TOP 10 ANTENNA DESIGN CONSIDERATIONS

Introduction

Digi International Wireless Design Services (Digi WDS) is a dedicated team of creative engineers who can take products from concept to production. Digi WDS has delivered technical design services and solutions for customers in the wireless realm for over 15 years. With hundreds of successful wireless designs delivered, the Digi WDS team understands the full complexities as well as the subtle nuances of designing and building a great wireless solution.

Among many of the design capabilities required for designing wireless products, antenna design is undoubtedly one of the most unique. It is a piece of hardware that creates simplicity and intricacy and is of great importance and yet is often overlooked. Small wireless devices, being a special subset of the entire wireless device family, usually require customized, miniaturized and concealed antennas, which pose additional challenges for product designers across a range of products, including IoT devices, M2M devices, medical devices and mobile handsets.

As an introduction to antenna design for small wireless products, this white paper discusses ten of the top antenna design considerations Digi WDS engineers feel are important to understand for anyone involved in wireless device design.

1. Early proof of antenna feasibility ensures product feasibility

Digi Wireless Design Services is often called in for last minute minute advice by customers whose products have gone through the full design cycle but are repeatedly failing certification tests. While WDS has an established record of debugging RF issues and getting failing products to eventually pass certification, cases exist where it was concluded that the antenna was not feasible for the intended technology and product form factor, and the product might never pass certification.

Based on design experience accumulated through a large number of successful projects, Digi WDS generally divides product development into four major phases.

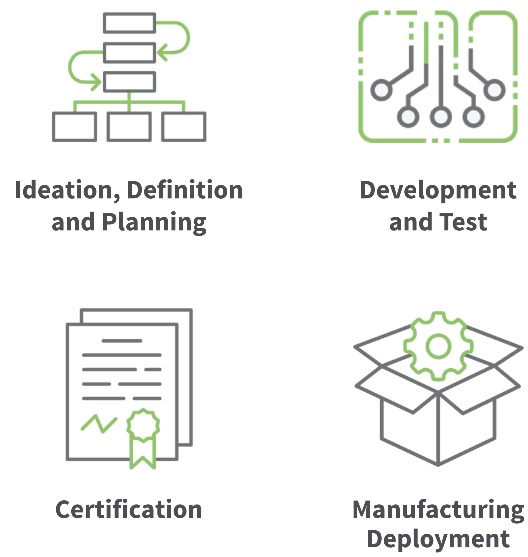


Figure 1-1 The four phases of product development

One of the root causes behind frustration during the certification phase is the late involvement of an experienced antenna designer. Ideally, an extensive process of feasibility research on the product is conducted in the initial phase of product ideation and planning. Digi WDS recommends that teams work with an antenna expert to take this step to ensure your project is successful from the start.

The antenna feasibility research will focus on different aspects of different products depending on the use case. For example, this might include assessing the placement of major system components such as microprocessors, power supply circuits, display, connectors and batteries. It would also include evaluation of mechanical features, fixtures, enclosure materials, device operating environment and intended geographic regions for deployment. Each of these factors must be evaluated and planned for, to minimize the risk of design failure.

Antenna feasibility is completely intertwined with the entire system, so it is always better done right away. Work with an antenna expert to help plan the path forward as early in development as possible.

2. Prototyping! Prototyping! Prototyping!

The main goal of antenna feasibility research is to validate the antenna concepts against the product requirements from all relevant perspectives. Decisions made at this point decide the general form factor and industrial design of the product, as well as the risk level of the development and certification, and also influence the future generations of the product. Therefore, it is important to establish a solid level of confidence in your antenna feasibility before going forward.

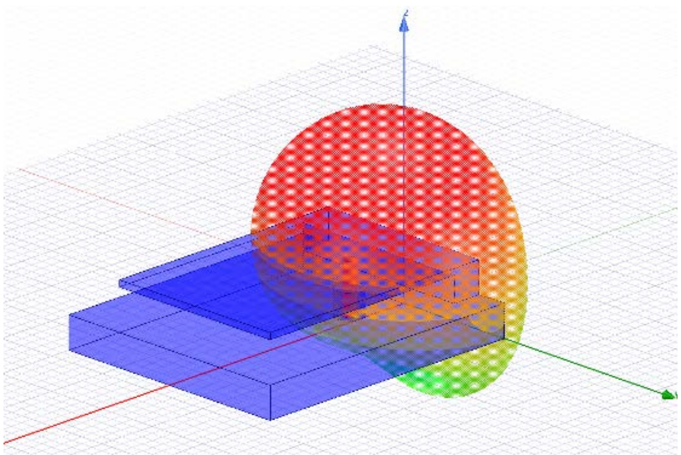


Figure 2-1 Prototyping leads to design confidence

This confidence comes from design concept validation through prototyping. Software simulation or hardware implementation and testing are the usual approaches. Software simulation is irreplaceable for its fast iterations of modeling, validation of design concept and refinement of design geometric parameters. However, it has unavoidable limitations.

During software simulation, antenna designers usually use simplified mathematic models to build the antenna structure, PCB, on-board components, mechanical fixtures, etc. All of these together will cause differences in EM characteristics between a simulated model and a real-world antenna.

To compensate for this inherent inadequacy in software simulation, Digi WDS always builds antenna hardware prototypes as an extra step of validation. Different development phases require different levels of quality for the hardware porotype.

Even though any antenna designer can build these antenna prototypes, typically only the most experienced designers have the right gauge, tools and established procedures to do it effectively so that the prototype generates the most trustworthy performance with the least effort spent.

3. Constant antenna inspection leads to final success

Thorough feasibility research and effective prototyping can ensure the product development starts out with minimum risk induced by the antenna. However, a good start doesn't always guarantee a good ending. Antenna designers need to be constantly checking and tuning the antenna throughout the entire product development process to ensure good performance. It is through those repeated inspections that potential antenna de-tuning and performance deviations can be captured and corrected.

A good antenna designer understands all possible impact factors well enough to know when to check antenna performance. Digi WDS suggests antenna performance checks after every board spin. This is because when a PCB gets populated or goes through variations in population or layout, differences in the RF ground current pattern will occur. This can disturb the existing electrical characteristics of the antenna causing frequency de-tuning or efficiency loss.

For more complicated designs, where multiple antennas are involved or antenna bandwidth is critical to cover enough bands, extra caution is highly recommended. Components such as shields, vias, cable connectors, long battery wires, components requiring large ground cutouts and test pins can all change the ground current pattern and cause antenna performance deviations. Some fabrication processes such as potting can also easily cause huge variations in antenna performance if not carefully planned.

The figure below shows deviations of a multiple-band cellular antenna S11 (one of the commonly used metrics for evaluating antenna power intake vs. frequency) before and after a board spin. In this case, when the product development progressed from Alpha prototype to Beta, Digi WDS did necessary inspection and caught the antenna performance deviation. The team was then able to take several counter-measures to address the deviation in time, which further led to a successful design in the end.

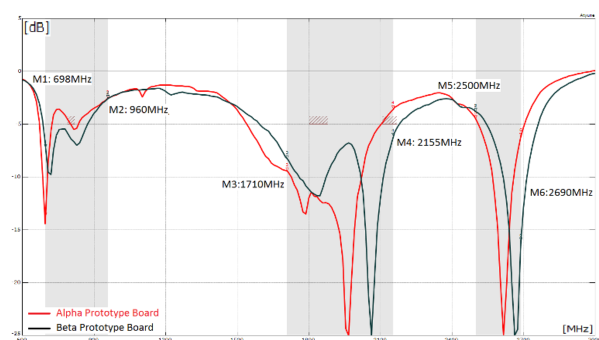
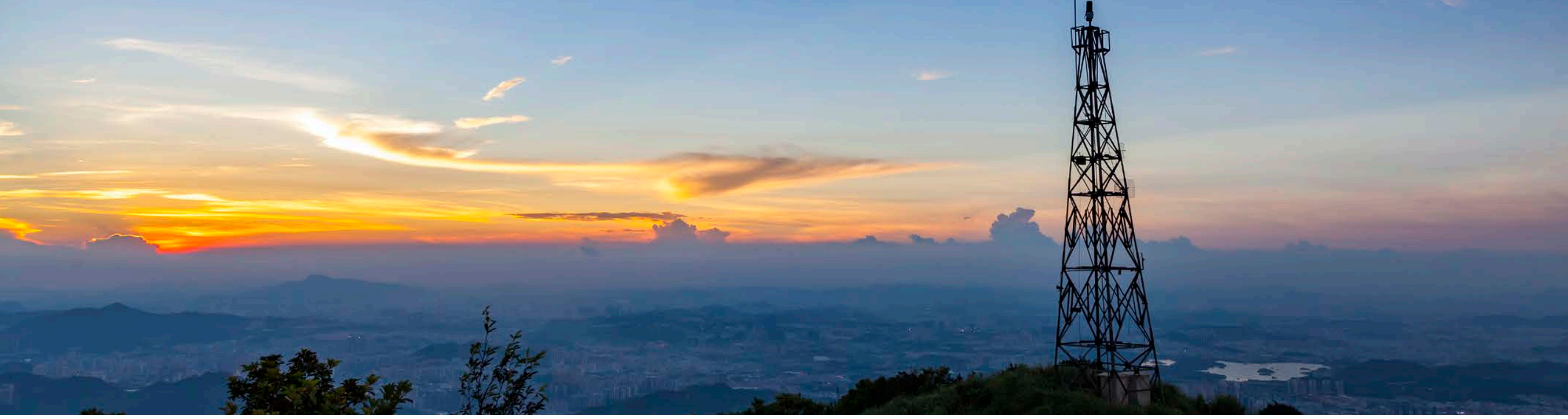


Figure 3-1 Deviations of a multiple-band cellular antenna S11

It is imperative that antenna designers anticipate antenna performance impact factors during the product development process. To do so, it is important to constantly check and tune the antenna.



4. Antennas must integrate with all components inside an antenna system

The antenna is just one of many components inside an antenna system. For this reason, the antenna design should be about designing a complete well-functioning antenna system. Antenna system components can vary depending on the system requirements, but the very basic one consists of one antenna, one matching network, one filtering network, and any necessary testability features (see Figure 4-1). Front-end modules might have filtering networks integrated and thus the filtering circuit (dash-line block in Figure 4-1) can sometimes be omitted from the antenna system diagram, but everything else must be integrated and well-designed. The main goal of any antenna system is to maximize power delivery either out of or into the front-end circuitry over selected frequency ranges.

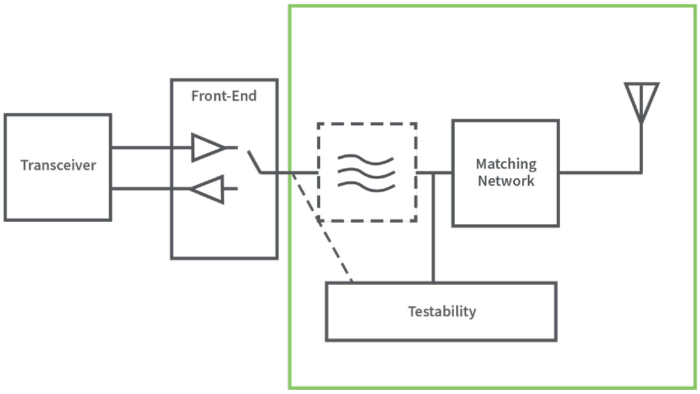


Figure 4-1 The basic antenna system structure

The matching network is critical to optimize power delivery and maximize the system power efficiency. Testability features such as RF connectors and lumped element provisions play a critical role in helping to determine whether you can get trustworthy measurement results during system testing. Apart from these obvious things, transmission line impedance control, optimal matching component locations, antenna feeding pad optimization, placement of vias, and noise considerations are all things to carefully evaluate before implementation. More advanced antenna systems such as those that require active aperture tuning, active impedance matching, and Multiple-Input Multiple-Output (MIMO) scheme, make the task of designing and optimizing an antenna system even more complex.

5. Double the frequency bands, triple the design difficulty

Assuming the RF front-end circuitry output and the interconnecting transmission line sections are strictly 50 ohm-controlled at a certain frequency point, there are actually many ways to match the input impedance of a given antenna to 50 Ω at the same frequency for maximum RF power delivery. However, for real-world applications, antennas will never only operate at a single frequency point, and the number of frequency bands and bandwidth of each band raises the difficulty in designing the antenna impedance matching network.

Let's look at a Bluetooth application first. A Bluetooth antenna needs to radiate a sufficient amount of power over the frequency range of 2.4 GHz to 2.48 GHz, which has a span of 80 MHz. It is generally easy to match the Bluetooth antenna to have S11<-10 dB across the 2.402 GHz to 2.480 GHz frequency band, because the required antenna bandwidth is small, only 3% (80 MHz/2440 MHz). Figure 5-1 shows one example of a Bluetooth antenna achieving S11<-10 dB at band center and band edges after impedance matching.

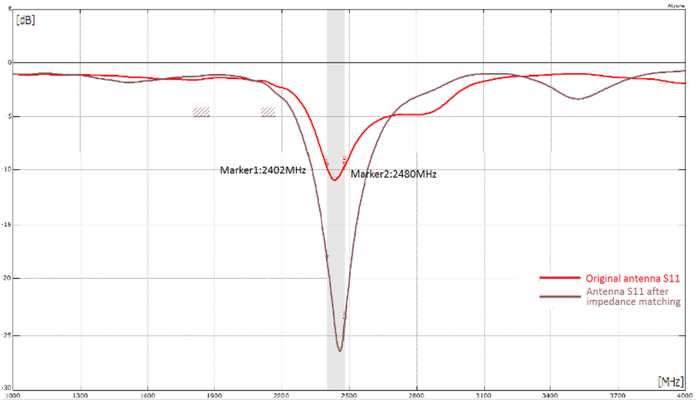


Figure 5-1 Bluetooth antenna after impedance matching

In the case of cellular applications, impedance matching becomes much more complicated. The root cause is that cellular antennas usually have multiple frequency bands, and each has a wide frequency span. For example, in an AT&T LTE network, the lower frequency band of the antenna needs to cover LTE band 12 and 5, which goes from 698 MHz to 896 MHz (198 MHz, 24%), and the higher frequency band needs to cover LTE band 4 and 2 which stretch across 1710 MHz to 2155 MHz (445 MHz, 23%).

Figure 5-2 shows the milestone result of a past antenna design project that Digi WDS worked on. The main task there is to increase antenna bandwidth to effectively cover all four AT&T LTE bands by incorporating a better matching network. The magnitude of design difficulty, judging by the number of bands and bandwidth span of each band, is much higher than that of Bluetooth antennas. In the end, Digi WDS was able to achieve 15% bandwidth increase on the 698 to 896 MHz band and 50% on the 1710 to 2155 MHz band with a carefully engineered matching network that helped the customer save both time and money.

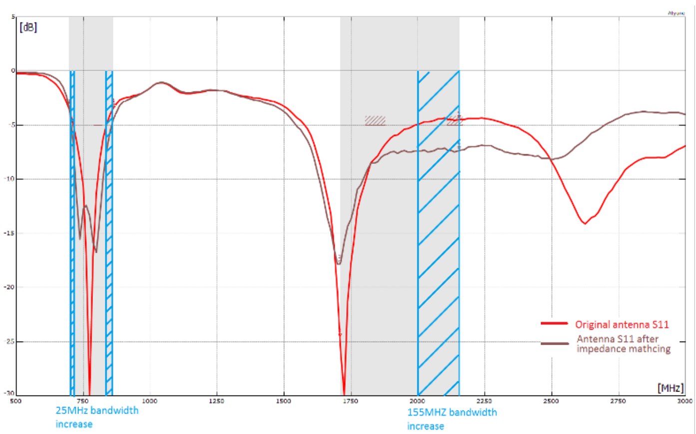


Figure 5-2 Antenna S11 comparison before/after impedance matching

While designing matching networks for these cellular antennas, especially in small wireless devices, better impedance matching at the band center will often mean worse impedance match at band edges. Also, better impedance matching across the low-frequency bands will mean a worse impedance match across the high-frequency bands. Antenna designers have to find the most balanced design that doesn't only aim to optimize the impedance matching at one certain frequency point but across several wide-frequency bands. This can only be done with an understanding of antenna system design techniques as well as regulatory and carrier certification requirements.

6. Effective impedance matching optimizes the upstream radio system

The impedance matching network plays a key role in almost every RF circuit by connecting two RF components. Based on RF design principles, maximum power delivery is realized when an upstream output port and a downstream input port have the same impedance. The matching network acts as a bridge to help transition the upstream port impedance to that of the downstream. Doing so maximizes power delivery. Figure 6-1 and Figure 6-2 illustrate this process.

In a transmitting system, the upstream block is the RF front-end power amplifier (PA) output while the downstream block is the antenna. As shown by the figures, a 5.4 dB increase in power delivery from the RF front-end to antenna can be expected after incorporating an effective impedance matching network, which further increases the total radiated power from the antenna.

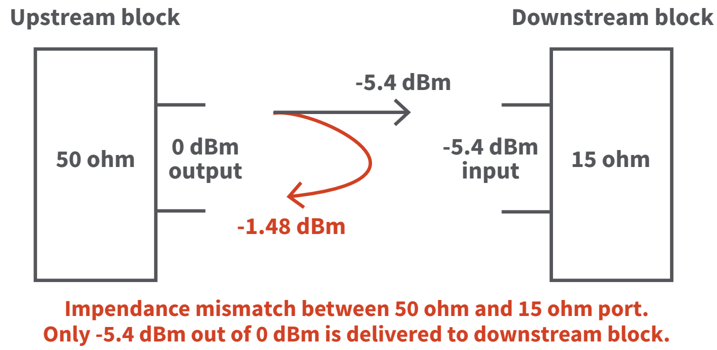


Figure 6-1

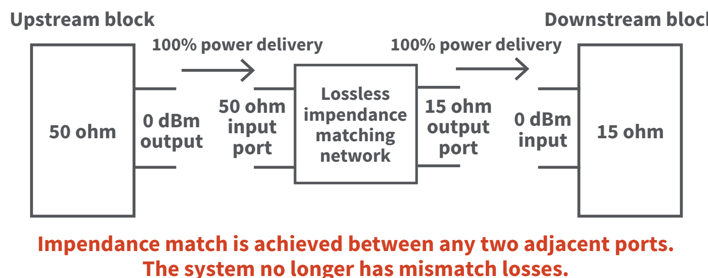


Figure 6-2

Note that instead of always looking downstream from the radio output toward the antenna, it is important to improve matching networks by looking upstream from the antenna toward the radio. There are a few reasons:

- First, delivering maximum power downstream minimizes the amount of power returned upstream, thus avoiding all the negative impacts on the upstream circuit block caused by excessive returned RF power.
- Second, battery-powered devices should see an increase in operational lifespan, since maximizing power delivery improves the device's power consumption efficiency.
- Third, the majority of RF components today are designed for optimum performance when implemented in a 50 Ω impedance-controlled system.

So, if any single point in the RF power delivery chain breaks that 50 Ω impedance rule, the resulting negative impact will propagate through the entire RF system, causing system performance degradation. There are other considerations in addition to those mentioned. The key take-away is that sometimes a seemingly complicated system problem can be fixed as easily as a minor capacitor value change on the antenna matching network.

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7. MIMO antenna system is more than a combination of multiple SISO systems

Multiple-Input Multiple-Output (MIMO) is a method for multiplying the capacity of a radio link using multiple transmission and receiving antennas. This is a well-known and well-developed concept that can significantly enhance data throughput of wireless products. A common misunderstanding surrounding MIMO is that in order to upgrade from SISO to MIMO, one just needs to add extra antennas to the existing system. However, coupling between these multiple antennas makes MIMO more difficult to implement.

Antennas belonging to the same MIMO antenna system occupy the same frequency bands. Therefore, part of the RF energy emitted by one antenna will be coupled to other antennas instead of being radiated out. A well-designed antenna system for MIMO minimizes this sort of RF energy loss, whereas a bad one does not and will suffer from communication coverage and range reduction.

Coupling can also occur through ground currents, especially when the MIMO antennas share the same RF ground plane. When an antenna's ground current flow is disturbed by coupling, the current distribution pattern is disturbed on the antenna arm. This impacts the antenna's radiation pattern and causes antenna performance deviations. Figure 7-1 shows an example of severe antenna efficiency reduction due to improper MIMO implementation of an LTE cellular antenna.

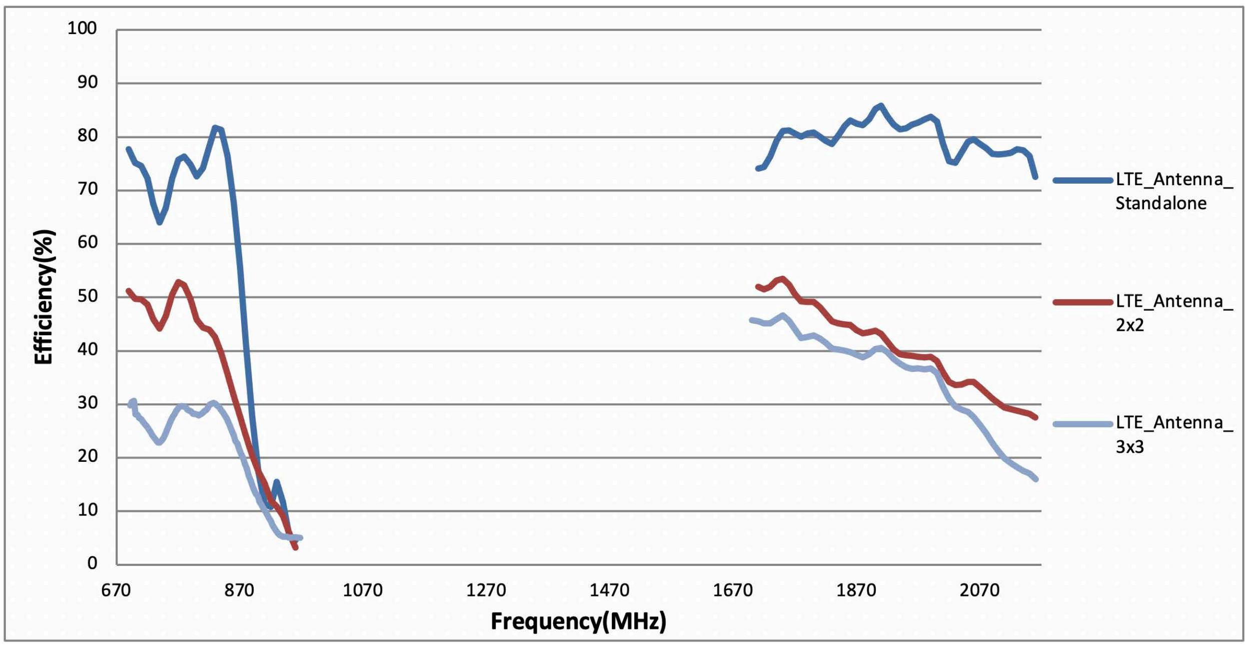

Figure 7-1 Antenna efficiency reduction when migrating from a SISO to a MIMO system

In this figure, severe efficiency reduction happened on both of the two major frequency bands due to adding extra LTE antennas into the existing system without careful planning and engineering. Digi WDS highly recommends having the right expertise on board to strategically plan, design, and test the antenna system to exploit the full benefits of MIMO.

8. An active antenna system is the ultimate solution

As much as antenna designers want to have significant amounts of space, board size and clearances, these are often luxuries that are unaffordable in relationship to many other design requirements. Again, this is particularly true of small devices such as mobile devices and wearables. Therefore, in a very stringent design situation, an active antenna system is often adopted to do what a passive antenna system can never do.

For a passive antenna system, the antenna is designed specifically to fit just one pre-defined use case. When the product is used outside this expected use case, antenna performance is likely to degrade. The basic active antenna system, on the other hand, controls the antenna performance to adapt to two or more pre-known use cases. This gives a wireless product the versatility to be deployed in different countries, on different carriers, or simply in different environments (such as in-hand, in-pocket or on-table). A more advanced active antenna system, using a certain algorithm, is smart enough to detect the device operating environment continuously and adjust to the best-fitting configuration autonomously without a designer pre-defining every possible use case.

Just to scratch the surface here, the most commonly seen active antenna systems are geared to do active impedance matching and antenna aperture tuning. To do active impedance matching, one or more of the lumped elements are controlled by either the radio module or a dedicated microcontroller. The components being controlled can be adaptively shut down, turned on and switched to different values. This enables the antenna system to have many different impedance matching networks without undergoing hardware changes, but it doesn't change the intrinsic characteristics of the antenna. Figure 8-1 shows a simple active matching implementation diagram.

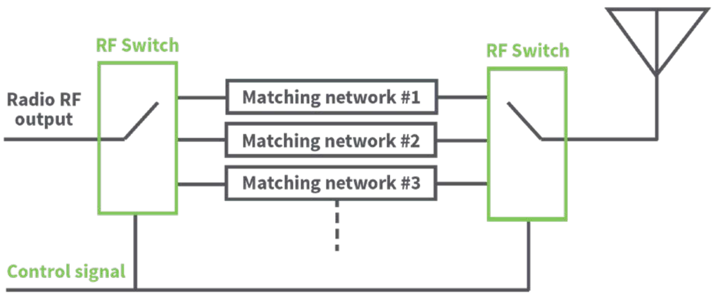

Figure 8-1 Active matching implementation

Aperture tuning, on the other hand, adopts a different concept. It directly changes the current distribution pattern on the antenna by altering the impedance at any chosen point on the antenna structure. Every set of antenna characteristics comes in from the unique current distribution on the antenna. Any change in current distribution makes the antenna electrically different even without a physical change of geometry. There are commonly two ways of actively changing current distributions on the antenna. One is through a voltage-controlled varactor, and another through the RF switch system. Figure 8-2 shows voltage control and RF switch implementations.

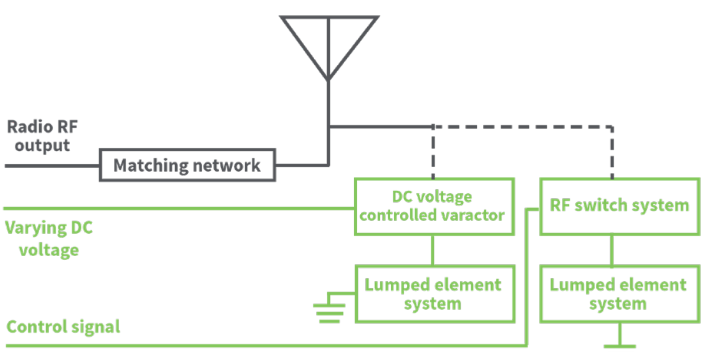

Figure 8-2 Voltage control and RF switch implementations

9. Always evaluate off the-shelf antennas

It is common for wireless product designers to consider off-the-shelf (OTS) antennas as their first option. This is a fairly good practice in many cases, as the majority of the off-the-shelf antennas have merits including low price, miniaturized size, verified efficiency and bandwidth, as well as quick-and-easy implementation. To ensure success, Digi WDS can help Digi customers select the most suitable OTS antenna for a wireless product.

At the beginning of the wireless product process, many product designers go through the datasheets of potential antenna candidates just as they do with other components such as capacitors, inductors, FETs and certain ICs.

Unfortunately, antenna datasheets often highlight the most unique technical merits such as footprint size or radiation pattern, and leave out less desirable features. The following are three critical things to look for in antenna datasheets for small wireless products:

1. **Antenna evaluation board size and shape.** All of the numbers shown in the datasheet are either calculated or directly measured from the evaluation board. In other words, the numbers are dependent on the evaluation board dimensions. Most of the time, even though the antenna part is small, its required PCB ground is large, and will not directly fit the end product. Therefore, it is critical to retain the ideal size and shape of the evaluation board when integrating such OTS antennas to avoid introducing performance deviations.
2. **Ground cutout region immediately underneath and around the antenna.** The ground cutout is itself part of the antenna. It helps form the ideal current distribution pattern by acting as a dimension extension of the antenna part. This is another reason it is critical to retain the size and shape of the cutout region; otherwise the antenna dimensions will vary, thus changing antenna performance.
3. **Antenna placement location relative to the evaluation board.** Depending on the basic antenna concept you use to design the OTS antenna, placement relative to the PCB matters. Typical locations are the center, edges and corners. Beyond these typical locations, WDS also recommends looking at feed point orientation relative to the shorter and longer edge of the PCB, and the cutout region orientation relative to the PCB.

One thing to always keep in mind when reading though the datasheet is that datasheet numbers are measured on a bare, integral, perfectly via-ed and un-populated evaluation board with just a few matching components. Antenna performance will differ or even degrade when measured on a fully-populated PCB. This means some degree of customization is still needed for every unique product to ensure maximum design confidence.

10. At the end of the day, it all depends

In the end, without going into any more technical considerations in antenna design, it is important to consider that antenna design is a unique type of work, and it always carries a certain level of customization. This concept is inherent in all the aspects of antenna design we have discussed. No universal antenna solution exists.

To summarize:

- Early in the stage of feasibility research for any wireless product, product designers should carefully consider antenna design and build several dedicated prototypes for antennas before choosing one that best fits your product. (See sections 1 and 2.)
- Antenna performance should be constantly checked during the entire course of product design, because antenna performance has dependencies on board layout and component placements. (See section 3.)
- It's important to view the entire antenna system as a whole. The performance of an antenna is dependent on every component within the system but also has impact on the entire RF system. (See sections 4, 5 and 6.)
- MIMO and active antenna systems are both more advanced and can bring unparalleled performance compared to that of the traditional passive single antenna system, but the added system complexity also increases the level of customization and requirements for expertise. (See sections 7 and 8.)
- In the case of integrating an off-the-shelf antenna part, it is critical to read every word of the antenna datasheet to ensure you are making an informed choice, and plan for customization and fine-tuning. (See section 9.)
- All aspects of antenna design are inter-dependent and subject to change for each unique case at different development phases.

These 10 key considerations can support a successful antenna design when carefully evaluated in the design process. As veterans of wireless product design, engineers at Digi WDS have the knowledge and expertise to support your antenna and overall product design, manufacturing test and go-to-market strategy.

Contact Digi for help identifying and procuring the right components for your next wireless design. Digi offers complete end-to-end solutions, including hardware, software, security, design and deployment services and remote device management to support success over the full product lifecycle.

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