

Advances in High-Performance Ceramic Antennas for Small-Form-Factor, Multi-Technology Devices

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Two trends are well underway in portable and handheld consumer electronic devices: shrinking form factors and the integration of multiple wireless technologies, such as Bluetooth™, cellular, GPS and Wi-Fi. These trends create challenges for device vendors and integrators by increasing the likelihood of RF noise and other system interactions that can undermine antenna performance.

Ethertronics' Isolated Magnetic Dipole™ (IMD) antenna technology addresses these situations by enabling higher isolation and frequency selectivity while maintaining good efficiency even as the antenna's size is reduced in order to meet form factor requirements. This paper describes the use of IMD technology for dual-band, dual-feed antennas created from a block of ceramic material. This surface mountable antenna features a unique dual-feed design, allowing for easier integration. Ethertronics' IMD antennas also provide reliable, consistent performance because they're more immune to their surroundings – a major asset in the tight spaces of today's mobile devices! This operational stability addresses one key drawback of current ceramic antennas: their susceptibility to significantly altered performance when other components are placed in close proximity. The root cause stems from some antennas' reliance on the board's ground plane to excite the radiation mode.

This issue creates challenges when developing an RF front end because specification sheets may not include key implementation details, triggering an iterative design cycle to try to improve results.

This paper also proposes new approaches for evaluating ceramic antennas for small-form-factor applications such as cell phones. These are necessary because implementations quickly depart from bare-board measurements, thus rendering product datasheets meaningless in terms of accurately predicting real-world performance. By offering a simple and fair test method for evaluating ceramic antennas – particularly in terms of their true volume requirements – Ethertronics aims to position ceramic antennas as a viable option for accommodating industry trends toward slim, multi-technology consumer electronics devices.

The Thin-is-In Trend: Challenges and Opportunities

Over the past few years, cell phones have been influenced by two major design trends: form factors that are increasingly smaller and slimmer – the Motorola RAZR is a prime example – and the addition of multiple wireless technologies such as Bluetooth, GPS and Wi-Fi. According to analyst firms such as Current Analysis, handsets are experiencing a 10% annual reduction in volume (currently at 106 cubic cm), with ultra-thin

(55 cubic cm) phones securing a growing market share. These trends reduce the amount of already scarce circuit board space and increase the likelihood of RF interference and other conditions that undermine performance.

These trends create a need for antenna technologies that can pursue the RF equivalent of Moore's Law, which foresaw great strides in size reduction and performance improvement. The physics governing antenna theory have shown that the operating frequency, bandwidth and efficiency are directly related to the antenna's overall volume. Reducing an antenna's volume without sacrificing performance becomes the design challenge because the "thin-is-in" trend is here to stay.

Very close quarters make it difficult to achieve requirements such as efficiency, selectivity and isolation. This environment also increases the likelihood that a metal shield will be placed only millimeters away from a critical antenna, creating RF performance issues. Yet most specification sheets don't communicate all of the details necessary to understand how the RF performance will be affected. For example, although an antenna's keep-out area is an important specification, it doesn't address the fact that antennas are three-dimensional [1]. These situations highlight the need for a new approach to designing and evaluating antennas capable of satisfying an increasingly complex set of requirements.

Isolated Magnetic Dipole Antenna Technology

Ethertronics has addressed these design trends and challenges by developing Isolated Magnetic Dipole (IMD) antenna technology, which achieves higher isolation, selectivity and performance even in small antennas. The patented technology uses confinement of the electrical field to create the antenna's mode. The strongly confined antenna mode reduces its coupling to the surrounding environment, a major asset for handset designers because it gives them more design flexibility while reducing the chances that a last-minute board spin will be required to optimize RF performance.

To visualize the coupling effects, Figure 1 illustrates the difference in current distributions generated on equal size ground planes for a Planar Inverted F Antenna (PIFA) and an IMD operating at the same frequency. Both antennas couple energy to the ground plane, with red indicating the highest level of current and blue the lowest. In the PIFA design, high currents are observed all the way to the edge of the ground plane. But in the IMD design, the currents are strongly localized to the antenna region and minimize propagation throughout the ground plane. This figure highlights the different modes of operation between PIFA and IMD designs, as well as how the ground plane is a significant part of the PIFA radiating element.

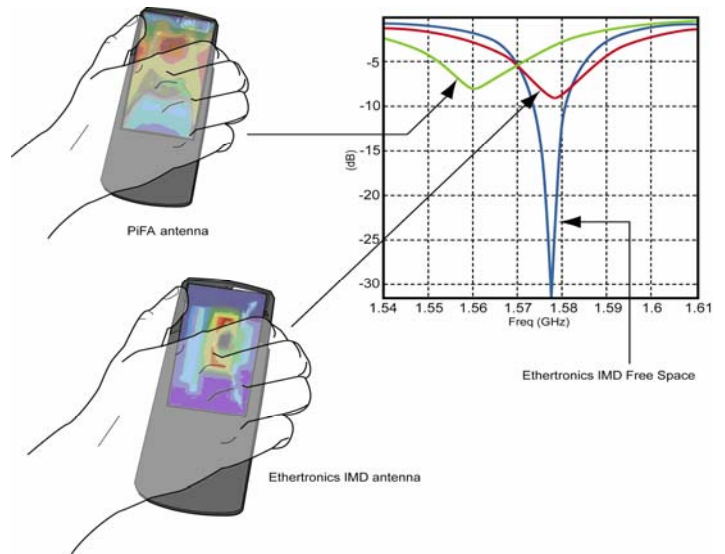
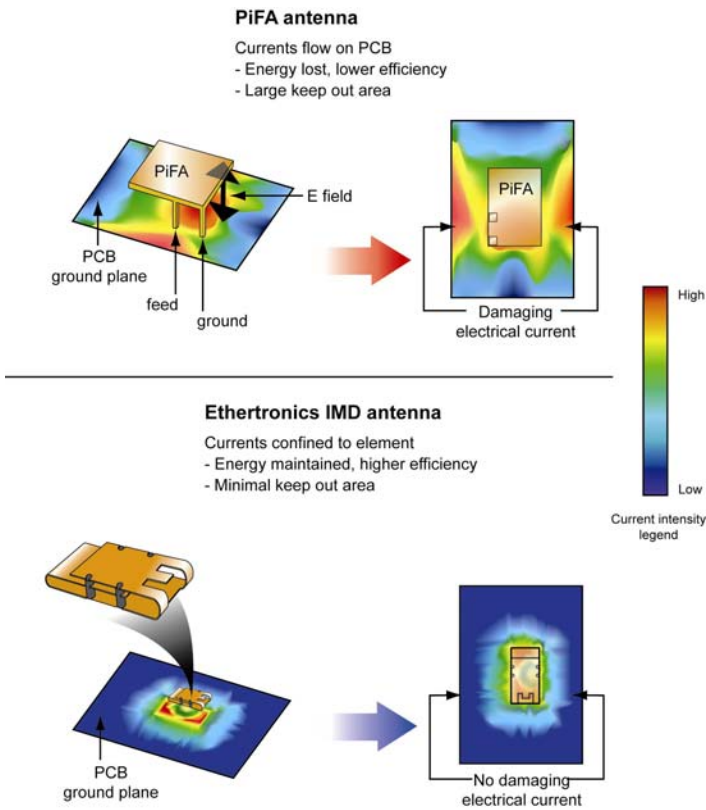


Figure 2: Difference in frequency shift - PiFA vs. IMD antenna

Another key consideration is selectivity. High out-of-band rejection is desirable because it allows two antennas to share a limited amount of space without the need for bandpass filters, a major advantage in today's compact devices. IMD achieves high selectivity via its ability to control the operational bandwidth of the antenna and produce sharp out of band roll off. By comparison, PIFAs tend to have a natural broadband response derived from their strong interaction with the ground plane which creates their effective large size. This makes it difficult to control a PiFA's out-of-band response.

GPS is ideal for understanding the challenges of compact, multi-technology environments. Because GPS signals are inherently weak, the ability to receive them reliably is key to meeting consumer expectations. Hence the value of high isolation is best expressed in terms of improving receiver sensitivity. As a result, the tests discussed later in this white paper focus heavily on GPS performance in compact environments.

Let us examine the performance requirements for the most common ancillary antennas: Bluetooth and GPS. Figure 3 benchmarks the return loss and isolation obtained between two antennas from a major OEM production phone, where the antennas are spaced 60 mm apart. This particular handset design struggled to meet the GPS receive sensitivity requirements until an IMD antenna was introduced, improving the isolation by more than 4dB from the original antenna. Although the frequency bands are separated by less than half an octave apart, the IMD still achieves more than 25 dB isolation by minimizing current flow on the ground plane, which enables further performance optimization by fine tuning the relative position of each antenna.

Figure 1: Current distribution. Top PiFA, bottom IMD

One of IMD's key advantages is that its RF properties depend primarily on the antenna structure itself rather than relying on its surroundings. As a result, multi-band IMD structures exhibit several desirable properties: high isolation, enhanced antenna collocation capabilities, independent optimization for frequency tuning and transmission line matching.

For more details about how IMD works, see "Optimizing Performance When Integrating Multiple Antennas," at www.ethertronics.com/resources/whitepapers/wp1.pdf.

One fundamental concept is isolation between antennas, or coupling. The two primary coupling mechanisms are conductive, which is created by currents induced by the antenna on the ground plane, and radiative, which is created by the antenna's near fields. Figure 1 illustrates how the potential for conductive coupling is much higher for the PiFA than for the IMD. By reducing the conductive antenna coupling effects with the main PCB, the antenna's performance characteristics can be maintained despite subtle layout changes, which routinely occur during the development cycle.

Frequency shift (in the presence of an object, such as the user's hand) is a good indication of the antenna isolation properties. Figure 2 shows that the resonant frequency of a narrowband GPS IMD antenna is nearly unchanged when the user holds the phone in different operating positions. By comparison, the PiFA experiences significant frequency shift due to the different loading of the ground plane as a function of the hand's position (note that the hand is not covering the antenna). Although both signals are attenuated by the hand's presence, the IMD antenna provides a stronger GPS signal than that of a PiFA.

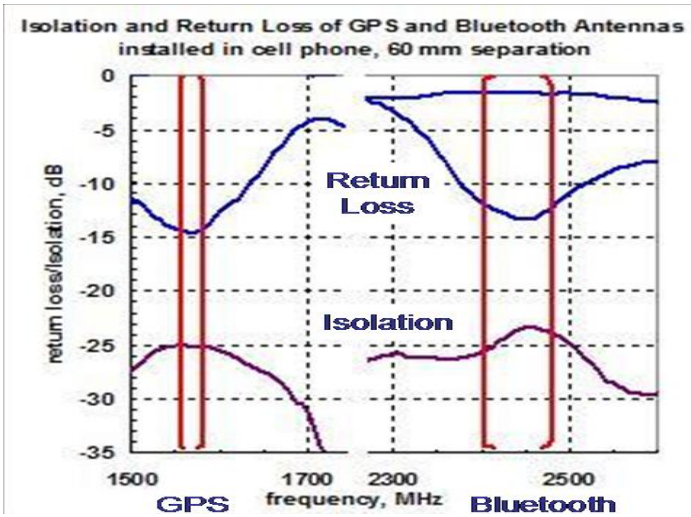


Figure 3: Return loss (blue) and isolation with separate GPS and Bluetooth antennas.

The Case for Ceramics

Over the past few years, several antenna manufacturers have developed lines of ceramic antennas in order to accommodate the trend toward compact form factors and integration of multiple wireless technologies. Ceramics are attractive because the dielectric material itself enables size reduction.

However, many of today's ceramic antennas behave more like probes than actual antennas because of the way that they excite the circuit board. Some handset integrators have a simple probe exciting the ground plane of the board; a design that aims to address problems with low link budgets. As a result, these probe-like antennas create other problems due to the fact that they were designed to maximize efficiency and exhibit minimal isolation; attributes that frequently lead to interference with many nearby components.

A handset designer needs to be cognizant of these issues up-front. However, an antenna's specification sheet rarely provides a complete portrayal of its real-world, three-dimensional performance characteristics and placement limitations.

New Approaches to Evaluating Ceramic Antennas

When comparing ceramic antennas from multiple vendors, device integrators should consider their immunity – or lack thereof – to their surroundings as a key parameter. Many of today's ceramic antennas are monopole types, which deliver high efficiency but at the expense of being highly influenced by environmental factors such as the size of the ground plane, critical placement on the circuit board and larger-than-specified keep-out areas.

For example, removing the ground plane under and near the antenna represents a design layout challenge because it means that no other signals or components can intrude on the antenna's space. This situation highlights the importance of considering both the physical dimensions of the antenna and its keep-out requirements when comparing solutions. Ethertronics' ceramic IMD design is based on the belief that device integra-

tors should not fixate on device size alone when evaluating ceramic antennas. Instead, other factors – such as keep-out areas, which affect the antenna's true volume requirements – often can justify going with a slightly larger ceramic device that has significant performance benefits. That's why device integrators should consider all of these details when evaluating multiple vendors' ceramic antennas.

To appreciate the factors that can and should influence ceramic antenna choices, it helps to understand the relationship between occupied volume and efficiency. Figure 4 illustrates the schematic of an antenna on a circuit board, where the antenna's dimensions are W_1 in width, L_1 in length and H in height. The volume of the antenna will be $V_1 = W_1 \times L_1 \times H$. Although most antenna integrators believe that smaller is better, in reality, the keep-out areas are needed to maintain the performance integrity of the device, so the true antenna volume is more likely to be $V_2 = W_2 \times L_2 \times H$.

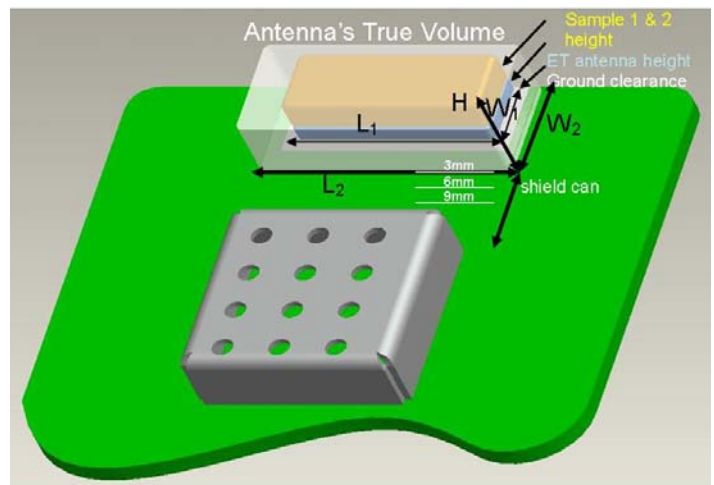


Figure 4. Layout defining antenna keep-out volume

Figure 4 illustrates how antenna volume is variable in up to three dimensions. (In this example, it moves in two dimensions because the height is fixed, due to the device size.) Figure 4 also suggests a test method for moving the shield to measure its performance impact. The issue is how to best measure the keep-out areas along all axes. One method is to place the antenna on a fixed position on the board and then move a metallic shield near the antenna in order to measure both the center frequency shift and impact to efficiency. Determining L_2 and W_2 provide the additional insights necessary for device designers to make an informed decision.

Testing GPS Performance

Ethertronics chose GPS for testing because it is a low-power, narrowband signal that is vulnerable to frequency shift. As Figures 2 and 3 illustrated, the right combination of frequency stability, return loss and isolation are hallmarks of a well-designed antenna, particularly one used for GPS applications. The design requirements here include staying on frequency, maximizing efficiency and achieving high isolation. As a result, Ethertronics' test focused on interactions related to frequency drift, efficiency, selectivity and board location.

In the test, three representative sample antennas from competitors were measured and compared to the Ethertronics dual-band, dual-feed GPS/Bluetooth ceramic antenna. It's important to note that the sample antennas tested were single-band devices, while the Ethertronics antenna contains two antennas, which cover both GPS and Bluetooth applications.

Figure 5 shows that in the test, three of the four sample antennas achieved overall efficiency greater than 60%. If the antenna tradeoff analysis were limited solely to selecting the highest overall efficiency, the apparent "winner" would be Sample 2.

However, it's important to note that GPS' 1.575 GHz frequency is close to one of the world's most widely used UMTS bands (1.7 GHz), as well as the recently auctioned AWS band in the United States. Given this situation, a wideband antenna – such as Sample 2 – would start to pick up UMTS signals, necessitating the use of bandpass filters. Those filters add costs, and they require board space, which reduces the attractiveness that broadband antennas offer.

But Ethertronics' IMD antenna has inherent selectivity, thereby eliminating the need for bandpass filters, saving money and board space in the process. Over the 200 MHz span displayed in Figure 5's efficiency plots, the Ethertronics dual-band, ceramic GPS/Bluetooth antenna shows both high efficiency and a narrowband response, which are highly desirable features for GPS applications.

GPS signals are quite narrow, less than 5 MHz, making them more susceptible to problems caused by center frequency drift. Yet drift is surprisingly common in today's GPS devices due to poor isolation. The antenna samples used in Figure 5's tests were subjected to the shield can test (Figure 4) to examine how peak efficiency and center frequency performance might be impaired in real-life environments.

This efficiency test (Figure 6) involved measuring antenna efficiency as a function of shield can distance from the antenna

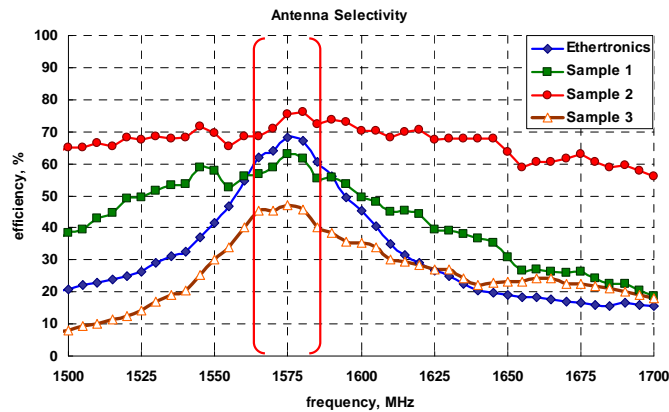


Figure 5: Antenna efficiency for GPS applications

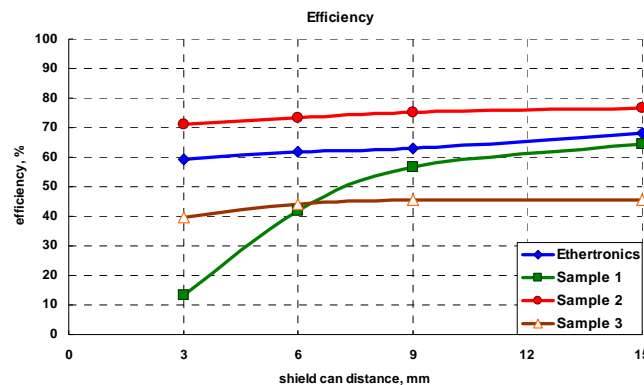


Figure 6: Shield can distance's impact on antenna efficiency

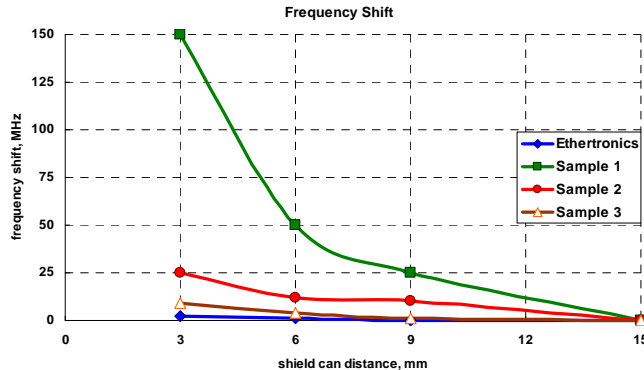


Figure 7: Shield can distance's impact on frequency shift

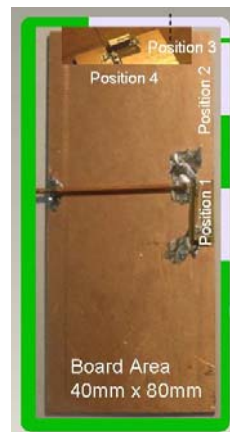


Figure 8. Layout of test board for position study

under test. The dimensions of the shield used for this test was 15 mm by 14 mm by 3.5 mm in height. Although this is a common height, it's important to note that the shield was taller than the Ethertronics antenna, creating a shadowing effect. Nevertheless, the Ethertronics antenna was able to overcome this effect.

A similar shield can test measured the effects on antenna center frequency shifts. A shift of more than 10 MHz can render a GPS link useless. Figure 7 shows that Sample 1 suffers a dramatic frequency shift, to the point that a GPS link would be severely degraded. By comparison, the Ethertronics antenna did not de-tune, effectively making the shield can distance a non-issue from a design standpoint.

Comparing Figures 5, 6 and 7 highlights the impact of shield can placements. For example, Sample 1 is significantly impacted – but design engineers wouldn't know that if the only specifications they had were the ones plotted in Figure 5.

Another key consideration for ceramic antennas is their flexibility in terms of position on the circuit board. Figure 8 shows a layout for a test board used to conduct a position study. The test board measured 40 by 80 mm. The three sample antennas, along with the Ethertronics dual-band, dual-feed GPS/Bluetooth antenna, were tested at each location to determine the amount of variation in antenna efficiency as a function of location. Figure 8 shows the locations tested.

Figures 9 and 10 illustrate the problem of relying on specification sheets, particularly for those antennas that exhibit significant performance variances when utilized outside the specified board location. In this test, Ethertronics tested four common locations, compiling data from the three best locations in order to calculate an average Efficiency value. The data from the worst location illustrate the relationship between location and performance. In this test, only two antennas have adequate performance of more than 40% efficiency in all locations. (One note: As per its specification sheet, Sample 3 works only in location No. 3.)

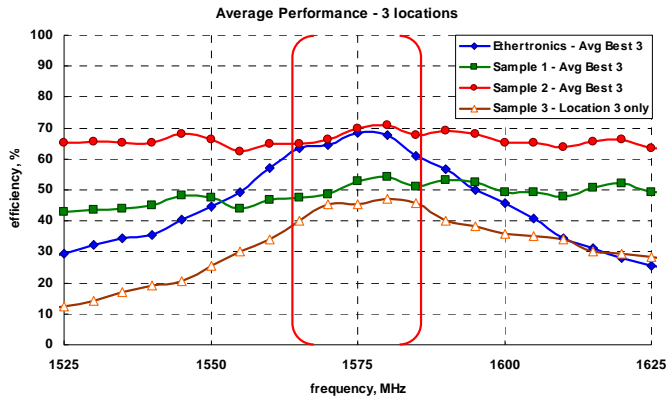


Figure 9: Average performance - from 3 locations, averaged

The key takeaway from Figures 9 and 10 is that board position doesn't significantly affect the IMD antenna's performance. As a result, vendors have far more design flexibility than with other solutions. They also have predictability and reliability, which dramatically reduce the chances that board spins and real-world variables (e.g., hand positions) will undermine RF performance.

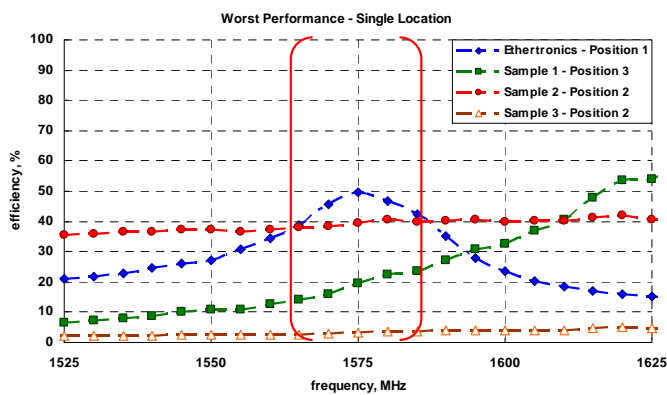


Figure 10: Worst-case performance - from single location

Table 1 provides a comparison between the actual dimensions of each antenna, the specified ground clearance separation and the resulting keep-out area. As a result of the shield can testing, it's possible to determine an additional separation distance based upon the measured decrease in performance. This larger separation defines the antenna's apparent volume requirements.

	L ₁	W ₁	H	Ground Clearance (GC)	Total PCB Area	Shield Can Offset	Real PCB Area	Antenna's Volume	Measured Efficiency
Sample 1	10	3	4	3	96	9	336	1,344	65%
Sample 2	20	3	4	0	60	3	156	624	77%
Sample 3	8	2	1.5	2	48	3	70	105	46%
ET BT & GPS	14	4	1.3	1	80	3	140	182	68%
ET GPS only	10	4	1.3	1	60	3	112	146	68%

all measurements in mm, sq mm, or cu mm

Area = (L₁ + 2x GC) x (W₁ + GC)

Use L₂ and W₂

Table 1: Summary of device size, keep-out area and volume

To recap the key findings from the testing:

- Sample 1 experienced a large frequency shift, and its efficiency fell when the shield can was less than 6-9 mm away. It also demonstrated poor performance from the upper right test location (No. 3)
- Sample 2 had highest measured efficiency and experienced some frequency shift, yet any performance changes were offset by its broadband response. A draw-back to a wide-band antenna solution is additional filters and board space impact.
- Sample 3 showed stable performance and had limited frequency shift, but its efficiency was the lowest of the four. Its thickness was 40% of Samples 1 and 2.
- The Ethertronics ceramic IMD was stable in terms of both frequency shift and maintaining good efficiency. It also demonstrated the smallest performance change due to board location variation.

There are two antennas that have shown superior performance and immunity to environmental changes: Sample 2 and Ethertronics' Ceramic IMD antenna. Although Sample 2 achieved higher efficiency, it's important to remember that this antenna is broadband, which is not necessarily a desirable characteristic, especially in handsets that support both GPS and UMTS 1700 or AWS. Put simply, broadband means poor selectivity. Additionally, Sample 2's antenna volume is three to four times larger than Ethertronics'. As a result, the Ethertronics antenna provides the ideal combination of high performance and high stability, while minimizing additional filters, components and PCB requirements. Ceramic IMD is ideally suited to compact form factors such as slim handsets. It provides the narrowband selectivity, smallest volume and flexible board placement necessary for today's multi-technology handsets.

Characteristics of the Ethertronics Dual-Feed GPS/Bluetooth Antenna

As mentioned previously in the comparison of GPS ceramic antennas, the Ethertronics ceramic antenna provides dual-frequency operation covering both GPS and Bluetooth functions. Each operating band also has its individual feed connection. Figures 11 and 12 illustrate the electrical characteristics of the dual-band, dual-feed GPS/Bluetooth antenna. Figure 11 highlights how more than 25 dB of isolation is maintained between the GPS and Bluetooth elements in the 14x4x1.3 mm

ceramic antenna. Figure 12 shows that the efficiency at the GPS frequency is greater than 65%, while the average efficiency across the Bluetooth frequency band is 48%.

By comparing the attributes of the ceramic IMD antenna (Figure 12) against the real-world metrics portrayed in Figure 3, it's easy to see that the ceramic IMD achieved a significant improvement for each of the three design criteria: isolation, efficiency and return loss, despite a reduction in antenna separation from 60mm to 1mm! This achievement highlights the value of combining the IMD's efficient design with ceramic's size reduction capabilities, which together meet the unique requirements of compact, multi-technology devices.

Conclusion

Ceramic antennas are a viable option for today's compact mobile and portable devices. For device integrators, the challenge to using them is that specification sheets often don't provide all of the details necessary to accurately predict their performance, which may trigger additional board spins or impair real-world performance. Instead of focusing only on the ceramic antenna's size, device integrators also should consider its immunity – or lack thereof – to its surroundings. These include environmental factors such as the size of the ground plane, placement at the circuit board's center or edge, true volume and keep-out areas.

Ethertronics' ceramic IMD design accommodates a variety of variables that integrators face in today's mobile devices. The ceramic IMD offers a package of benefits that include:

- A small profile
- High efficiency
- Excellent isolation
- Natural band selectivity
- Dual-band and dual-feed support

The bottom line is that all of IMD's attributes save designers time-to-market and development costs. The IMD design accelerates antenna integration and optimization because it enables the use of systematic procedures that are independent of the device. IMD mitigates the possibility that last-minute design changes will affect antenna performance to the point that a new spin is necessary. As a result, there is far less chance that the handset manufacturer will have its product launch delayed or

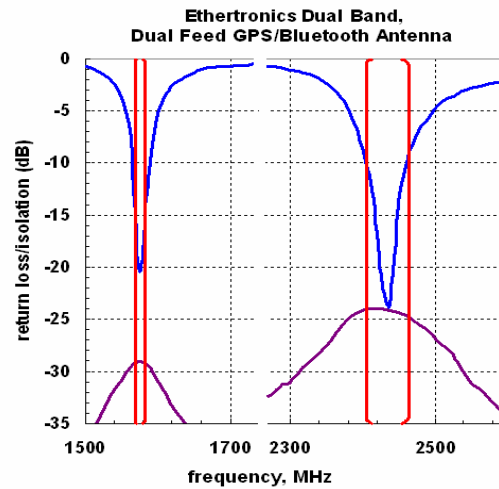


Figure 11. Return loss and isolation of Ethertronics' dual-band GPS/Bluetooth antenna

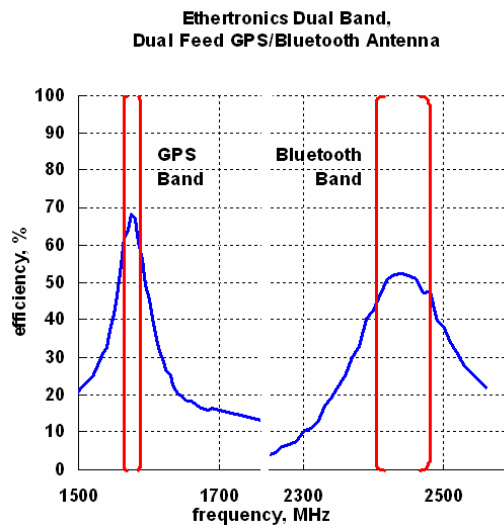


Figure 12. Efficiency of Ethertronics' dual-band GPS/Bluetooth antenna

development costs increase simply because the antenna no longer can meet its requirements.

As a result of IMD's inherent physical properties, it is able to stay on frequency in the presence of other objects while maintaining its isolation characteristics, an essential attribute when multiple radios are integrated in close proximity. It's important to note that even small improvements (e.g., 3-5 dB) can be noticeable to users. As a result, noticeably poor or superior performance can affect a device's sales potential. Simple things make all the difference.

References

- [1] "Fundamental limitations of small antennas", H. A. Wheeler Proc. IEE , Dec. 1947, 35#12, p. 1479-1484

Dr. Laurent Desclos has 20 years wireless industry experience specializing in the design of antennas and RF integrated circuits. Since Ethertronics inception, he has been intimately involved in developing Ethertronics patent portfolio, expanding our operations in Korea, China and Taiwan, and recruiting our world class engineering and in country management teams. Prior to Ethertronics, Desclos held various research and development positions with NEC in Princeton, NJ and Tokyo, Japan, where his research teams focused on the advancement of CMOS, BiCMOS and GaAs RF ICs for WLAN applications at 2.4, 5 and 60 GHz.

Additionally, Desclos was a consultant to the French military for EMI, EMC and frequency coordination issues in France and Gabon. He holds over 40 international patents and has authored over 150 papers on subjects including radar cross sections, electromagnetic radiation theory, RF circuit design, antenna theory and applications. Laurent received his Doctorate from the National Institute of Applied Sciences in Rennes, France. He is a senior member of IEEE, and a technical advisor to several wireless startups.