



The Cellular Antenna Selection Guide



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1 Introduction

One of the most important aspects of a new cellular-enabled IoT device is the antenna. Without a well-functioning antenna, the radio link will may not be stable and the user's experience will suffer. Thus, cellular antennas for IoT should be carefully selected for best performance.

But how do you ensure you are selecting the best antenna for your device? The answer to this question is often complex and dependent on many factors relating to how the device is built and deployed.

To bring light to these factors, Taoglas has created this handy guide to bring designers up to speed on what aspects of a device design inform the antenna selection, and how you can use that information to pick the right antenna for your product.

Let's begin...



Thaddeus Gulden

Field Applications Engineer at Taoglas

2 Carrier Antenna Requirements

One of the biggest stumbling blocks for a new cellular design can be meeting a cellular carrier's antenna performance requirements. Though it is not the case in most other countries, US-based carriers like Verizon, AT&T, Sprint and T-Mobile all enforce specific radio performance targets governed in part by the antenna, and anybody trying to launch products on one these networks will have to meet them. The requirements are few, but they have significant implications when it comes to antenna choice and device design. They are as follows...

2.1 Frequency Band Support

Each cellular service provider uses multiple frequency bands to ensure maximum coverage. For IoT devices, these frequency bands may fall anywhere from 600MHz at the low end to 3.5 GHz at the high end. For a device to gain approval on any of the major carrier networks, its antenna must radiate at a defined minimum efficiency on all the bands that carrier uses for IoT devices. Additionally, if a device is being designed for global deployment, the antenna must support the frequency bands for carriers in all regions the device will be deployed in.

2.2 Number of Antennas

Cellular carriers approve LTE radio modules for use on their networks based on conformance to standards created by an industry consortium called 3GPP. The 3GPP standards define what functionality an LTE-compliant radio should have, and defines different categories of LTE radio based on throughput and signaling features. In order to support more throughput, many categories of LTE radio require more than one antenna arranged in either a receive diversity or multiple-input/multiple-output scheme.

When an LTE module is selected, the carrier that module is activated on will typically mandate that the radio make use of the full number of antennas specified for its LTE category. Except in a few very specific situations (most of which can be addressed with the emergence of LTE Cat-M), this requirement is generally not waived.





2.3 TRP

TRP, or **Total Radiated Power**, is a measure of all power that radiates from an antenna over a given band. TRP depends on both the power being output by the radio, and the antenna's efficiency. Because cellular radio modules have a standardized max transmit power, antenna efficiency mostly dictates TRP. Carriers require a minimum TRP level for any device being approved for use on their networks. If you do not meet this minimum, your device will not be approved and so will be unable to be deployed. Sometimes waivers are given for narrow TRP failures (i.e. <1dB failure margin), but this is completely at the carrier's discretion and should not be taken for granted. For cellular devices that are very small (i.e. have limited antenna efficiency), or where antennas are being integrated late in the design cycle, failing the TRP test is a major risk factor for a development program.

2.4 TIS

TIS, or **Total Isotropic Sensitivity**, is a measure of how well your LTE receiver works. Carriers will enforce a maximum power level for TIS. Unlike TRP, the influence of antenna performance on TIS is relatively small. TIS is instead a function of noise (i.e. spurious radiation) coming from electronics nearby the antenna. Noise levels well below the FCC spurious emissions limits can cause TIS failures, which makes failing this test one of the largest single risk factors in a cellular device development program. As with TRP, waivers for narrow failures on TIS are occasionally granted, but are discretionary and never guaranteed.

2.5 MVNOs

MVNOs, or **Mobile Virtual Network Operators**, are network operators that don't have their own radio infrastructure for cellular communications. These operators instead buy services from other companies who do own said infrastructure, and resell that access to subscribers. These virtual networks rarely enforce antenna requirements, and so offer a way to mitigate performance risks that might prevent your product from going to market. MVNOs are not a cure-all though, as they may have limited coverage areas or have subscription fees that are too high to be economical for very large deployments.

3 Types of Antenna

There are many different types of antennas, but for the most part they can be separated into one of two categories: embedded or external.

3.1 Embedded Antennas

Embedded antennas are antennas that are concealed inside a device's housing. This type of antenna is always be subject to the carrier's antenna requirement. Within the embedded antenna category, there are two subcategories: On-PCB antennas (i.e. antennas that are soldered to the PCB), and off-PCB antennas (i.e. antennas that are attached to the enclosure). Best practices for applying each style of antenna varies, and so care should be taken to choose the right one based on your constraints.

See Fig. 3.1

3.1.1 On-PCB

PCB-mounted antennas offer a miniaturized, low-cost way to integrate a cell antenna into a box product. For the most part, these antennas are monopoles, a style of antenna that needs a sufficiently large PCB ground plane to work. PCB-mounted antennas are typically mounted on the short edge of the PCB to maximize the electrical length of the ground plane, and so the antenna's efficiency. Again, efficiency has a large impact on TRP, and should always be maximized. If device miniaturization is a key design parameter, a study should be made of antenna efficiency early on to understand is passing TRP at the target size is feasible. Depending on your carrier of choice, there may be different TRP requirements for different categories of LTE. Machine-to-Machine type radios like LTE Cat-M may have lower TRP requirements compared to higher data rate categories like Cat-1 or Cat-3 (talk to your carrier for details). For Cat-1 and above though, a device using an off-the-shelf PCB-mounted antenna will generally need at least **90mm of ground plane** to meet the TRP requirements for the lowest bands used by AT&T and Verizon. Bear in mind, this 90mm is just the ground copper. A PCB-mounted LTE antenna will typically also need a 15-20mm wide copper-free landing area beyond the ground plane, for a minimum total PCB length of ~110mm.

T-Mobile has recently added a band 71, which is lower still than AT&T and Verizon's low bands, and may require ground plane lengths well in excess of 110mm.



Fig. 3.1
PA.710.A

3.1.2 Off-PCB

Off-PCB antennas are ones that have most or all of its radiating parts separated from the PCB, usually attached to the device enclosure. They will generally either attach to the radio via a small-diameter coaxial cable with a press-on connector, or via a leaf spring contact.

This category of antennas offers a certain degree of flexibility that on-PCB antennas don't in that they can often be selected and applied after the PCB has been designed, and/or can be retrofitted into a finished enclosure. However, they do have some disadvantages.

One disadvantage is that off-PCB antennas tend to incur a slightly higher unit cost than on-PCB antennas, which can be a mitigating factor for very high-volume products. A notable exception to this is **Laser Direct Structured**, or LDS antennas, which is a type of enclosure-integral off-PCB antenna that has a very low unit cost at volumes greater than 100,000 units annually. It should be noted that LDS antennas are always highly customized and incur a high, front-loaded NRE cost.

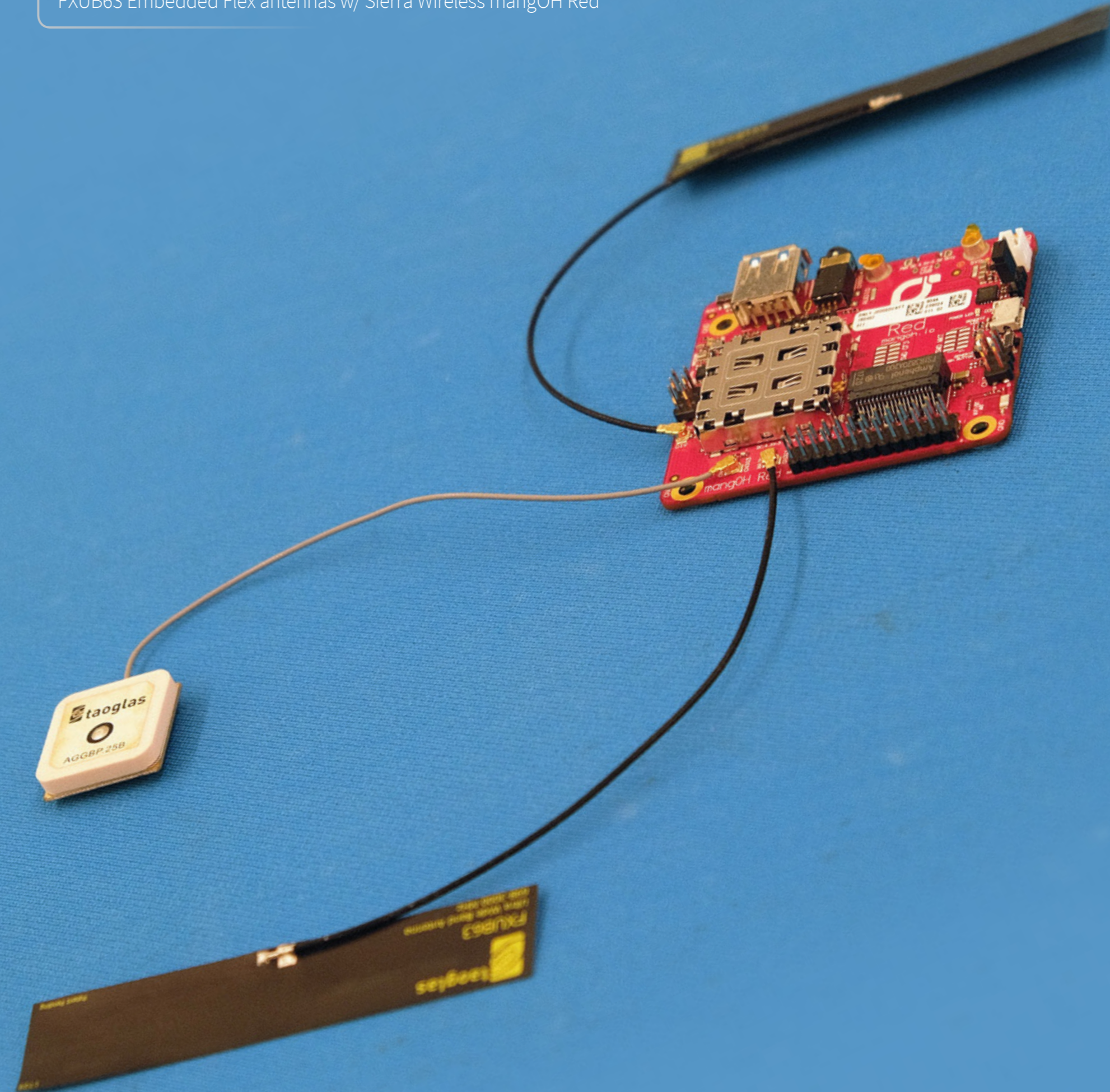
Another disadvantage of off-PCB antennas is that, because such antennas are often designed to work independent of a ground plane, placing it too close to the PCB can hurt antenna efficiency and TRP. Generally, this type of antenna should have **a minimum of 20mm separation from the PCB or any other metals** that might hurt antenna performance.

Also, if the antenna is planar (like on a rigid or flexible PCB), the antenna should ideally be oriented perpendicular to the main PCB to mitigate undesired capacitive interactions between the two. Lastly, cable routing can sometimes influence the frequency response of the antenna, and so should be controlled and repeatable.

See Fig. 3.1.2

Fig. 3.1.2

FXUB63 Embedded Flex antennas w/ Sierra Wireless mangOH Red



3.2 External Antennas

External antennas are antennas where the radiating part of the antenna exists outside the device enclosure.

These types of antenna are also split into two categories with unique design implications: **terminal-mount and cabled**.

3.2.1 Terminal Mount

A terminal mount antenna is an antenna whose body is directly attached to a connector on the housing of the device.

Some terminal mount antennas are monopoles, designed for use on a ground plane similar to an on-PCB embedded antenna, and need to be placed on a sufficiently large metallic surface to radiate efficiently. These monopole antennas tend to be fairly small, around 2 to 3 inches long, and are good antennas for devices with metal enclosures, or PCB-mounted coaxial connectors attached to longer PCB's.

Other terminal mount antennas are **dipoles**. Dipoles are antennas that have the antenna ground built in, so they do not need a long ground plane to function well. This kind of antenna is usually about 4 to 6 inches and tends to be highly efficient and easy to apply, offering an easy and straightforward integration strategy.

Both styles of terminal mount antenna are subject to carrier requirements.

See Fig. 3.2.1

3.2.2 Cabled Antenna

Cabled antennas are antennas that attach to a device remotely via a long external cable. This subcategory of antenna offers a certain degree of flexibility in that many different mounting styles exist, including ruggedized panel mount antennas, small adhesive antennas, both ground plane dependent and independent antennas, multi-antenna arrays, etc. Of all types of cellular antenna, these are the easiest to apply.

Unlike all the other antennas mentioned, any antenna with more than 20cm of externally routed cable is not subject to carrier performance requirements, which offers a quick path to market. Also, due to the antenna's separation from other electronics, this antenna type tends to protect against TIS problems.

See Fig. 3.2.2



Fig. 3.2.1

TG.30 Dipole LTE Antennas on a router



Fig. 3.2.2

G30 Olympic Cable LTE Antenna

4 Antenna Choice Through the Development Cycle

Where you are in your product development cycle may constrain which antennas may be used in your device.

Taoglas always recommends addressing antenna selection as early in the development cycle as possible to avoid risks and increase options, but in the event the antenna becomes something of an afterthought, this section may offer some insights into what can be used.

4.1 Concept

The concept phase is the best phase in which to engage Taoglas about antenna choices. In this phase, constraints like physical dimensions of the housing and PCB layout have not been locked down yet, which offers the most flexibility with respect to antenna choice. Off-the-shelf, on-PCB antennas can be integrated with relative ease, mechanically speaking.

If the target enclosure size is not large enough to accommodate an off-the-shelf antenna, initiating a discussion about custom solutions early in the development cycle gives us ample lead time to ensure the delivery date for your customized solution occurs well in advance of your planned build date, keeping your program timing on track and controlling overrun costs. It also builds in more time to address electromagnetic compatibility issues like TIS failures before the product is targeted to launch.

4.2 Post-ID

Post-ID, or **Post-Industrial-Design**, is a phase where the housing dimensions and form factor have been finalized. In the post-ID stage, the only things that may be changed about the product are the arrangement of PCB's and components inside the housing. In this phase, integrating an embedded antenna can be more difficult, requiring a customized solution, if a solution can be offered at all. Integrating an antenna in this phase is risky, and reduces the amount of time and options you have to address unforeseen issues with antenna performance. In certain circumstances, it may be advisable to switch to an external antenna, as the environment outside a device enclosure typically offers fewer obstructions and parasitic masses.

4.3 Retrofit

Retrofits present the highest risk of all the integration scenarios. In this scenario, the only thing that can be changed about a device is the antenna. Antennas that can be retrofitted are typically fully modular, being fitted with some sort of connector. The biggest risks to antenna performance in this scenario are passive and active interference. Passive interference happens when some object, usually metallic, sits too close to the antenna and alters the mode and over which frequencies it radiates.

This can only be controlled by physical separation between the antenna and the interfering objects. Active interference happens when noisy electronics radiate power to the antenna and interfere with the receiver. Without allowing changes to the electronics, this too can only be controlled by separation between the antenna and the noise source.

5 Mechanical Considerations

As alluded to before, objects near the antenna have big influences on performance. The material composition and topology of the enclosure and mounting surfaces must be carefully chosen to be electromagnetically compatible with the antenna.

5.1 Enclosure

If using an embedded antenna, your device enclosure must be transparent to RF radiation. Generally, this means using some sort of plastic for the enclosure material. Metal cannot be used, or must be used selectively, as it just will reflect all the energy radiated by the antenna back to the antenna. Carbon composites like carbon fiber can also be a problem, as carbon fiber absorbs RF and will limit the amount of radiation that can escape the device.

Polymers like ABS, PTFE, and polycarbonate however are poor conductors, have low electrical permittivity, and are low loss, making them virtually transparent to RF radiation. These materials, and others like them, will be the best choices for use with embedded antennas. If a particular device use case requires a metallic enclosure, you should look at replacing one or more faces of the enclosure with plastic, or just use an external antenna.

5.2 Pigments, Fillers & Coatings

Similar to how housing materials impact antenna performance, additives and coatings can also influence antenna performance. Certain pigments absorb RF strongly (e.g. carbon black), and will reduce the amount of radiated power that can escape the device. Conformal coating too can have unwanted effects on antenna performance if applied directly to the antenna, reducing efficiency.

Metallic suspensions (e.g. silver spray paint) will have effects similar to solid metal, blocking or strongly attenuating radiation from the antenna. Glass fillers too, though permeable to RF radiation, can dielectrically load an antenna that sits too close to it, changing the antenna's frequency. Any and all materials that will end up as part of a final product must be evaluated for electromagnetic compatibility.

5.3 Small or Mechanically Complex Devices

As demand grows for smaller and thinner devices, mechanical complexity and electrical smallness become a concern when integrating an antenna.

Devices that are considered electrically small are those whose largest dimension is less than a quarter-wavelength of the lowest frequency the device uses to do wireless communication. When a device is electrically small, the antenna efficiency that it can achieve diminishes greatly. As a rule, the ground plane for an embedded cellular antenna should never be less than 20% of the wavelength of your carrier's lowest band.

Mechanical complexity can also hamper antenna efficiency due to parasitic coupling from metals nearby the antenna, or from metals blocking the radiation path around the antenna. Multi-board devices can offer integration challenges in this manner, as can devices with large electromechanical components or display panels. Generally, it is recommended to keep 20mm of clearance between metallic components and the antenna. It should also be ensured that the antenna has clear RF line-of-sight to free space in at least one hemisphere about the device.

Both of the above factors influence TRP by way of antenna efficiency, and so should be considered early on and be well-controlled to prevent TRP failure.

5.4 Wearable Devices

The human body is no exception when it comes to influencing antennas. Animal bodies (humans included) are comprised primarily of salt water, a very lossy propagation medium, and so tend to block and absorb RF radiation. Fortunately, this behavior is known to cellular service providers, and there are often separate and easier-to-meet requirements for body-worn antennas. However, the combined effects of miniaturization and body proximity can cause TRP failures quite easily, **so any very small body-worn product will require a study of whether the requisite antenna performance is feasible.**

5.5 Multi-Antenna Systems

One last mechanical consideration that must be mentioned relates to the electrical isolation between antennas.

In systems that have more than one antenna, each pair of antennas will have the propensity to couple to and possibly interfere with one another. This is especially of concern for MIMO LTE systems, as antenna isolation has a huge impact on throughput. There are ways to mitigate this cross-talk, but they require careful mechanical planning.

The first major contributor to crosstalk is physical proximity. The closer antennas are to one another, the more strongly they pass energy to one another. Conversely, coupling can be mitigated by separating them in space. Usually, you'll want to separate them by at least a quarter wavelength of the lowest frequency supported by either antenna. For cellular, that's around 700MHz, which has $\lambda/4$ of about 10cm. On-PCB antennas that share a ground plane couple even more strongly, and so require can require up to twice as much separation compared to antennas in free space.

Another contributor to cross-talk is alignment of antenna polarizations. Cellular antennas tend to be linearly polarized, meaning the electric field generated by the antenna tends to be oriented in a straight line relative to the antenna. Antennas will only couple strongly to one another if their electric fields match orientation. Because of this, two of the same antenna will tend to couple more strongly if they are parallel to one another. If they are perpendicular to one another though, the electric fields between the two become misaligned, and cross-talk is reduced.

Thus, it's usually best to place two antennas of similar frequency at 90° angles relative to one another to improve isolation.



6 Tying It All Together

We've now defined most of the important terms and discussed a number of practical considerations pertaining to choosing the right LTE antenna. But how do we apply it? How do we make a procedure of it? As alluded to in the introduction, it's not so straightforward, and can't be rendered into a step-by-step process. That said, it is often useful to reframe all this information into a series of questions to guide yourself to a useful selection. Questions you should ask yourself include:

6.1 "What are the design mandates for my product?"

What are my requirements?"

These questions are perhaps the most important, as they pertain to the commercial viability and marketability of your device. Constraints are not just mechanical in nature. They include cost targets, look and feel, what other features and components need to coexist with the radio and antenna, program timing considerations, deployment geography, etc. Enumerating these constraints establishes the framework for the rest of the decision-making process, and not going through this step in a comprehensive and deliberative fashion will put you at risk of making inappropriate antenna choices that could derail your project.

6.2 "How much space do I have?"

Some constraints are physical, and there's no choice but to work within nature's confines. When it comes to antennas, you are more constrained by physics than you are by market trends like miniaturization. Ensure you're setting realistic goals on both the gross dimensions of the device, as well as the space apportioned for the antenna.

6.3 "What can I change?"

Sometimes companies or designers decide on a set of requirements that preclude or undermine the successful integration of an LTE antenna. Some of these requirements are 'hard' requirements, that is to say that not adhering to them creates a physical or commercial barrier that will prevent the product from being useful or commercially successful.

Other requirements though are 'soft' requirements, or requirements that a device maker feels may add to the value of the device or differentiate it from alternatives, but do not necessarily undermine the product's broader viability. It is important to understand what category each of your device requirements falls into, because in some circumstances it may be necessary to drop one or more of the soft requirements to integrate an antenna successfully.

With these questions in mind, re-read the previous sections. Let the recommendations and guidelines take shape in the context of your device. With a mental model of your device and its constraints, finding the right off-the-shelf antenna should be much easier.

Of course, if you have any lingering questions, or just want an expert opinion, feel free to reach out to us at customerservice@taoglas.com for more information.



Enniscorthy, Ireland (HQ)

Unit 5, Kilcannon Business Park, Old Dublin Road
Enniscorthy, Co. Wexford, Y21 XW56, Ireland
+353 53 9169500 | emeasales@taoglas.com

Dublin, Ireland

DCU Alpha, Innovation Campus,
Old Finglas Road, Glasnevin, Dublin 11, Ireland
emeasales@taoglas.com

Munich, Germany

Erika-Mann-Straße 25, Second Floor
80636 München, Germany
+49 89 3803 7426 | emeasales@taoglas.com

San Diego, USA

8525 Camino Santa Fe, Suite A & B,
San Diego, CA 92121, United States
+1 858 450 0888 | nasales@taoglas.com

Minneapolis, USA

15 S. 5th St. Suite 150,
Minneapolis, MN 55402, United States
+1 858 450 0888 | nasales@taoglas.com

Florida, USA

5497 Wiles Rd. Suite 205,
Coconut Creek, FL 33073, United States
+1 954 977 4470 | nasales@taoglas.com

Tainan, Taiwan

4F.-2, No.15, Guoji Road, Xinshi District,
Tainan City 744, Taiwan (R.O.C.)
+886 3 3681223 | asiasales@taoglas.com

Taoyuan, Taiwan

No.2-2 Ln. 66, ZhongShan 1st Rd.,
Bade City, Taoyuan City 33454, Taiwan (R.O.C.)
+886 3 3681223 | asiasales@taoglas.com

Shenzhen, China

Unit 509, Neptune Building, Lanxiang 1st Street,
Nanshan District, Shenzhen 518067, China
+86 755 86538292 | cnsales@taoglas.com

www.taoglas.com