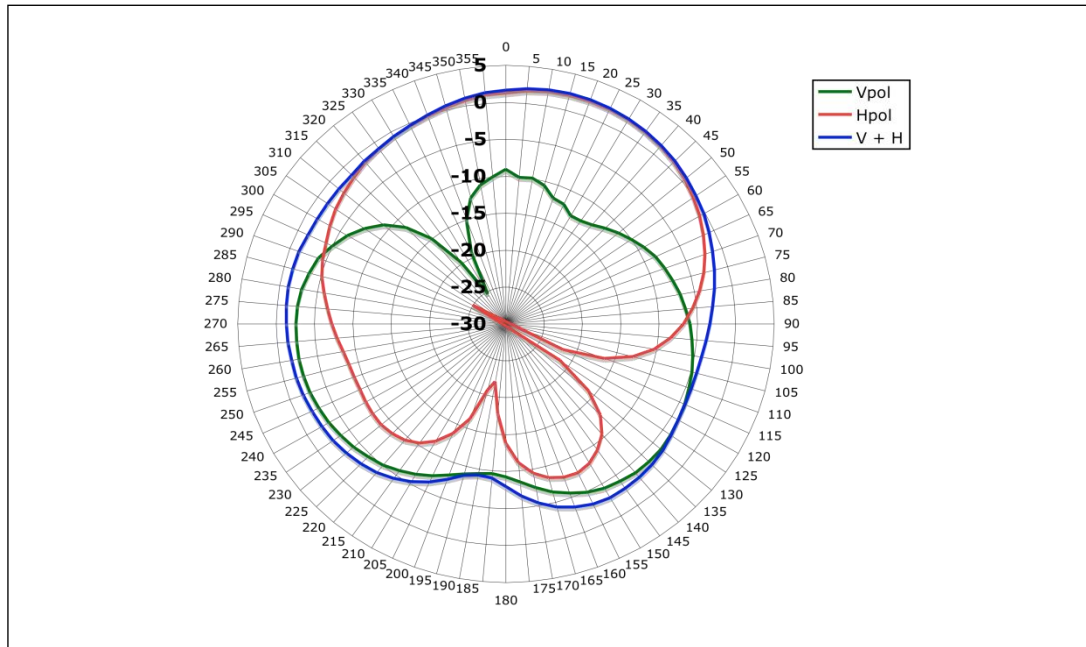
For example, when a 2.4 GHz ISM band wireless link is operating indoors, antenna polarization can largely be ignored because reflections and multipath completely randomize the polarization at any given point in space. Once beyond LOS, even just a few meters from an antenna, the original polarization is completely lost. Most wireless devices (in the category under discussion in this paper) have small antennas mounted on small ground planes. The physics of antenna radiation stipulate that radiation from these structures will *not* have narrow directional lobes



with high gain. In other words, the radiation patterns will generally not have directions where the gain exceeds +3 dBi and will also not have directions with very little radiation. The radiation patterns will be generally omni-directional because high-gain, and the narrow radiation lobes of associated with high-gain, require electrically large structures to form array-like antenna structures. Of course, there will be nulls in the radiation patterns in various directions but the nulls will usually be polarization dependent. If a null exists in a particular polarization, it will not exist in the orthogonal polarization.

Figure 3 below shows a typical embedded antenna radiation pattern. The three traces are antenna gain in vertical and horizontal polarization (in dB relative to an isotropic radiator, or dBi) and vertical plus horizontal (the total gain). While this pattern would not normally be considered "omni", it is acceptable from a gain and overall coverage perspective. It must also be understood that the radiation pattern shown below is just one "slice" from the three dimensional sphere surrounding any device. The features of the pattern (nulls, polarization, maximum gain) will often change dramatically with the angle in what is conventionally called the "pattern cut".

Figure 3 . Typical Embedded Antenna Radiation Pattern



In the 850 and 1900 MHz cellular bands, the reflections and scattering effects are somewhat less but the same principles apply. A typical cellular band wireless link has many reflections and significant scattering and is virtually never LOS. Therefore, antenna polarization is of little concern. Additionally, a handheld mobile device can be used in many orientations, so optimizing the radiation pattern shape is not useful. For devices that are in a fixed location, some design and optimization of the radiation pattern should be considered in a limited way. For example, a wireless device in a wall-mounted electric meter should waste as little energy as possible directly up or down or in the direction of the building.

3.4 Antenna Selection and Implementation

A typical wireless device, like a handset or a laptop wireless modem, has an electrically small ground plane in the 850 and 1900 MHz frequency bands. Because of this, the antenna(s) will interact substantially with the entire device. In fact, the more efficient an antenna is, the more it will interact with the local ground plane – high efficiency, by design, implies interaction. Commercial antenna products may



be described as having “immunity to nearby materials” but this is generally either untrue or the antenna has low efficiency. Directional antennas (like a microstrip patch) and antennas using new band-gap technologies can have limited interaction with nearby materials but these are unusual situations. Most often, the integrated antenna is a structure that includes the product within its near field, so interaction is inevitable.

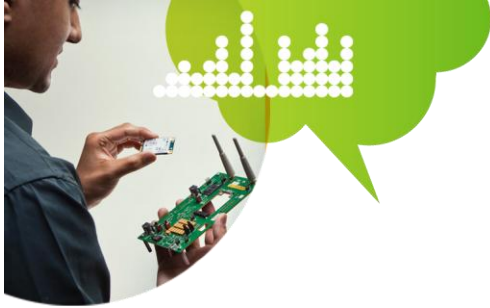
The antenna/ground plane interaction creates a complex situation where the antenna impedance (and impedance bandwidth), overall efficiency, and radiation pattern all depend heavily on the characteristics of the entire device.

Intelligent implementation of the antenna must be holistic in approach, involving the entire device and considered from the very beginning of the product design. As Larry Zibrik of Sierra Wireless told us during an interview for this paper “An OEM must realize that, almost without exception, the industrial design of the device *will be* impacted by the antenna design. Understanding and anticipating this fact from the very beginning of the design process is critical to success.” For obvious reasons, the conductive parts of the device have the largest influence on the antenna, but non-conductive components (enclosure, PCBs, etc.) will also affect antenna design and performance.

Manufacturers of radio modules are an excellent source of antenna element design or selection and antenna location within the device. These manufacturers have likely seen similar devices and are therefore familiar with both the electrical and mechanical design issues, as well as the manufacturing issues of particular antennas. Obtaining antenna design and implementation advice from the radio module manufacturers is worth the effort and cost involved, especially considering the very high costs associated with a product re-design after the failure of FCC regulations, PTCRB, or carrier requirements.

The following sections discuss antenna types and configuration. The discussion assumes that the antenna is a dual-band device.

4.1 Embedded vs. External



Antennas for wireless devices can be completely embedded inside the product or can be mounted external to the product housing. Each implementation has its particular advantages and disadvantages.

4.1.1 External Antennas

In the following discussion, an external antenna is assumed to be a short vertical wire or a trace (or traces) on a PCB, typically encased in a plastic housing. An external antenna is external to the main housing of the device, is connected to the device in one place (often with an RF connector), and generally is perpendicular to the largest dimension(s) of the device.

Dipoles and monopoles are typical external antennas, with a size of $1/2$ and $1/4$ wavelength, respectively. These antennas, if designed correctly, provide excellent performance. External antennas achieve high efficiency and have, in general, better immunity to the self-generated noise of the product, although any antenna is susceptible to external noise.

While external antennas can provide superior performance, there are significant disadvantages: susceptibility to damage, additional manufacturing cost, and potential performance degradation due to the user's interaction with the exposed antenna. While external antennas clearly have their uses, they are generally not recommended for the typical modern hand-held wireless device.

4.1.2 Embedded Antennas

An embedded antenna is any antenna that lies completely within the device housing. It is most typically mounted parallel to the largest dimension(s) of the device. An embedded antenna may or may not use connectors.

Embedded antennas may be printed on the edge of a PCB, can be a separate sheet metal part (or wire) that is soldered to a PCB, or can be a hybrid of these techniques. The antenna can be sprayed or painted (using conductive paint) on the plastic housing of the device. An embedded antenna can also be created from conductive parts of the device structure. Very small "chip" antennas that can be



placed on a PCB like a standard circuit component are available, although these antennas suffer considerably in efficiency and should be used with caution. *AT&T discourages the use of dielectric chip antennas on the AT&T network.*

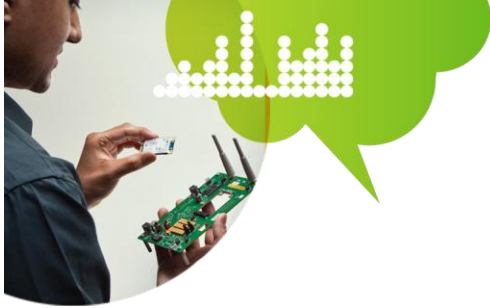
Printed antennas are strongly influenced by the PCB substrate material properties, namely the dielectric constant (DK) and loss tangent, often called dissipation factor (DF). The PCB substrate material will reduce the resonant length of the antenna which will result in a reduction of the usable bandwidth.

Additionally, the PCB substrate will introduce a loss mechanism and reduce the antenna efficiency. PCB substrate and plastic housing losses can substantially reduce embedded antenna efficiency and it is important to remember, as noted earlier in the efficiency discussion, that normally low-loss plastics can introduce significant loss when very close to and around an embedded antenna.

4.2 Antenna Type and Location

In this paper, the type of antenna discussed is limited to dipoles and monopoles (usually external antennas), the inverted-F (and its many variants), and the microstrip patch antenna. Other basic antenna elements, like the loop antenna and the slot antenna, have only limited applications, especially as embedded antennas. Detailed design information for each antenna type is beyond the scope of this paper but general design guidelines and common mistakes will be discussed.

While a properly designed external antenna will generally provide the best performance in almost all situations, today's product design constraints often completely eliminate the external antenna as an option. As such, external antenna implementation will be discussed from only one perspective - orientation. Simply put, *the orientation of a dipole or monopole type external antenna must be generally perpendicular to the local ground plane of the wireless device.* A dipole or monopole antenna that is positioned parallel to (and within about 30 mm of) the local RF ground plane, will have degraded return loss and compromised efficiency.



This point cannot be emphasized enough as it is a common mistake. *The mounting of dipoles and monopoles parallel to the local RF ground plane must be avoided.*

One additional point with respect to external is that when selecting a commercially available external antenna, it is critical to verify that the antenna performance meets the manufacturer's specifications. Most electronic components available today have detailed and accurate specifications. However, this is generally not true of off-the-shelf antennas. Purchasing from a known or respected supplier and/or performing independent testing are the only ways to ensure that the antenna conforms to what the datasheet claims. In the world of commercial antennas for small devices, especially at the low end of the cost scale, incorrect and misleading datasheets are much more common than one might expect.

4.2.1 Embedded Antenna Type

Inverted-F Style Antenna (IFA)

The inverted-F antenna is the most common embedded antenna in use today in wireless devices in the 900 MHz to 6 GHz frequency range. It can be formed in a multitude of ways, has excellent multi-band capability, and can be made highly efficient. Originally designed in the early 1960s as a single-band conformal UHF antenna for use on aircraft, the inverted-F has evolved into a low-profile multi-band antenna than can be integrated into today's small and complex product designs.

In its most basic form, the inverted-F is a quarter-wave long conductor parallel to and within a few mm of the RF ground plane, grounded at one end, and has a 50-ohm feedpoint close to the grounded end. The quarter-wave conductor can be a thin wire, a trace on a PCB, or a 3D surface and can be straight or folded into complex shapes. The 3D version is commonly called a PIFA, or Planar Inverted-F Antenna. An IFA can be referred to as a two-dimensional antenna while the PIFA would be a three-dimensional antenna. The following photos show sheet metal and



printed versions of Inverted-F type antennas. The sheet metal antenna is a PIFA and the printed antenna is an IFA.

Figure 4. Sheet-Metal Inverted-F Antenna

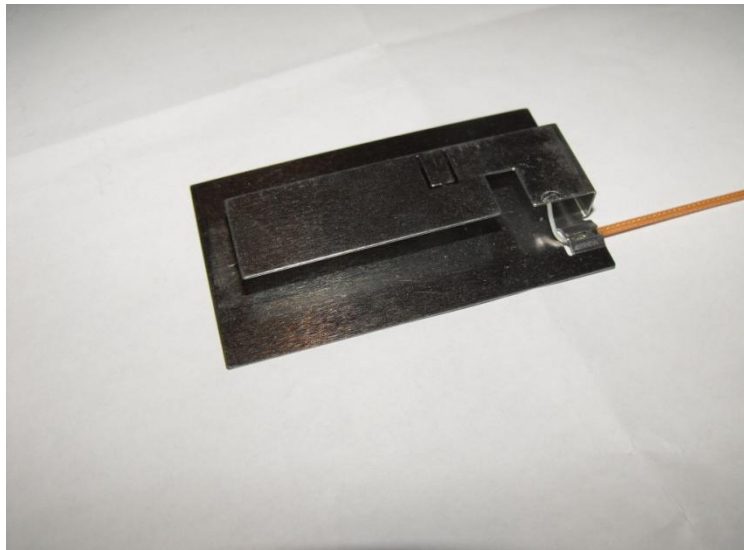
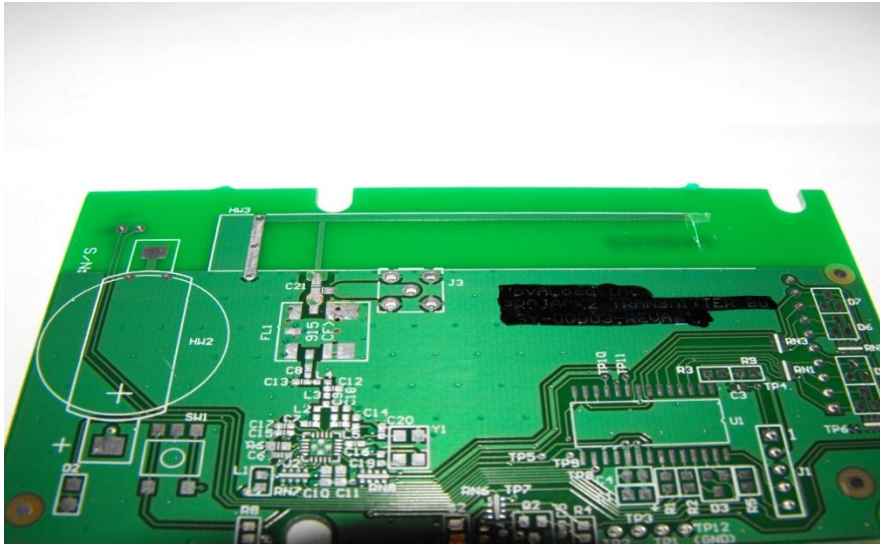


Figure 5 . Printed Inverted-F Antenna



IFAs of all types are ground-plane based antennas, meaning that the size and shape of the local ground plane and the relatively close spacing of the ground plane to the antenna element are both an integral part of the antenna design. IFAs should always be placed on the edge of a ground plane, like the edge of a PCB, or on top of a planar ground plane surface. An IFA should never be completely surrounded by ground planes and other conducting surfaces.

IFAs and PIFAs are considered "psuedo-omni" antennas, meaning there is no predominant direction of radiation. These antennas radiate in both orthogonal polarizations, depending on the direction.

If the IFA structure is disconnected from ground and fed from one end, it can be considered a meandered-line antenna. This type of antenna is similar in performance and capability to the standard IFA and is mentioned only for reference. In some single-band cases, a meandered-line antenna can be smaller than the corresponding IFA.

Microstrip Patch Antenna

The microstrip patch antenna is another common low-profile antenna. The patch antenna requires a ground plane beneath it and can exist much closer to the local

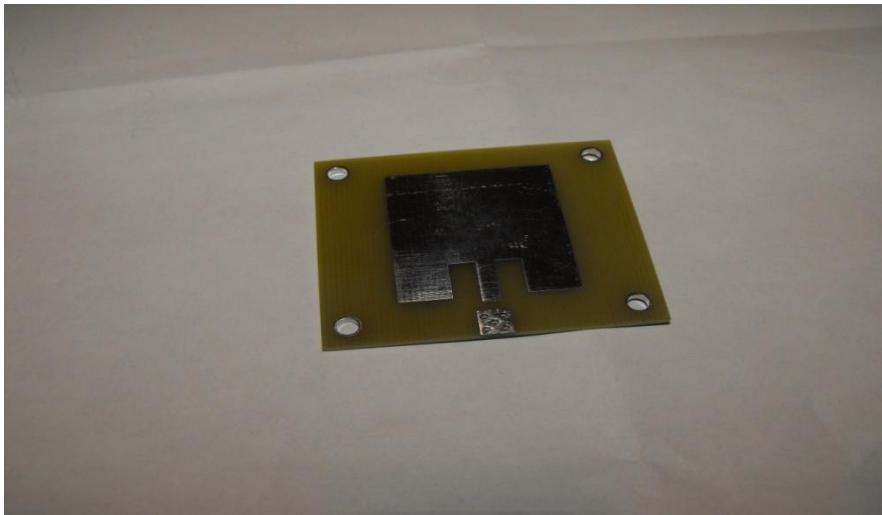


ground plane than the IFA. The patch can be made multi-band, although not quite as easily as the IFA. A microstrip patch antenna is most often a $1/2$ wavelength structure although it can also be made as a $1/4$ wave element. The patch can be very low-profile, only a few mm thick.

Most often, patch antennas are printed on the top surface a 2-layer PCB, although sheet metal patches over a ground plane with an air-dielectric are also in wide use.

Patch antennas are considered directional antennas with a primary lobe of radiation over an approximately 70×70 degree sector (in the direction away from the ground plane). The photo below shows a typical printed patch antenna.

Figure 6 . Printed Patch Antenna



Because of the directional nature and surface-area requirement, patch antennas are rarely used on hand-held mobile devices. However, the patch antenna may be an excellent choice for a fixed-mount device on the side of building where the



radiation from a more omni-directional antenna would be wasted in the direction of the building.

4.3 Common Implementation Mistakes

The following discussion is on typical antenna implementation problems and mistakes. This is not a comprehensive list but simply a discussion of the most common issues.

Dipole or Monopole Parallel to Ground Plane

As discussed earlier, a commercial dipole or monopole style antenna is often mounted close to and parallel to a ground plane. These antennas *must be mounted perpendicular* (or within about 25 deg of perpendicular) to the local ground plane. It makes little difference if the edge of the ground plane or a surface of the plane is used. Both impedance and efficiency can suffer dramatically from improper mounting.

Antenna in Conductive "Window"

Sometimes a product is housed in a metal enclosure, for functional and/or aesthetic reasons. If the antenna is not external to the enclosure, the typical solution is to open up a "window" in the metal enclosure. This idea appears simple and straightforward but this approach is usually disastrous. An antenna in a conductive window, even if tuned correctly for this situation, will have seriously degraded efficiency. Efficiency degradation of up to 15 dB has been measured on otherwise efficient antennas that have been exposed in a window within a conducting surface. In general, windows for antennas should be avoided completely.

Printed Antenna Surrounded by Ground Plane

Printed antennas should be placed on the periphery of the PCB under consideration. Ideally, the antenna should have three edges exposed (at one end



of the PCB). If this is not possible, the printed antenna should be placed in the corner of the board so two sides are exposed. Surrounding the printed antenna on three sides, or even worse, on all 4 sides, will degrade performance substantially.

Antenna Impedance not Validated in Product

Commercial antennas, either external or embedded, often have return loss specifications that have been measured by the manufacturer. While this is useful data, *the antenna impedance must be validated with the antenna installed in the product, with all of the surrounding materials (conductors and non-conductors) in place, and with all components installed on the PCB.* Even the small details of a plastic enclosure can influence the impedance of the antenna.

Antenna Too Close to Digital Noise Source

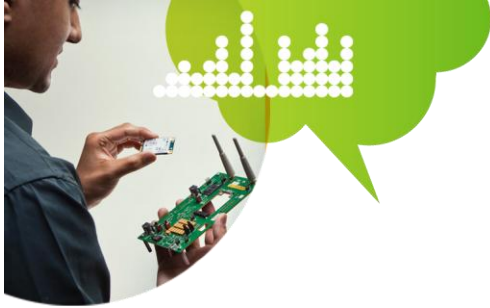
Electrical noise generated by the circuitry of the device can enter the antenna directly and result in poor or intermittent performance, and failure at the PTCRB test lab. Care should be taken to locate the antenna as far as possible from noise sources.

Antenna Placed In Poor Location with regard to Body Effects

If the product is to be hand-held or otherwise in contact with the human body, remember that interaction with the human body will introduce power loss external to the product in both receive and transmit operation. As a separate issue, interaction with the human body will also cause de-tuning of the antenna. Both of these effects seriously degrade performance. Testing should be performed to properly quantify the effects of the human body.

4.4 Antenna Design and Implementation Assistance

There are several approaches available to achieve the intended antenna implementation and performance. The three primary approaches are:



- 1) Commercial off-the-shelf antenna element(s).
- 2) Reference design (typically supplied by radio module vendor).
- 3) Custom antenna design (usually requiring an antenna-design consultant).

Most industry experts recommend approaches 2 and 3 with the caveat that using a reference design should be considered a “semi-custom” design – meaning that while the reference design may be correct, some adjustments to the design will likely be required in a new device.

When evaluating a reference design, it is important to know exactly what the reference design represents: actual measured data from a working antenna, or perhaps just simulations from antenna-design software. Simulations are useful but often need substantial adjustments once implemented in hardware. A reference design, no matter how straightforward, should never be implemented without confirmation (by measurement) of its performance parameters. During a discussion with David Bissonette of 7 Layers, Inc., he echoed the issues above and added “For most OEMs, obtaining antenna design services at the beginning of the product design phase is critical to the product success. Although qualified design help can be expensive, the cost of a substantial product re-design – at the moment when the device should be starting volume production – is much higher.”

As briefly discussed earlier, commercial antennas often have inaccurate or misleading specifications. Remember that the antenna cannot be considered in isolation because the entire device defines the antenna impedance, bandwidth, and efficiency. Therefore, a specification or datasheet is of only limited usefulness. Off-the-shelf antennas can be excellent solutions but only if implemented as carefully as a full-custom antenna design.

Some radio module vendors and certified test labs are now offering antenna design assistance at whatever technical level is required. The expertise provided by these vendors should be used whenever possible.

4.5 Antenna System Issues



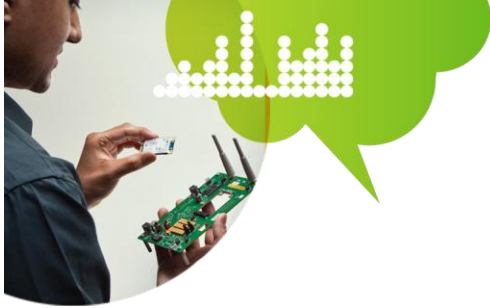
This section discusses antenna issues, including connecting the antenna, self-interference and co-existence with other wireless technologies.

4.5.1 Connecting the Antenna

The antenna is one critical component of the radio system or, more precisely, the radio system *front-end*. The front-end is comprised of the antenna, any components (like filters, amplifiers, switches) between the antenna and the RF chain of the radio, and the connections between the various components. It is critical that the various connections are made with controlled impedance structures. These structures can be coaxial cable, controlled impedance PCB traces like microstrip or stripline, spring-loaded pogo pins or spring fingers, flex circuits with controlled impedance lines, and so forth. Attention must be paid to the various interfaces between these structures and the antenna and circuit terminals. Circuit components and antennas that are well-matched when measured in isolation can suffer from impedance-matching issues when used in combination with poorly designed interconnects. For example, spring fingers have become common in cellular handsets (to connect to the antenna mounted in the housing) and work quite well. However, during the design process, both the impedance and noise-pickup potential of the fingers must be taken into account.

Another good example of the front-end interconnect issue is the use of a filter which utilizes antenna element as one termination. Very often, antennas in actual devices may have VSWRs of 3:1 (possibly higher), especially at the band edges. Most reflective-type filters rely on good impedance matching to provide the specified filtering and a VSWR of 3:1 is typically not adequate to properly terminate the filter component. Some tuning, external to the antenna and filter, may be required to insure that the filter is operating correctly. An improperly terminated filter can introduce substantial insertion loss in addition to a distorted filter response.

Cables and PCB traces will introduce losses (in both transmit and receive) and must be carefully considered. Cables and traces create opportunities for noise to enter the system at the especially vulnerable point of the receiver input. Care must be taken to route all interconnects away from or around noise sources.



The mechanical and electrical reliability of interconnects is also important. Normal “wear and tear” can degrade the integrity of the interconnect system and produce degraded device performance and even outright device failure.

4.5.2 Self-Interference

Self-interference is created when the emissions from a device's own internal circuitry enter the antenna (or the radio front end) and raise the receiver noise floor, thereby degrading the receiver sensitivity. Larry Zibrik told us that “self-interference, due to poor antenna selection or implementation, is the single biggest challenge to successful device certification”.

The effect of self-interference may be just a few dB, and perhaps go unnoticed, or it can result in a sensitivity reduction of 10 to 20 dB or even higher and dramatically reduce the operating range and performance of the device. Self-interference issues may delay or even cancel a product launch.

The primary noise source is the digital circuitry – usually the processor (or processors) and the system memory. Other noise sources are possible, of course, but the processor, its associated clocks, high-speed memory, and display and graphics processors are very often the highest in level and produce the widest range of frequencies. *It is also critical to realize that a device that displays emissions low enough to pass the FCC regulations can still suffer from self-interference.* In most cases, the receiver sensitivity is much lower than FCC test limits.

Eliminating self-interference is a complex subject and beyond the scope of this paper but the following guidelines should be followed:

- 1) Shield the digital electronics with PCB-mounted shield cans. Rarely is some shielding of the digital electronics not required.
- 2) Place the antenna(s) as far from the noise sources as possible.
- 3) Route the antenna interconnect(s) away from the noise sources.



- 4) If non-shielded antenna interconnects are used (like spring fingers or pogo pins) give these interfaces special attention with regard to exposure to noise sources.

Unfortunately, it is difficult or impossible to completely understand the full extent of any self-interference until a device is actually operating in the form-factor it will ultimately use. Therefore, it is critical to design shielding and other self-interference mitigations into the device from the very beginning and then to measure and analyze the self-interference situation as early as possible to avoid problems with receiver sensitivity during PTCRB testing.

4.5.3 Co-existence with Other Wireless Technologies

Today, wireless devices often have multiple transceivers, operating in various bands: Wi-Fi (possibly with Multiple Input Multiple Output or MIMO), Bluetooth, ZigBee, GPS, 915 MHz ISM, other Part 15 devices – all of which have antennas associated with them. On a small device, antennas must sometimes be placed very close to one another. Most of these wireless technologies will transmit their own intentional signals and also generate noise, both of which can interfere with the cellular band reception.

Conversely, the cellular band transmitter generates large-amplitude signals (most often the largest signals a device produces) that can overwhelm a nearby receiver and cause severe distortion. The transmitter output of the typical cellular radio is high enough to interfere with a nearby Wi-Fi or GPS receiver, even though the frequency bands are separated by hundreds of MHz.

As with self-interference, co-existence issues are difficult to quantify before a product is assembled and operating so good design decisions early in the process are important – another reason to obtain qualified advice as early in a project as possible. Co-existence issues are also an opportunity for the radio module manufacturer to provide advice and lessons learned from experience.

5. Antenna Performance Measurements



To successfully design (or purchase) and then integrate an antenna into a wireless device, a number of measurements must be made to quantify the antenna performance in the actual product. Simply relying on a manufacturer's datasheet, bench measurements of an antenna in isolation, or an un-verified reference design will likely result in poor performance in the device.

Impedance and Antenna Bandwidth

As discussed above, antenna impedance is typically measured as return loss or VSWR. The equipment used to measure this parameter is a *Network Analyzer*. The impedance (and the bandwidth over which the impedance is acceptable) must be measured with the antenna installed in the device with all components installed. The impedance measurement often requires special fixtures and assemblies to allow access to the antenna terminals. It is not uncommon that the antenna requires some small tuning adjustments when the device is finally fully assembled. At this stage, if the initial design was well done, most embedded antennas are often quite easily tuned with small changes to the PCB layout or sheet metal part, and/or with the addition of passive components on the antenna or the radio PCB.

Gain and Radiation Patterns

Calibrated measurements of antenna gain and radiation patterns are made in an *Anechoic Chamber*. The anechoic environment eliminates all reflections and allows precise and repeatable measurements to be made. The device under test is typically rotated 360 degrees in multiple orientations to determine the shape of the radiation pattern from many different directions. Reference antennas are used as calibrated gain standards.

As with impedance measurements, gain and radiation patterns should be measured using a complete product.

Efficiency Measurements

As mentioned earlier, efficiency may be the single most important parameter to be measured, especially for an embedded antenna which can have degraded



efficiency due to its tight integration with the device. Efficiency can be calculated from the calibrated gain and radiation pattern measurement but this can be a time-consuming effort.

Within the last 10 years, a new type of efficiency measurement tool has become available – sometime referred to as a “3D Chamber”. The most common manufacturer of this tool is Satimo. The 3D Chamber uses a circular array of test antennas (measuring energy in two orthogonal polarizations) and a rotating table to quickly measure the total energy generated by the antenna under test. The resulting total efficiency measurement is accurate, repeatable and can be used to compare various antenna topologies quickly.

6. Antenna Issues Related to Product Certification

Successful certification of a wireless device requires compliance with FCC regulations, PTCRB conformance test requirements, and AT&T specifications. FCC regulations are primarily concerned with radiated emissions from the device (both intended and un-intended) while the PTCRB conformance testing is primarily intended to verify the proper RF parametric operation in a conducted RF environment. AT&T's device requirements focus on device functionality and interoperability with the AT&T network. In addition, AT&T requires the measurement of a device's Total Radiated Power and Total Integrated Sensitivity. The AT&T TRP and TIS requirements can be obtained upon execution of a non-disclosure agreement (NDA).

While writing this paper, we wanted to know what kind of antenna issues arose most commonly during the certification process so we interviewed several experts from major certification labs. When asked what were the primary antenna-related reasons for certification failures, Lothar Schmidt of Cetecom Laboratories told us “The most common antenna-related failures, in order, are high levels of



transmitter harmonics, TIS failures due to self-interference, and TRP failures due to compromised antenna efficiency.”

Failure to meet FCC regulations is rarely an antenna-only issue. The antenna cannot produce emissions on its own, although the antenna can influence transmitter harmonic generation that can lead to FCC test failures. Generally, FCC failures are system related issues which may involve the antenna.

Devices intended for operation on the AT&T network must display high antenna efficiency and a low level of self-interference in order to meet AT&T's acceptance criteria. Devices with antennas which fail to meet AT&T's TRP requirements may not only be inefficient, they may create other problems, such as excessive harmonic generation from the transmitter. Devices which fail to meet AT&T's TIS requirements may have an efficient antenna, but the receiver sensitivity is compromised by self-interference, such as noise entering the antenna from within the device itself.

In short, the antenna and its complex interaction with the wireless device is part of every radiated measurement a device is subjected to during the certification process and will influence the measurement results.

6.1. Using a Certified Radio Module

For obvious reasons, it is important to begin any product design with a radio module that has already been certified. The certified module, when connected to a correctly implemented “typical” antenna, will provide acceptable performance in both receive and transmit modes.

6.2 Transmit Mode Failures

Assuming the radio module is certified and capable of generating the appropriate amount of RF power, transmit mode failures are typically caused by low antenna efficiency or degraded return loss (which appears as low efficiency due to the



reflected power). Unfortunately, improving poor antenna efficiency at the late stage of development where PTCRB testing takes place is very difficult and will almost certainly require a significant re-design of the product enclosure and antenna type. Poor efficiency results from either the choice of antenna or its position and orientation within the product, both of which are fundamental design parameters.

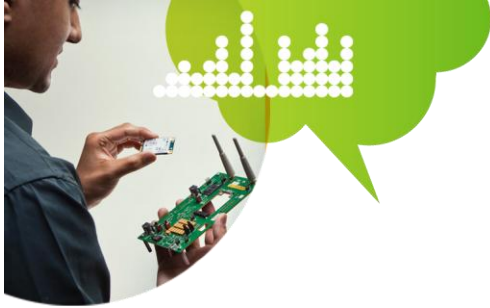
It is possible that the efficiency of the antenna element itself is acceptable but the antenna has become mis-tuned, either in the design process or during final assembly of the device. In this case, restoring the performance can often be quite simple by slightly adjusting the antenna geometry. However, it is critical to understand exactly what the source of the failure is. Simply improving the tuning of an inherently low-efficiency antenna will not yield good results.

6.3 Receive Mode Failures

Receive-mode failures of a device with a module that has acceptable receive sensitivity can be caused by poor antenna efficiency, self-interference or a combination of the two. As is the case with transmit-mode failures, improving antenna efficiency at this stage is very difficult, but re-tuning a mis-tuned antenna is often easily done, even at this late stage of product development.

Resolving a self-interference issue at the PTCRB testing stage is possible (although still challenging) and will likely require changes to the hardware. Analyzing the extent of the issue is complex and requires special test equipment and careful analysis. Additionally, antenna tuning and self-interference can sometimes be interactive – the antenna impedance may influence the level of self-interference. For these reasons, taking self-interference into account early in the design phase is critical.

6.4 Harmonic Generation Failures



A failure to meet FCC regulations or PTCRB radiated-spurious-emissions-conformance requirements due to a level of harmonic energy generated by the device is often blamed on the antenna. In truth, the antenna can often influence the level of the harmonics but does not generate these signals. An antenna almost never has gain at the harmonics of the intended band of operation. Provided the radio has acceptable harmonic performance, excessive harmonic generation is typically an interaction between the impedance of the antenna and the impedance of the final stage of the transmitter.

The antenna is designed to have acceptable impedance in the bands of use. Outside of these bands, the impedance is usually uncontrolled (and often unknown). Unusual or unanticipated impedance conditions can sometimes raise the harmonic levels of a Tx power amplifier by 10 or even 20 dB. As with other failures, the out-of-band impedance of the antenna is difficult to change at the regulatory or conformance test phase. Often, filters between the antenna and transmitter are added as a last resort, but these components have their own impedance issues and can often reduce one harmonic while raising the level of another.

Therefore, as early in the project as possible, the antenna and transmitter should be tested together with harmonic generation in mind. It is very difficult to design or purchase an antenna that has a specific impedance at each potential transmitter harmonic. Approaching the issue in this way will not yield good results. Instead, the power levels of the harmonics should be measured as soon as it is practical to do so, when mitigation steps can be readily taken to reduce individual failures.

6.5 Device Pre-Testing

Most radio-module vendors offer some limited pre-testing of the radio and antenna as a system in their own laboratories. While these facilities can vary widely in accuracy and repeatability, they should be used if available. Very often, a radio vendor will be familiar with the issues that their particular module may have when



used with a particular type of antenna and early testing related to these issues will be useful.

The test results should be evaluated carefully as radio vendors' test facilities are usually not certified and may have limitations such as inaccuracies, calibration issues, and incomplete tests. In short, this is useful data to have during product development, but it is not a substitute for certified lab tests.

7. Conclusion

Successful integration of an antenna into a wireless device depends on the understanding that the entire device is part of the antenna. The antenna cannot be added at the end of the design phase; it must be designed in from the very beginning of the product concept. Fixing antenna problems at the FCC or PTCRB testing facility is difficult, time-consuming, and expensive.

The primary antenna performance goal must be efficiency. Efficiency is *the* primary performance metric of the antenna as a transducer between the radio and the propagation medium. Antenna tuning and impedance issues can usually be adjusted to some degree during development. However, an antenna design with inherently low efficiency, most often because of size constraints imposed by the industrial design, will often require substantial product re-design for improvement. Pre-testing of the entire system, especially with transmit harmonics and self-interference in mind, is critical. Testing as early as possible to identify potential issues, when they can be more easily fixed, will result in shorter development time and will ultimately result in substantial cost savings.

Use the knowledge, experience, and if available, the test facilities of the radio module manufacturer. The radio designers are familiar with the typical performance problems and test failures related to antennas and can provide excellent advice from the very beginning of the product design.