An Evaluation of Multiband Antennas for Use with LoRa Edge™ [Part One]

Semtech

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Introduction

Semtech's LoRa Edge™ LR1110 integrates a LoRa® transceiver, a modem compatible with the LoRaWAN® protocol, Semtech's LoRa Cloud™ Device & Application Services, and a Wi-Fi b/g/n scanner and a hybrid GPS/Beidou scanner. Connected devices onboard the LR1110 must support at least three radio frequency bands:

- Upper UHF bands (hereafter referred to as *LoRa bands*), where unlicensed LPWA connectivity is available—anywhere from 863 to 928MHz, depending on region.
- GNSS bands: 1.575.42 MHz for the GPS L1 band and 1561.098MHz for the B1 Beidou band.
- 2400 to 2483.5MHz for the 802.11 Wi-Fi band.

The intention of this paper is to survey the available solutions for tri-band antennas. The industry, influenced by multiband cellular technologies such as the last generation 4G smartphones, has developed multiband antennas, and most of these concepts are applicable to our LoRa Edge platform.

In this document, we address the following:

- Pros and cons of several antenna technologies
- Common traps that are inherent to wireless product design, including the do's and don'ts
- Guidance for board size, matching requirements, and antenna placement as a means of reducing the risk of poor product design
- Maximizing the chances of running successful proofs-of-concept
- Optimized reference designs, including performance metrics

This is the first in a series of papers providing experimental results of the commercial, off-the-shelf (COTS) multiband antennas we have analyzed, and is a starting point for companies wanting to integrate the LR1110 without needing to create an expensive study regarding custom antennas.

Overall Methodology

The antenna manufacturers' websites offer baseline information for their antenna products: VSWR, gain plots, and efficiency, all measured under specific test conditions. Most of the time the test board is specified, showing the antenna feed point and the board size used during the experiment. Because trackers may be size-constrained, highlighting the reasons why the antenna may not behave as specified is critical: for instance, when the antenna is "loaded" by specific materials in its proximity, or when it is de-tuned by a counterpoise of the wrong size.

During this study, the guiding principles were to explain how to:

- Select an antenna based on its generic characteristics, such as size and efficiency. Of course, the focus is on tri-band antennas (wherever possible), since the LR1110 is optimized to provide radio functions across three bands.
- Simulate or evaluate the performance that an antenna is expected to have for a given set of test cases. This test scenario can be reproduced for many antennas and tests can be compared easily to highlight the benefits of the various models.
- Measure the antenna performance dependency on board size; given that some use cases call for extremely small, highly-integrated solutions. Our intention here is to reiterate that the laws of physics demand a certain board size to maintain a correct efficiency, and the corollary that antenna tuning also depends on board size.
- Estimate the detuning sensitivity of the antenna. Pet trackers work in close proximity to animal tissue, whilst cold-chain monitoring trackers operate close to metal, which has a substantial effect on the antenna performance.

In future papers, passive antenna tests will be augmented with active antenna tests.

Our goal is to provide guidance for antenna selection, and to highlight the pitfalls related to sizing and detuning, which are common mistakes that can lead to underwhelming performance observed in the field or during qualification.

Why Should Antennas be as Efficient as Possible?

The bands in which LoRa operates, mostly between 863 and 928MHz, are employed around the world for unlicensed radio devices: garage-door openers, remote controls, and domestic alarm systems, to name a few. With the strong interest generated by the LPWAN market opportunity, traditional cellular network carriers have invested in nationwide deployments, installing gateways with an average density of anywhere between one gateway for ~1000 km^2 (rural deployment), to one gateway for ~5 km^2 (dense urban deployment), and will densify networks in the coming years to absorb more traffic.

When rolling out a network, carriers use traditional propagation models and tools to simulate coverage, making general assumptions such as:

- Height of the gateways (*base stations* in cellular terminology)
- Radiated power and sensitivity of the gateway
- Effective radiated power of the connected IoT device
- Radiated sensitivity of the IoT device

The first two elements in the list above are well controlled: gateways are industrial-grade equipment that can cost anything from a few hundred to a few thousand dollars, with well-placed and high-quality antennas strapped to a fixed point on a rooftop or on a telecom tower. The propagation models, although imperfect, benefit from decades of experience and refining from the cellular and pager industries, and are reliable.

More importantly, to guarantee coverage, carriers make an assumption about the actual power that the connected device radiates towards the network. In Europe, the effective radiated power (e.r.p.) is legally limited to 25mW, and Telecomm operators will guarantee a certain coverage of territory *assuming* that the actual power going out of the objects will be 25mW. Without a proper (device and) antenna design, the coverage maps and Service Level Agreements (SLA) become irrelevant. This is why it is paramount to get the LoRa antenna design correct from the start.

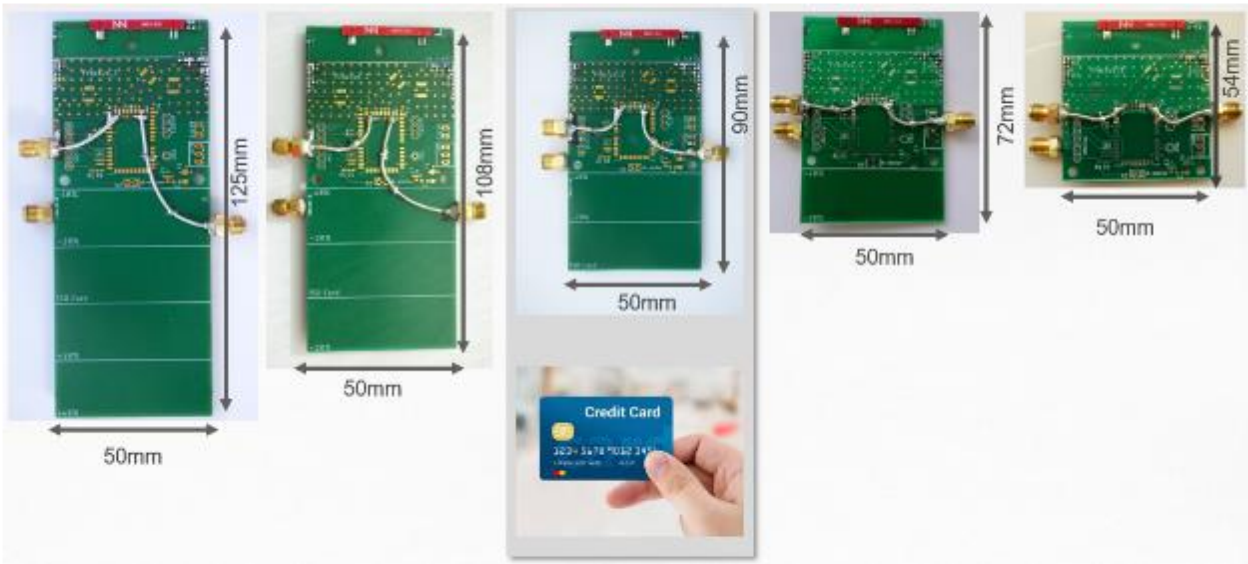
For the assisted GNSS scanner onboard Semtech's LoRa Edge products, the performance of the GNSS antenna is equally important. Our assisted GNSS scanner renders a sensitivity of approximately -141dBm. The US military guarantees that, at any spot on the planet, the GPS signal will be greater than -130dBm (https://www.gps.gov/technical/icwg/IS-GPS-200L.pdf). This represents some margin, however, given that trackers designed for the Internet of Things (IoT) are size-constrained, not necessarily well oriented, and typically without circular-polarized antennas facing the sky, every percent of efficiency of the GNSS antenna is important.

Wi-Fi band efficiency is somewhat less critical; with many Wi-Fi access points (AP) usually available in densely populated areas. Nonetheless, having a well-designed antenna ensures that as many access points as possible are being observed.

TRIO mXTEND™ Antenna

The antenna selected for this reference design is the TRIO mXTEND™ (NN03-310) provided by Fractus Antennas, which owns this disruptive Virtual Antenna™ technology. This antenna is the only solution available on the market that is capable of managing three different radios (LoRa, multiband GNSS, and Wi-Fi/Bluetooth) at the same time, inside a single antenna package. Its miniature, off-the-shelf, multiband, high-efficiency, and tunable features make it ideal for use in combination with the LR1110.

The image below shows the TRIO mXTEND adjustable-length board.



Images courtesy of Fractus Antennas

The antenna performance has been assessed with different printed circuit board (PCB) characteristics:

- Adjustable length: the nominal size is 90 mm x 50 mm, in line with the ISO card standard. Vertical lines are placed on the silkscreen, as guides to cut the board and vary its length from 54 to 126 mm. Five boards are equipped and optimized, highlighting the impact of board size on the tuning / efficiency for each band.
- Built-in module: an FMLR-1110-x-STL0 module from Miromico replaces a chip-down implementation. This module integrates an SP3T switch, and only three antenna feed points are available: LoRa, Wi-Fi and GNSS.
- Antenna space and keep-out are implemented on the left of the board.
- External matching is placed next to the antenna.
- Ground is laid out under the complete board, even though there are no active parts on the right-most half of the board; this is to emulate a large counterpoise of an IoT object.
- Jumpers, JTAG interface, and positioning holes are added for the power measurement, programming, and positioning of the device on its substrates.

Fractus Antenna Technology

Fractus Antennas owns a new and revolutionary antenna technology, called Virtual Antenna™. Already installed in more than 25M edge devices, this technology can replace conventional and custom antenna solutions by a new class of so-called *antenna boosters*, delivered in the form of a new range of miniature and off-the-shelf chip antenna components. These new chip antennas are, by nature, multiband and multipurpose, so they fit in a variety of wireless platforms to provide a wireless link for many different communication services. By using a Virtual Antenna component, the design becomes more predictable than custom solutions, making the entire process faster, cheaper and easier.

Common techniques for designing small multiband antennas in wireless devices are based on the use of complex geometries, where the resonant modes of the antenna determine the frequency bands of operation, requiring a high level of expertise for correctly shaping the antenna geometry and for achieving acceptable behavior operating at a given frequency band.

The TRIO mXTEND chip antenna component used in this reference design is built on a glass epoxy substrate, and belongs to this new generation of off-the-shelf antenna solutions based on Virtual Antenna technology. It offers the advantage of being non-resonant. Its frequency-neutral characteristic allows designers to easily select the operating frequencies according to their needs, since they are not set by the antenna geometry, unlike conventional antenna solutions. Such an antenna supports a number of applications and provides many benefits:

Applications	Benefits
Asset Tracking	High efficiency
Smart Meters	Large bandwidth through the same single feed point
Smart City & Home	Small size
IoT Devices	Multiport: Three radios in one antenna component
Modules & Sensors	Easily tunable to the required operating regions
Routers and Gateways	Multiband coverage (worldwide standards)
eHealth	Off-the-Shelf Standard Product (no customization is required)
	Automated assembly (Pick and place)
	Shorter Design cycle

The TRIO mXTEND™ chip antenna component offers the versatility of being usable in a single port or multiport configuration and the flexibility of being tuned to other frequencies by simply adjusting the matching network. The configuration for LoRa, GNSS, and Wi-Fi is illustrated here, but you can configure it to operate with any communication standards that fit your needs

What Makes an IoT Device Radiate Properly?

All well-designed "things" have good connectivity, and that means a better uplink (UL) and downlink (DL) packet success rate (PSR), if all of the following conditions are satisfied:

- The **antenna matching** is correct, ensuring that a vast majority of the incident power is radiated by the antenna, and not reflected back to the source
- The antenna **efficiency** is good, ideally 100 percent. This would mean that ALL the forward power injected into the antenna (and not reflected to the source), is effectively radiated (and not dissipated) by the antenna
- The RF source supplies the right power to the antenna through its matching network, meaning that the **PA matching** is correct

The effects of mismatching are as follows:

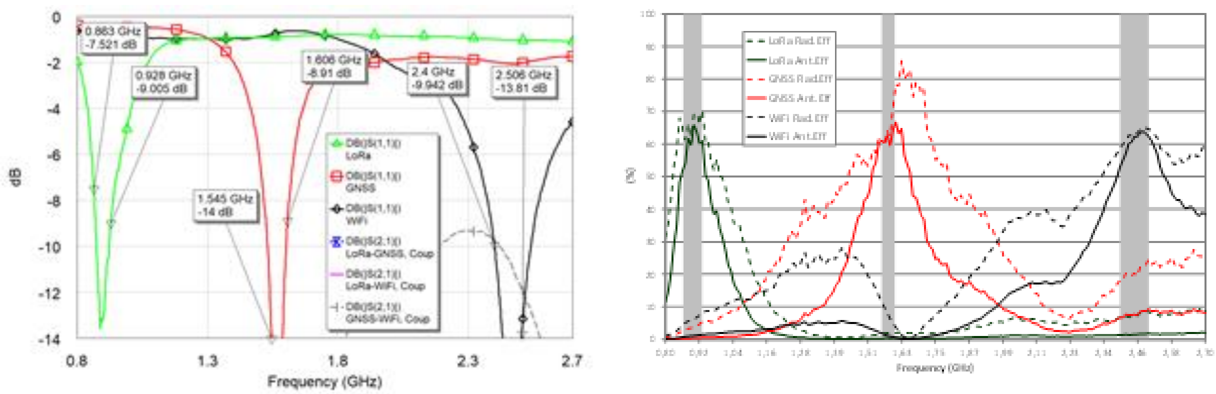
	When the module is in	
	Transmit Mode	Receive Mode
The antenna and its matching network…	*… expect a 50 Ohm RF Source.* Failing this, some power will be reflected back to the source	*… source the module at 50 Ohms.*
The module including its matching network…	*Source the stated output power (e.g. 14dBm) only if loaded by 50 Ohms.* If misloaded, it may not deliver the expected RF power to the load (antenna).	*… expect a 50 Ohm source for the Receiver to have a good sensitivity.* Failing this, the receiver may be less sensitive, and some mismatch loss may reduce its performance further.

Most of the mismatch effects described in the previous table are estimated with a passive antenna efficiency measurement, where the "efficiency" number accounts for both the mismatch loss, and the intrinsic inefficiency of the antenna.

The graph below on the left shows the measured reflection coefficient (S_{11}) for the reference PCB size (90mm x 50mm). This value represents the amount of power injected by the RF module to the antenna system that is reflected. Generally, the lower the $S_{11,}$ the better the antenna performance. This parameter can be easily improved through the proper adjustment of the matching network to effectively adapt the antenna performance to the environmental conditions. In the reference design presented herein, the three bands (LoRa, GNSS, and Wi-Fi) were properly matched with a reflection coefficient below –6dB. The associated mismatch loss can be computed as follows:

$$Mismatch\ Loss\ (dB) = 10 * log(1 - |S_{11}|^2|)$$

Another important parameter to consider is antenna efficiency, which considers both mismatch loss and the intrinsic radiation efficiency of the antenna. The graph below shows the radiation efficiency (η_r) and the antenna efficiency (η_a).



Images courtesy of Fractus Antennas

The radiation efficiency indicates the proportion of power that would be radiated to space if there were a perfect match (mismatch loss = 0dB), whereas the antenna efficiency represents the proportion of power actually radiated to space once mismatch losses are considered. It is computed through the following expressions.

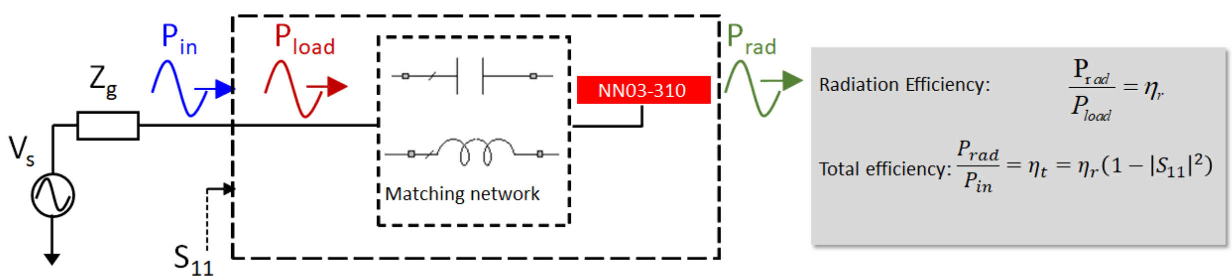


Image courtesy of Fractus Antennas

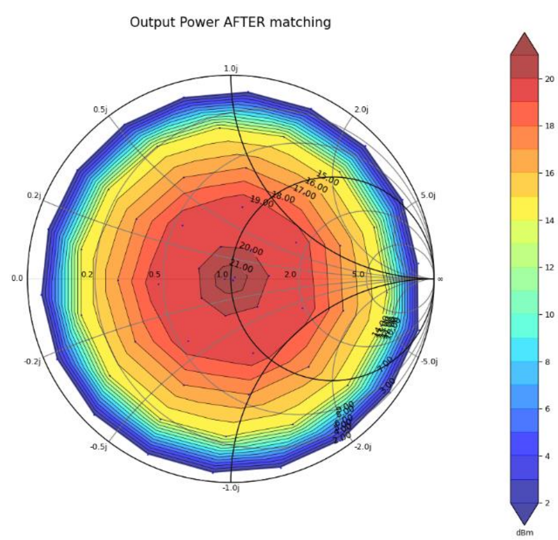
The following table shows *Return Loss*, *Mismatch Loss*, *Radiation Efficiency*, and *Antenna Efficiency*.

	$\lvert S_{11}\rvert$ (dB)	$\lvert S_{11}\rvert$	Mismatch loss(dB)	Rad. Eff (%)	Rad. Eff (dB)	Ant. Eff (%)	Ant. Eff (dB)
900MHz	13.0	0.22	-0.22	69.2	-1.60	65.8	-1.82
1575MHz	20.6	0.09	-0.04	62.3	-2.06	61.7	-2.10

2450MHz	16.5	0.14	-0.09	63.7	-1.96	62.5	-2.04

It is important to understand that highly-efficient and non-linear power amplifiers used in LoRa devices, specifically for the sub-GHz LoRa bands, are sensitive to their mismatch and may offer different output power, harmonic content, and intake power consumption, when their load changes. This effect isn't evaluated here, as it requires an active antenna measurement method, but will be documented further later in this series.

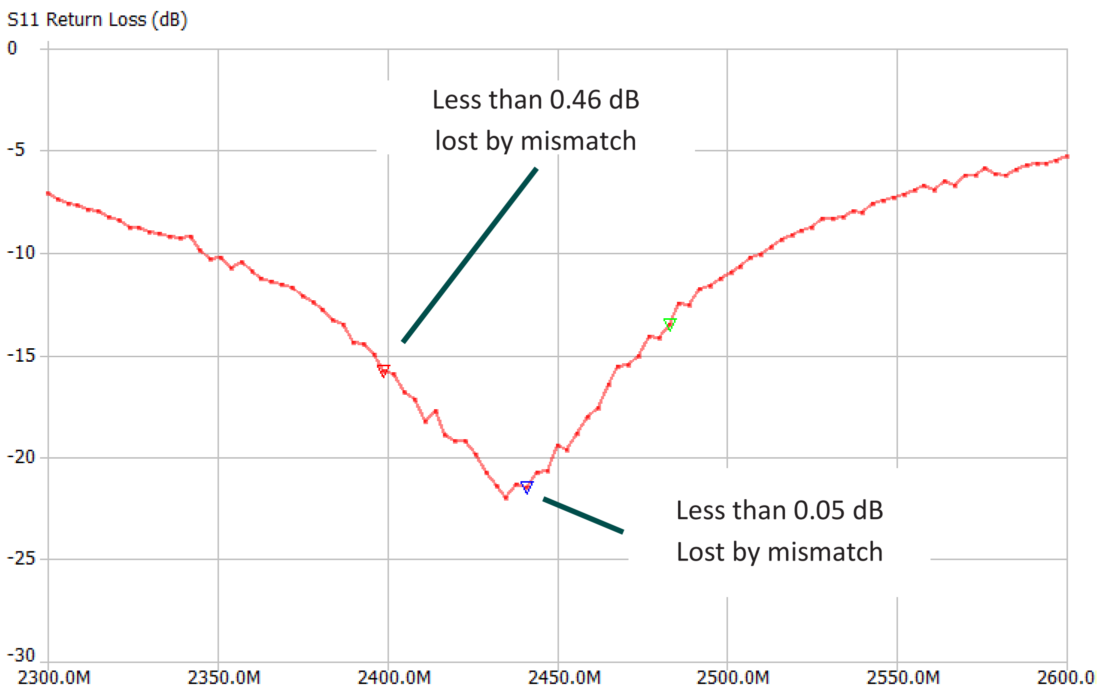
The image below describes a principle and is not the result of any actual measurement. It shows how a power amplifier (PA) maintains its stated power over a certain zone of proper matching. Beyond this zone, the PA induces some losses, is misloaded and, therefore, has a slightly degraded performance.



Mismatch Loss: Understanding the Quantities

Most of the following results are expressed in terms of reflection coefficient. They are published with a scalar plot, with frequency on the horizontal axis, and a negative dB value on the vertical axis. The lower the number in dB, the lower the amount of power reflected back to the source; conversely, the more power is absorbed (and radiated) by the antenna.

The following graph represents the return loss of the TRIO mXTEND™ antenna in the Wi-Fi band, for the standard board, with no material loading on the antenna.



Just to put the numbers into perspective, the mismatch loss induced by a certain “miss” on the load impedance, is given below:

S11	Quantity of power Reflected back to source	Quantity of power forwarded to load	Mismatch loss
0 dB	100 %	0 %	-infinite
-3 dB	50 %	50 %	-3dB
-6 dB	**25 %**	**75 %**	**-1.25dB**
-10 dB	10 %	90 %	-0.46dB
-20	1%	99%	-0.05dB

This is why the -6dB bar is displayed in the coming plots and is used as a performance indicator; keeping -6dB of return loss, indicates that no more than 1.25dB are lost during the power transfer, which is a reasonable target in extreme conditions, even if a perfect matching of 50Ohms with no reflected power is desirable.

Board-size Impact: Matching and Resonance

With the virtual antenna technology, as well as with any other conventional antenna design, the board size impacts the resonance of the object. Conversely, the antenna matching networks (in an LR1110 design, there are three: LoRa, GNSS, and Wi-Fi) must be modified to ensure that the RF power delivered by the LR1110 is effectively radiated.

As you can see in the table below, all elements of the matching network must be modified as a function of board size, to maximize return loss and therefore good performance:

All matching networks depicted below were designed with the objective of obtaining the lowest S_{11} and the highest antenna efficiency in the frequency bands required to cover the whole spectrum, from 863–928MHz for the LoRa case, 1561–1606MHz for GNSS, and 2400–2483MHz for Wi-Fi. The PCB size affects the performance of any antenna, not only in terms of radiation efficiency, but also in terms of impedance. This may mean detuning, but can easily be solved by readjusting the matching networks properly. That is why each PCB size has its own matching network to optimize the performance in the three bands. A minimum number of components is used for this purpose, to reduce the associated losses as much as possible. The use of high quality factor (Q) and tight tolerance components is recommended to avoid efficiency losses in the matching network, and to ensure repeatability of the solution. Unlike classic resonant antennas, which are specifically designed to work on certain bands, Virtual Antenna technology can be used for all bands. The antenna element remains the same and a readjustment of the matching networks means the antenna can work on the desired bands with the maximum performance.

The following table shows the TRIO matching elements for each board size.

	126x50	108x50	90x50	72x50	54x50
Z_1	15nH	16nH	3.7nH	0Ω	4nH
Z_2	2.3pF	1.9pF	10pF	4nH	Open
Z_3	Open	Open	Open	Open	18pF
Z_4	4.0nH	1.3nH	10pF	0Ω	12pF
Z_5	Open	Open	3.7nH	Open	2.8nH
Z_6	0Ω	0Ω	0Ω	0Ω	0Ω
Z_7	6.0nH	8.4nH	8.4nH	8.4nH	8.4nH
Z_8	1.6pF	1pF	1pF	1pF	1pF
Z_9	0.7pF	0.5pF	8.7nH	9.1nH	8.7nH
Z_{10}	2.2nH	1.8nH	5.6nH	5.6nH	5.6nH
Z_{11}	8.4nH	Open	Open	Open	Open
Z_{12}	9.1nH	10nH	7.5nH	9.1nH	8.7nH
Z_{13}	2.3pF	2.2pF	3.2nH	5.6nH	3.5nH
Z_{14}	4.4nH	2.3nH	1.7pF	0Ω	0Ω
Z_{15}	28nH	28nH	-	-	-
Z_{16}	0.8pF	0.8pF	0.1pF	0.1pF	0.1pF

The Notch filter indicated below is used to guarantee a certain isolation between LoRa, GNSS, and Wi-Fi. In the same way, the first two components of the Wi-Fi branch (Z7 and Z8) are part of another notch filter that isolates Wi-Fi from GNSS. The other components of each branch compose the matching networks used to minimize the S_{11} and maximize the efficiency of the antenna.

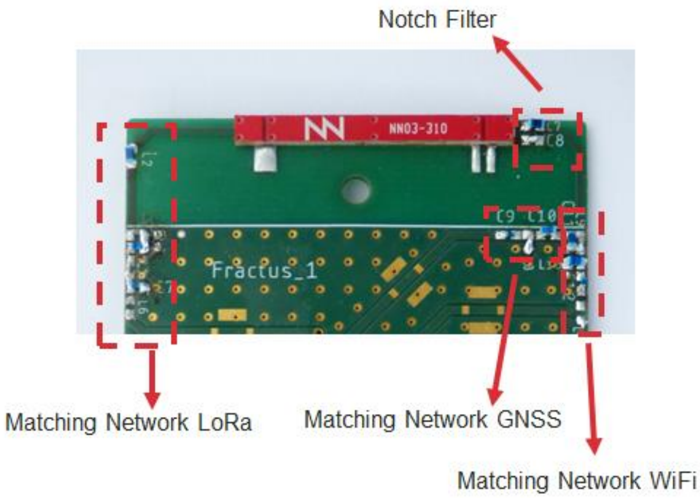
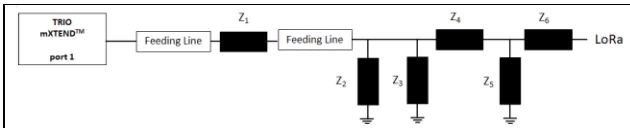
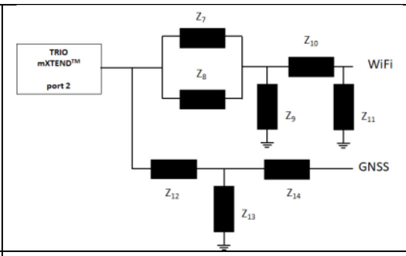
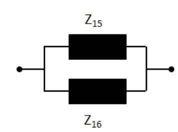


Image courtesy of Fractus Antennas

The network diagrams below illustrate the differences among LoRaWAN, GNSS, and Wi-Fi networks.

		
LoRa Matching Network	**GNSS & Wi-Fi Matching Network**	**Notch Filter**

Images courtesy of Fractus Antennas

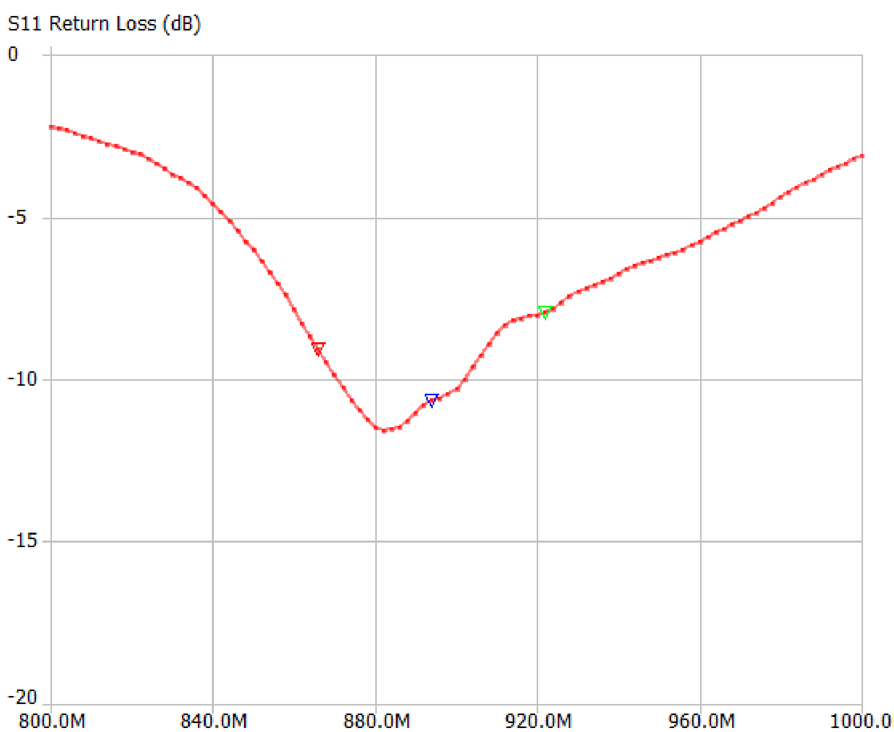
	The antenna tuning components must be optimized for the board size. Likewise, if the board shape is different, these elements may have to be tweaked as well.

As part of the free-of-charge NN Wireless Fast-Track service, Fractus can assist in designing or optimizing your own matching network. Visit: https://www.fractusantennas.com/fast-track-project/

The Importance of a Wideband Design

Unlicensed bands in different regions of the world are not harmonized and span from 863MHz (bottom of the European band) to 928MHz (top of the US band). The LR1110 power amplifiers are capable of sourcing, a carrier at any frequency across these 65MHz, at high efficiency and at the legal level of power. As seen in the next graph, when properly tuned, the TRIO mXTEND™ antenna offers a wide bandwidth, allowing for a single tuning for all frequency bands across the different PCB sizes.

The first graph below illustrates the return loss for 90mm Board in Air. The second graph shows the reflection coefficient for all Board in Air sizes.



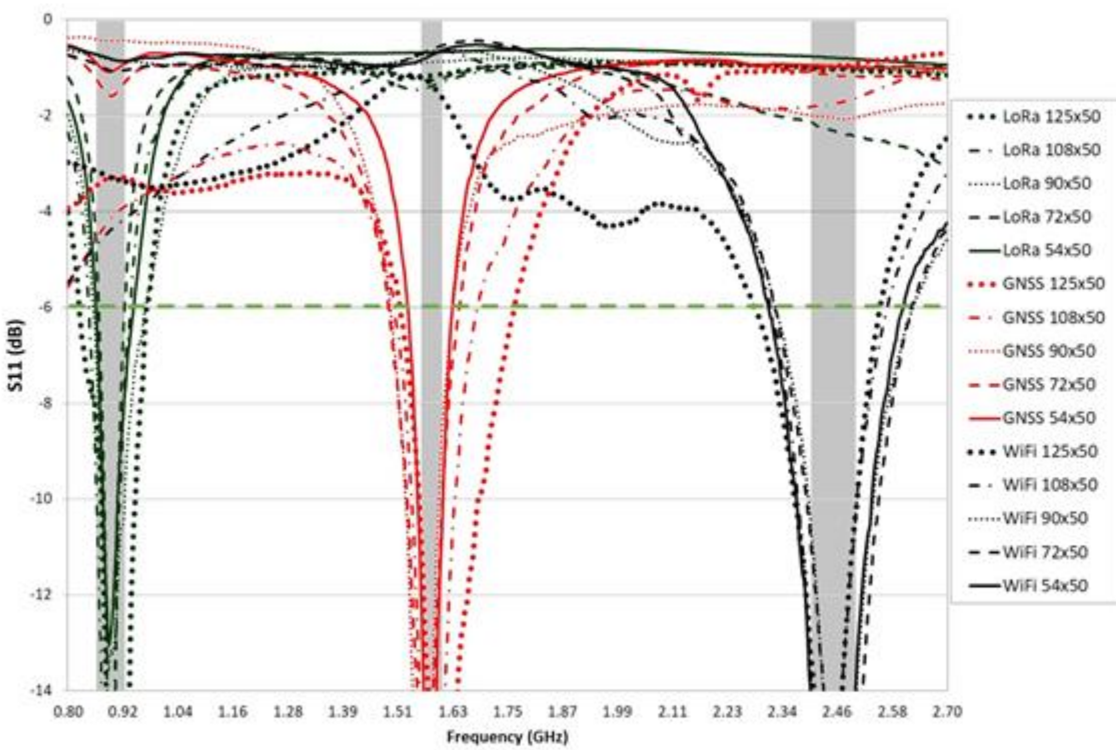


Image courtesy of Fractus Antennas

Board Size Impact: Antenna Efficiency

The ability of an antenna to radiate the power it is being fed is typically expressed in terms of efficiency, either in dB or as a percentage:

Source power dBm	Antenna Efficiency: Percent	Antenna Efficiency: dB	Total Radiated Power (TRP) dBm
+ 14	100	0	14
+ 14	80	-1	13
+ 14	50	-3	11
+ 14	25	-6	8
+ 14	10	-10	4

The Total Radiated Power (TRP), shown in the table above, expresses the sum of all power radiated by an antenna, connected to an RF source and integrated in all directions. It is not to be confused with *e.r.p.*, which is the observed power in one direction. Regulatory laws typically request that the peak e.r.p. be below a certain threshold, whilst the overall performance of an omnidirectional antenna such as the ones being measured here, is better described in terms of TRP (indeed, the orientation of most IoT devices with regard to the network they are broadcasting to, is generally an unknown).

The graph and table below show a summary of the efficiency numbers obtained for all frequency bands of interest, and all PCB sizes that were tested:

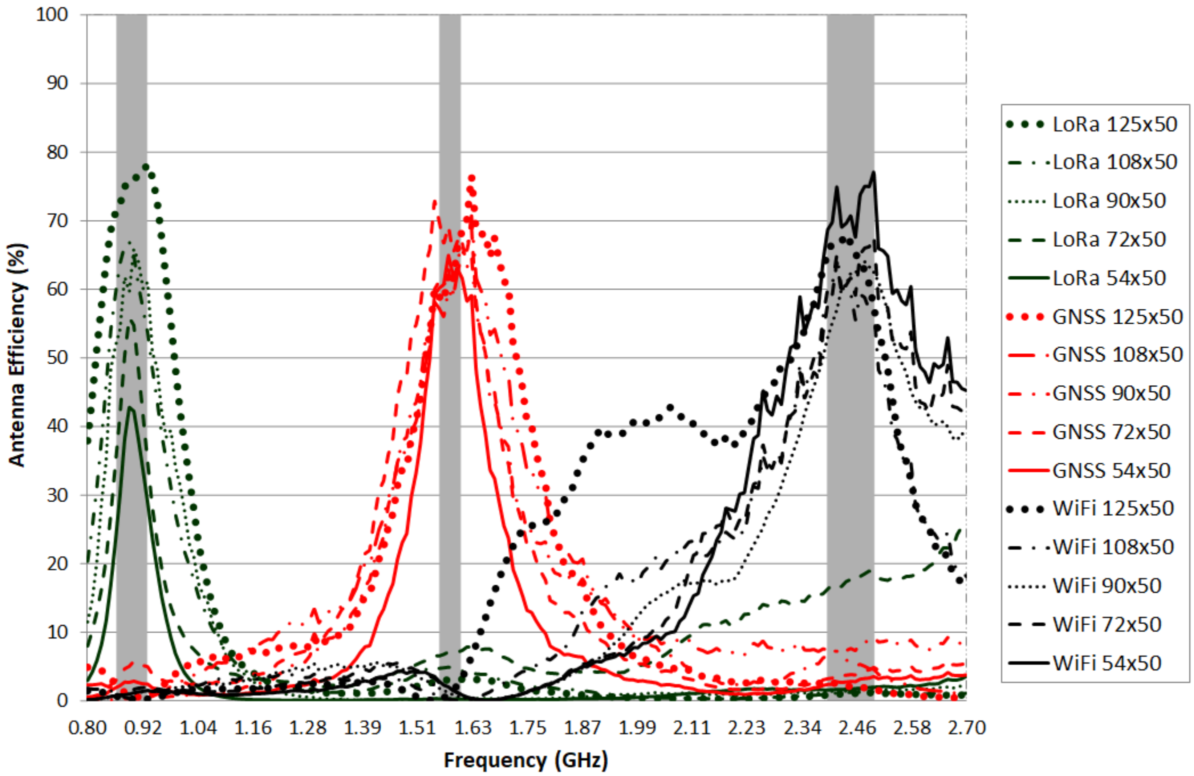


Image courtesy of Fractus Antennas

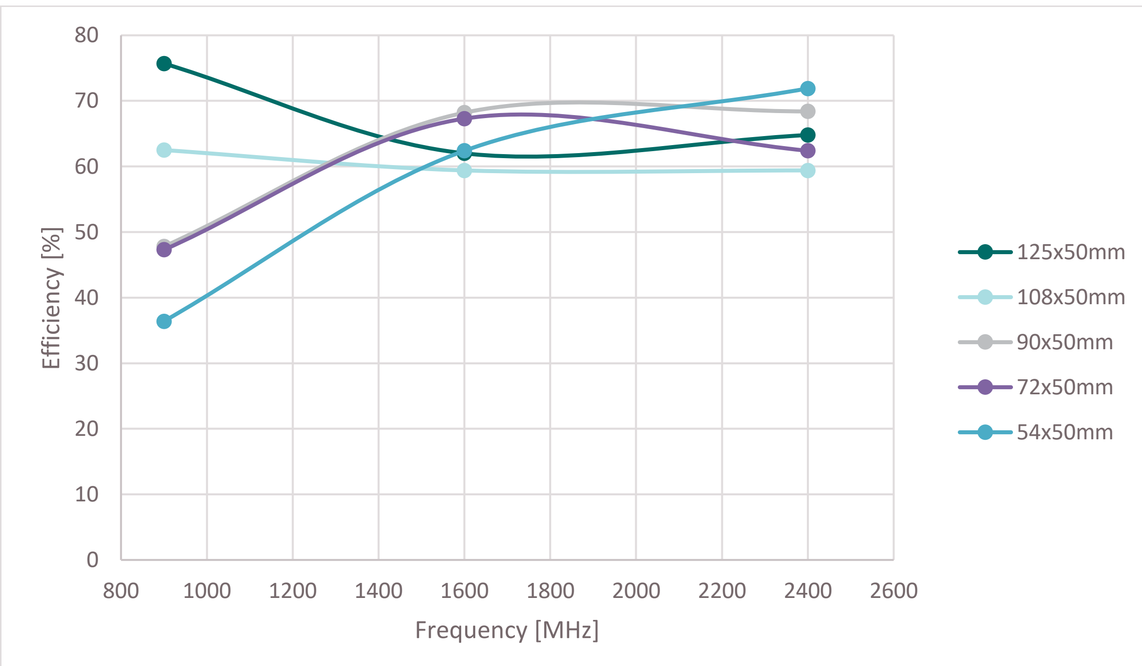
Ant. Eff	863MHz	928MHz	AVG LoRa	1561M Hz	1606M Hz	AVG GNSS	2400M Hz	2500M Hz	AVG Wi-Fi
125x50	71.5	78.1	75.7	58.8	67.7	62.0	65.3	57.2	64.8
108x50	60.6	54.2	62.6	57.1	64.3	59.4	59.9	56.7	59.4
90x50	52.4	60.9	60.6	61.1	65.8	61.9	52.9	62.4	60.5
72x50	36.5	35.9	47.3	69.5	66.9	67.3	57.6	67.3	62.4
54x50	25.1	29.6	36.4	60.2	62.1	62.4	68.5	76.7	71.9

The efficiency numbers stated in this report include mismatch losses induced by any detuning of the antenna.

On the Wi-Fi band, the antenna efficiency remains high, and even increases as the board gets smaller. At these frequencies, the radiation is the contribution of the longitudinal and transversal radiating modes of the PCB. The resonant frequency of the longitudinal mode increases as the PCB length reduces, being closer to the Wi-Fi operating frequencies, thus providing better performance.

However, for the LoRa bands where the wavelength is much longer (about 33 centimeters), the main resonance is obtained on the longer board edge, which gets shorter and shorter as the board is cut. Efficiency drops from 76 percent to about 36 percent on average, this is a 3dB hit on the antenna performance (UL and DL) for the smaller object.

The TRIO mXTEND has the advantage of embedding three antennas in a single component, simplifying the integration and bring-up of the IoT device.



The efficiency in the LoRa band might be optimized with the smaller board sizes by selecting an independent antenna for that frequency band.

Board Size Impact: Radiation Pattern

The TRIO mXTEND antenna has an omnidirectional pattern for all board sizes and frequency bands. This is an important feature when, typically, the orientation of the device is unknown. The only exception to this would be the GNSS antenna radiation pattern where, irrespective of the device location on the planet, the satellite signals will always be the most powerful when the SV is "over" the device (at least in line-of-sight conditions), meaning an elevation of 90 degrees from the horizon.

See the measured radiation patterns below for the reference PCB size (90mm x 50mm). The three main cuts, as well as the 3D illustrations, are represented for the central frequency of each frequency band.

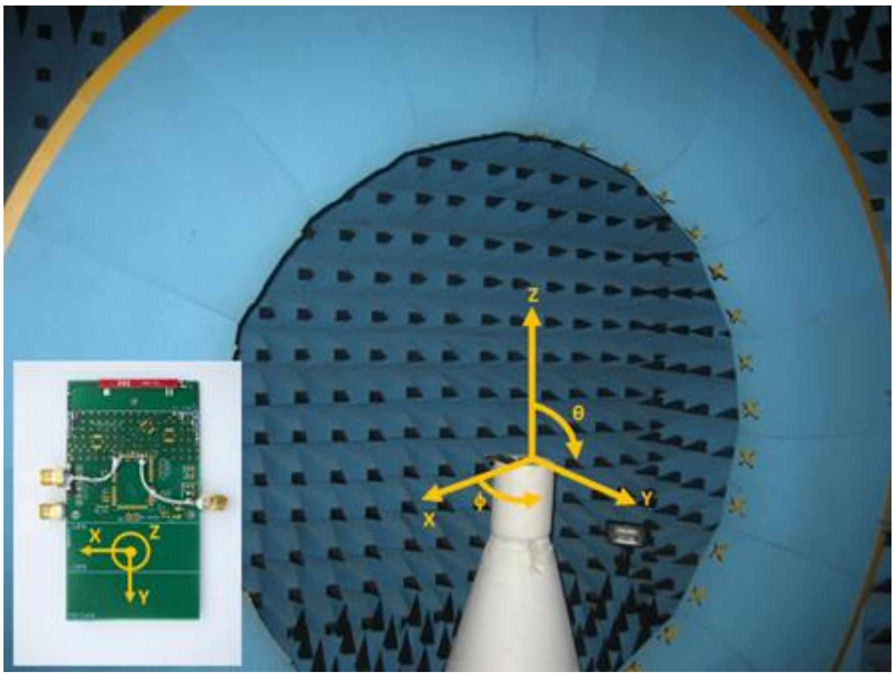
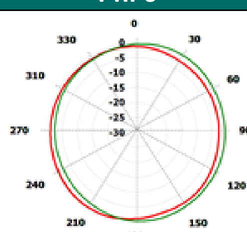
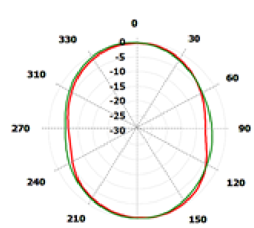
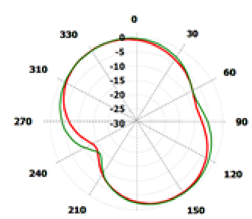
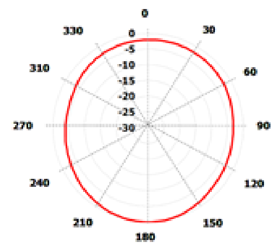
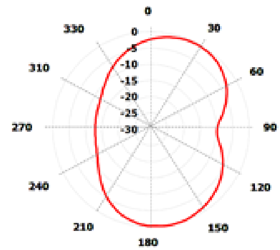
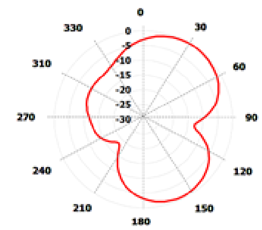
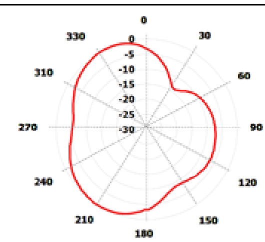
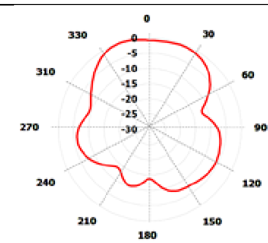


Image courtesy of Fractus Antennas

The following diagrams show 2D radiation plots for a 90mm board.

Frequency Band	Phi 0º	Phi 90º	Theta 90º
866MHz 915MHz			

1575MHz			
2450MHz			

Images courtesy of Fractus Antennas

The images below show 3D radiation plots for a 90mm board:

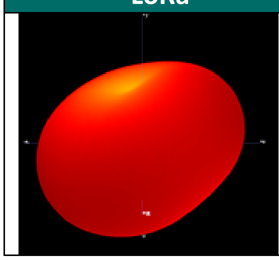
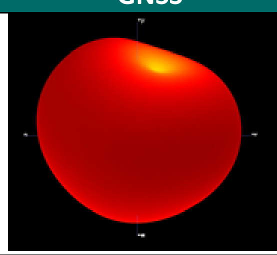
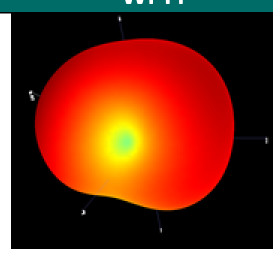
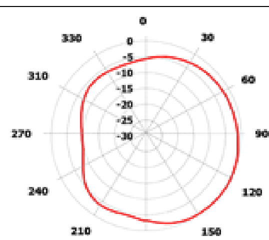
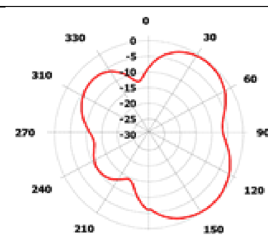
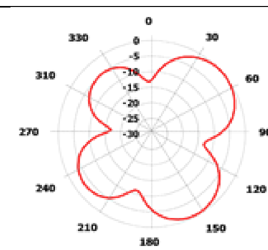
LoRa	GNSS	Wi-Fi
		

Image courtesy of Fractus Antennas

The main radiation pattern cuts for GNSS frequencies remain omnidirectional for all PCB sizes, so are preferable for those devices in constant movement where the direction of the incoming waves is unknown.

Frequency Band	Phi 0º	Phi 90º	Theta 90º
25x50			

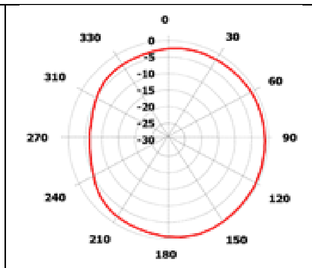
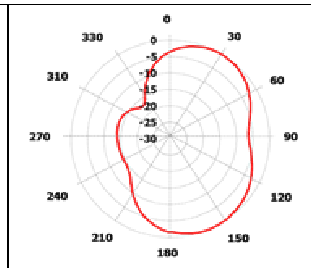
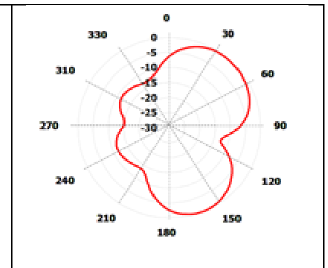
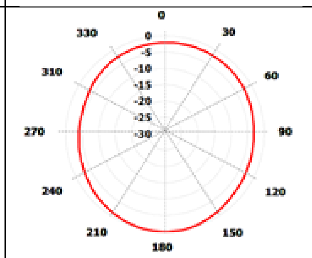
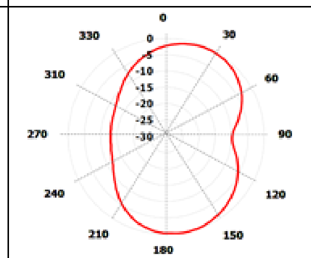
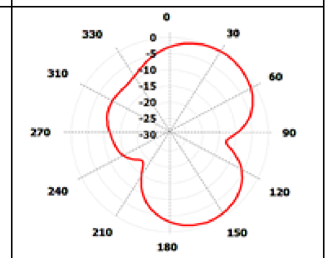
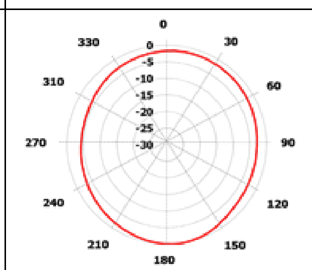
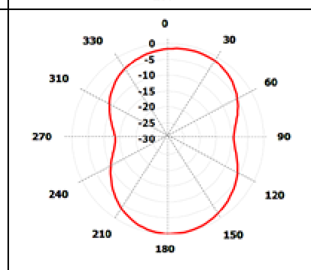
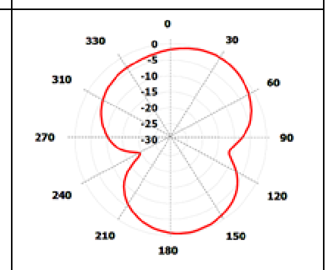
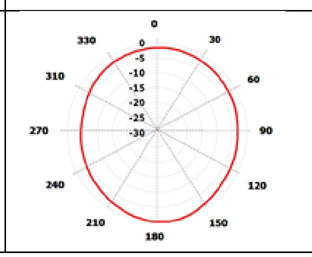
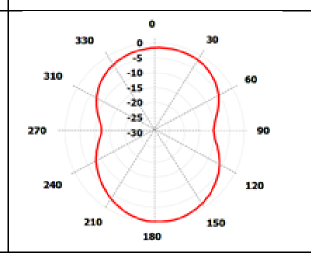
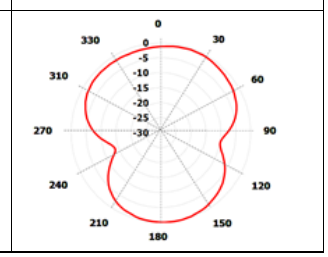
108x50			
90x50			
72x50			
54x50			

Image courtesy of Fractus Antennas

Based on the results above, we can conclude that the TRIO mXTEND is a suitable antenna capable of working at LoRa, GNSS and Wi-Fi bands at the same time. The larger the PCB, the higher the performance that is expected for the LoRa band. Apart from that, any change in antenna impedance due to PCB size or changing environmental conditions can easily be compensated through the matching network. This is one of the advantages of Virtual Antenna technology: it can work at any standard and under different conditions using the same antenna component, by just adjusting the matching network.

Antenna Detuning with Select Materials

IoT use-cases are diverse: Smart Home, Smart Utility, Smart Farming, Asset Tracking etc. In any of these scenarios, the connected device is somehow anchored to an asset. Trackers may be placed on top of a shipping container, or may be integrated on a wooden or plastic pallet. Connected thermostats may be placed on a wall made of concrete, plaster, or on a metal beam in an industrial building. Pet trackers are placed near animal tissue. The list goes on.

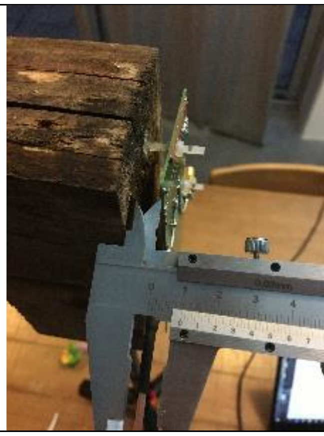
Test Setup

It is important to estimate and even better, **anticipate**, the material that will surround the device, to ensure that the antenna has the best possible performance in its use case.

	
Tracker on a Wood Pallet	Tracker on Concrete
	
Tracker on Metal	Tracker on Body Phantom

Images courtesy of Fractus Antennas

Multiple experiments show that the underlying material and, more importantly, the distance to it, plays a critical role in the antenna performance, both in terms of mismatch losses, and in terms of efficiency:



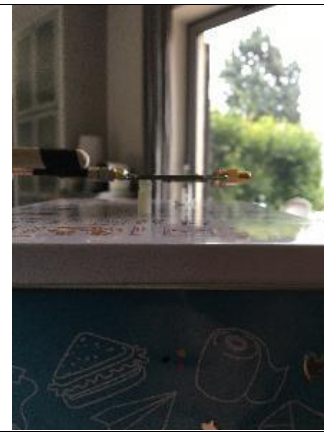


Image courtesy of Fractus Antennas

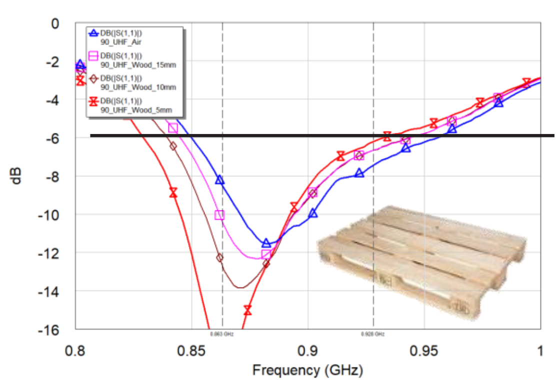
The following graphs show the impact of the substrate on antenna resonance per frequency band.

The vertical dotted lines indicate the extremes of the frequency bands of interest.

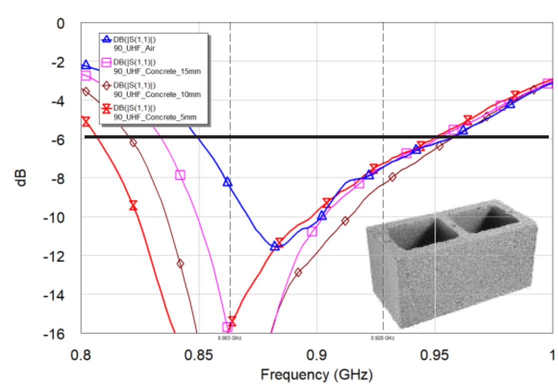
Legend:

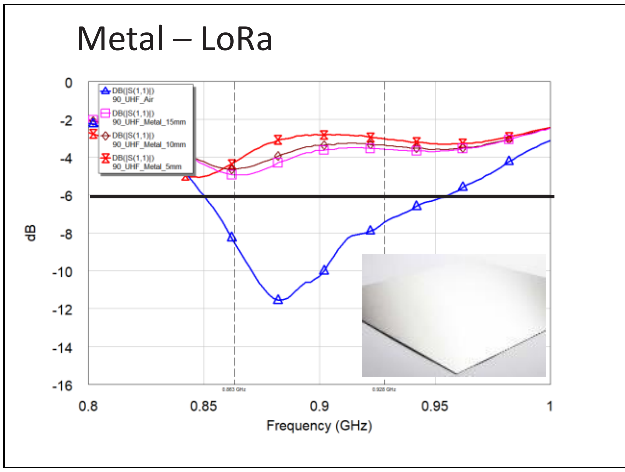
Antenna in "Air"
Antenna at 15 mm distance from substrate
Antenna at 10 mm distance from substrate
Antenna at 5 mm distance from substrate

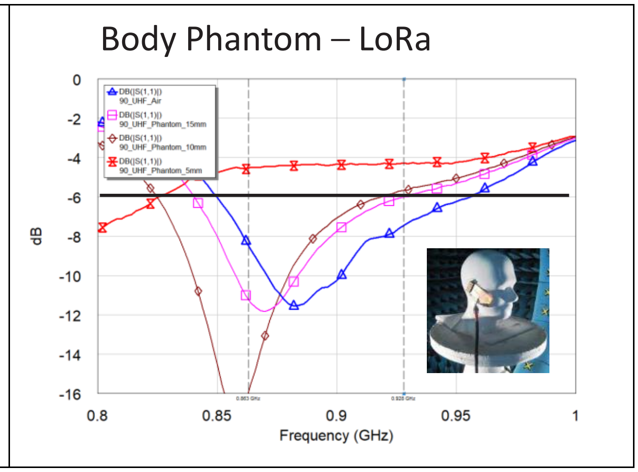
Wood – LoRa



Concrete – LoRa

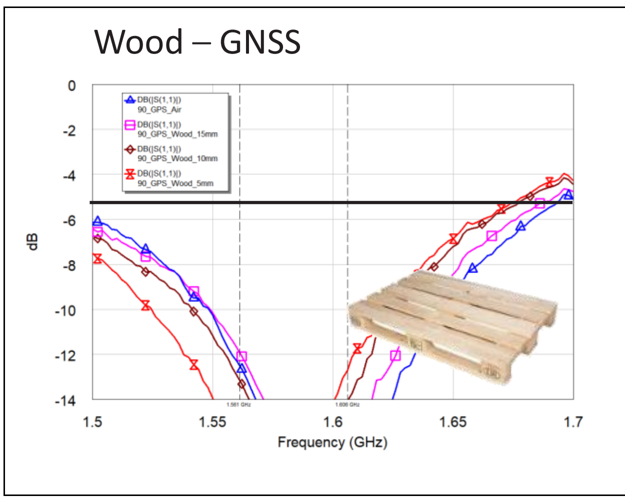


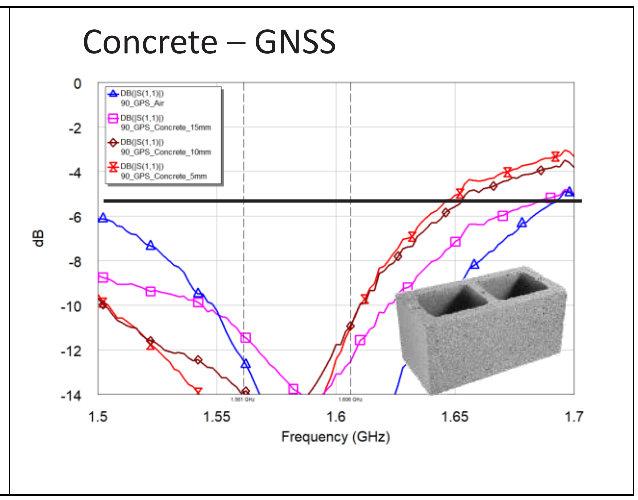


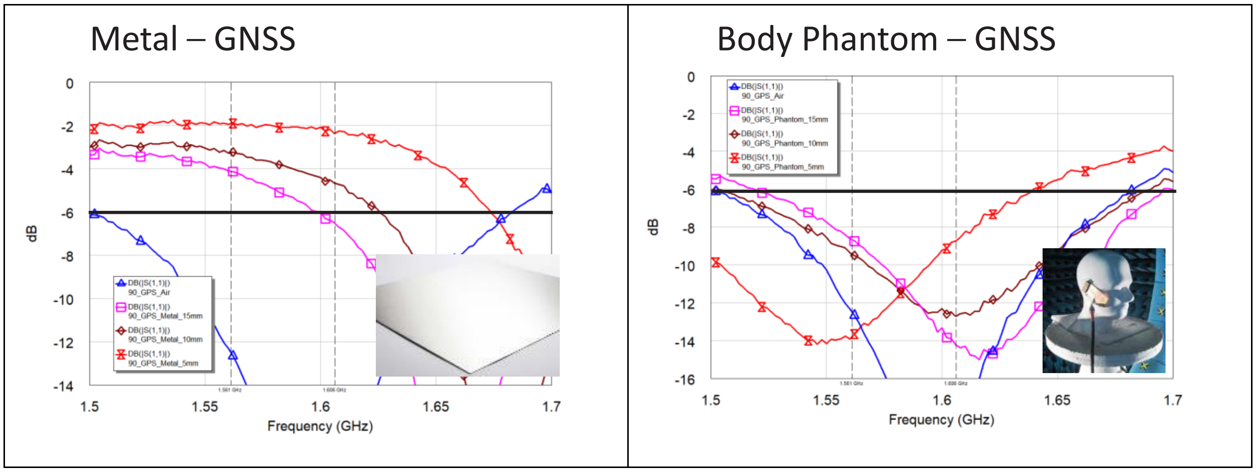


Measurements performed by Semtech. Image courtesy of Fractus Antennas

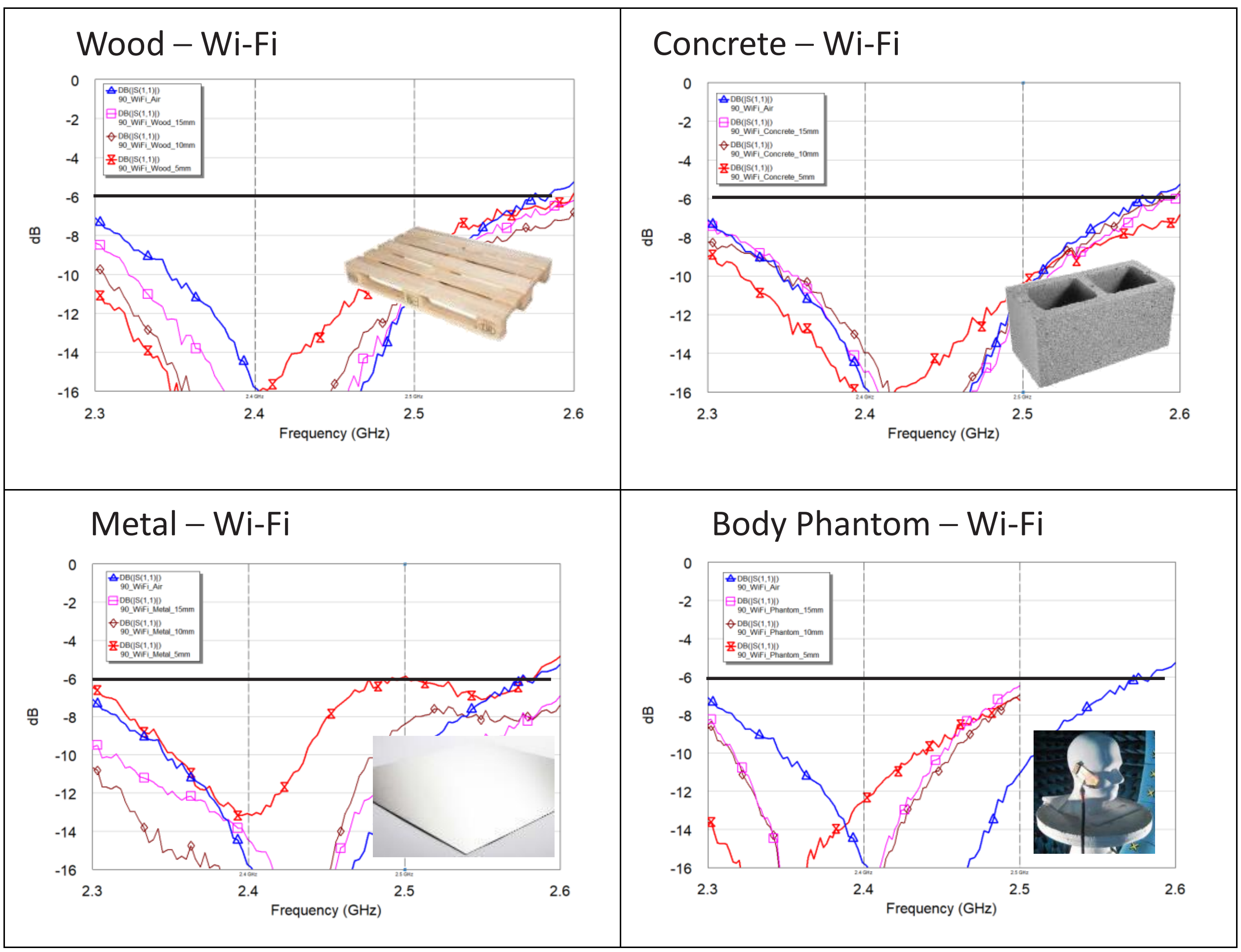
The S11 = -6dB performance target is displayed, guaranteeing mismatch losses of less than 1.25dB.







Measurements performed by Semtech. Image courtesy of Fractus Antennas



Measurements performed by Semtech. Image courtesy of Fractus Antennas

Note that the matching network considered for the material impact in this analysis differs from the reference matching network selected for maximizing performance in LoRa bands. Nevertheless, the qualitative results and conclusions extracted apply to both. Details are available in Appendix A6: Alternative Matching for the 90mm Board.

Summary of our experimental learnings:

1. The TRIO, generally speaking, behaves well when loaded with these materials, at a distance of 5, 10 or 15mm. In the nominal case, it guarantees less than 1.25dB of mismatch losses by maintaining the return loss below –6dB.
2. Metal loading has a dramatic impact for the LoRa and GNSS bands, at all distances. Specific recommendations are discussed later in this paper. Metal loading has an acceptable impact to the detuning in the Wi-Fi band.
3. Human Phantom loading has a bearable impact, except for the LoRa band when the antenna is too close, with a 5mm gap. Increasing the gap to 10mm appears sufficient to keep a reasonable detuning.

Detuning Results: Efficiency and Mismatch Losses

In addition to detuning, the materials in the vicinity also induce a dissipation effect which depends on the electromagnetic characteristics of each material; some materials cause more loss than others. The antenna efficiency has been measured for the reference board size (90mm x 50mm), placed 15mm from the material in the vicinity, to illustrate this effect.

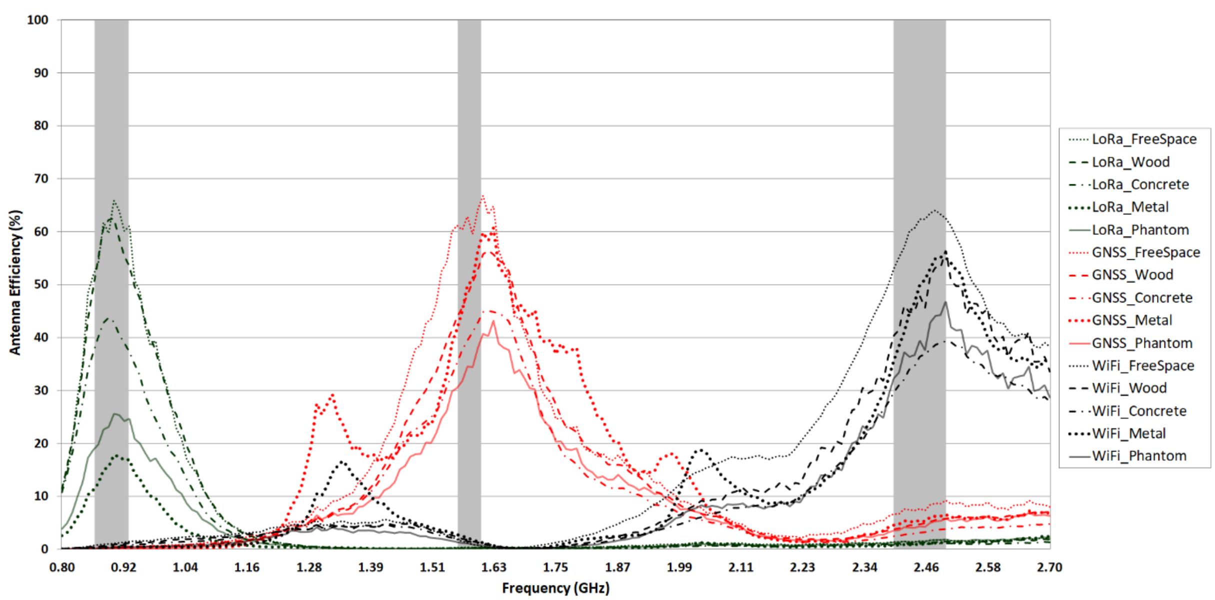


Image courtesy of Fractus Antennas

When studied at the 15mm distance, the antenna impedance is generally robust to any detuning effect, except for the metal case in LoRa frequencies, where $S_{11} < -3dB$. In this case, a retuning to improve S_{11} values is possible using the virtual antenna technology to simply retune the matching network to optimize antenna performance (which is more difficult to attain with other antenna technologies where the operating frequencies may be determined by antenna geometry). The required bandwidths for all other cases are always covered completely with $S_{11} < -8dB$ and good antenna efficiency.

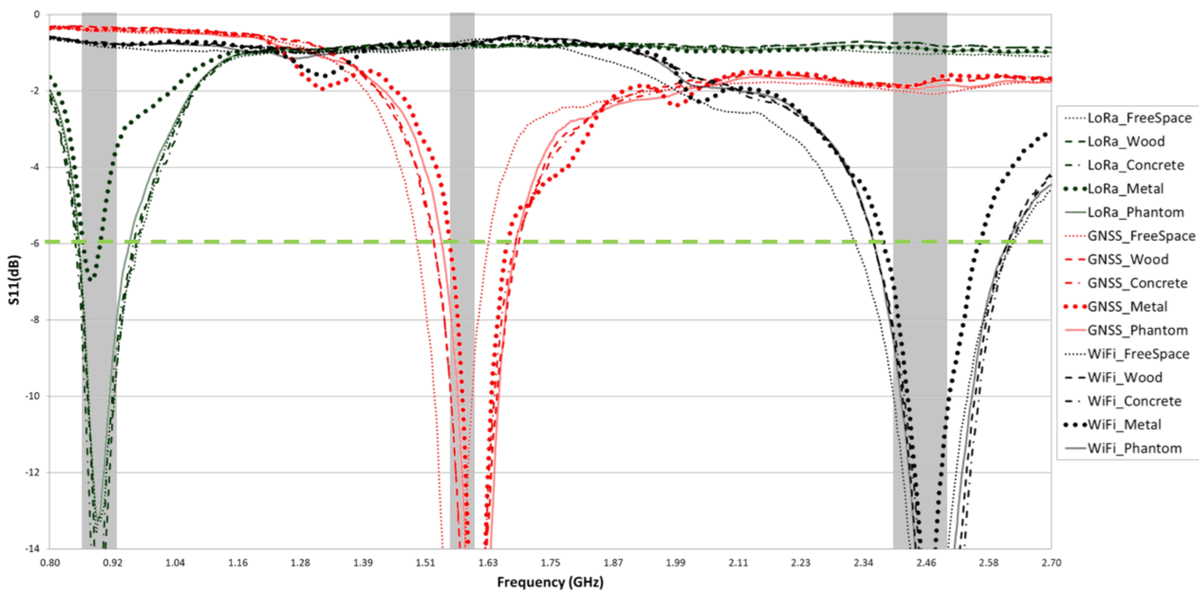


Image courtesy of Fractus Antennas

The recommendations to preserve good performance in these environments are as follows:

1. Increase the distance between the device and the material in the vicinity as much as possible. The recommended distance depends on the material. For all the scenarios above (wood, concrete, body phantom) except metal, a distance of 15mm is enough to guarantee very good performance in all bands.

2. In metallic environments, align the device as closely as possible to the edge of the metal (ideally with the antenna area protruding the metallic environment) while maximizing the distance between the device and the metal, with a minimum distance of 25mm. See Appendix A5: 10mm Placement Tests for Metal Case for images

TRIO mXTEND™ Conclusion

The conclusions extracted from the analysis above can be summarized as follows:

1. TRIO mXTEND™ is currently the only antenna available in the market capable of handling three radio bands (LoRa, GNSS, and Wi-Fi) inside the same single and compact antenna package, thus reducing integration complexity.

2. TRIO mXTEND provides high performance in these three bands for the reference PCB size (90mm x 50mm). As a general rule, the bigger the PCB, the better the performance for LoRa channels.

3. The performance starts to degrade as the PCB shrinks, such as in the lower frequency bands where the board dimension is much lower than the wavelength, as happens with other conventional antenna solutions. The advantage of the TRIO mXTEND is that the detuning caused by PCB size reduction can be compensated by matching network adjustment, meaning that no customization of the antenna is needed. This adjustment is more difficult to attain with conventional antenna solutions where operating frequencies are determined by the antenna geometry.

4. The radiation patterns are omnidirectional in all cases, which is preferable for devices in constant movement, where the direction of the incoming waves is unknown.

5. The materials in the vicinity affect the radiation from two perspectives: antenna detuning and power absorption.

6. The TRIO mXTEND is robust in terms of detuning by the proximity of materials in the vicinity. The largest impact on detuning occurs in metallic environments, followed by human body interactions.

7. If a detuning occurs, it can be compensated by adjusting the matching network.

8. As a general rule, the larger the distance from the material in the vicinity, the better the performance. For the most critical case, the metal scenario, place the device as closely as possible to the edge of the metallic section, at a minimum distance of 25 mm. Even better performance is expected if the antenna area protrudes the metallic area.

Appendices

A1: References: Phantom Solution Recipes and Matching

Detuning experiments were run at home (due to the Covid-19 pandemic), in a do-it-yourself (DIY) fashion. For use cases such as pet or cattle tracking, the detuning induced by human tissue becomes an important performance factor, therefore a sucrose-based phantom solution was prepared. The National Institute of Health in Maryland has published a phantom solution calculator, for both sucrose and PVT-based recipes. It is available on: https://amri.ninds.nih.gov/cgi-bin/phantomrecipe.

The resonant frequency of human tissues is tabulated in this study: https://www.emf-portal.org/en/cms/page/home/effects/radio-frequency

The conductivity is tabulated in this study: https://drum.lib.umd.edu/bitstream/handle/1903/3532/umi-umd-3365.pdf on Table 2.3 on Page 10. An extract is here:

Table 2.3: Target dielectric values for tissue-equivalent liquids at specific frequencies

Frequency (MHz)	Relative Permittivity ϵ'	Conductivity σ (S/m)
300	45.3	0.87
450	45.3	0.87
835	41.5	0.90
900	41.5	0.97
1450	40.5	1.20
1800	40.0	1.40
1900	40.0	1.40
2000	40.0	1.40
2450	39.2	1.80
3000	38.5	2.40

The following body phantom solution was prepared and boiled for a couple of minutes:

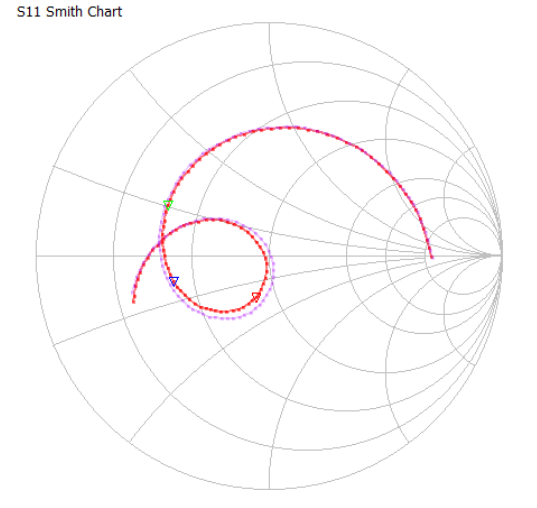
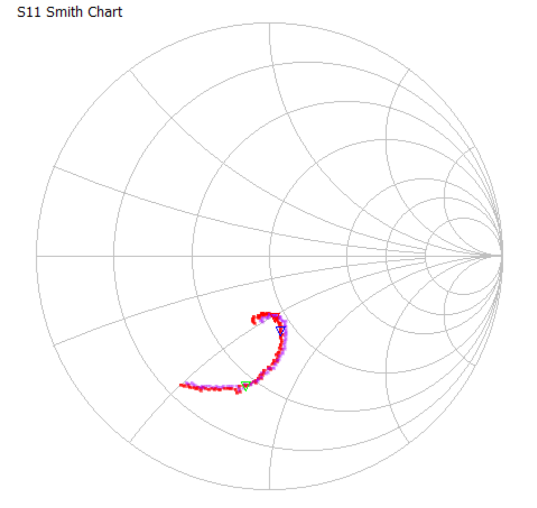
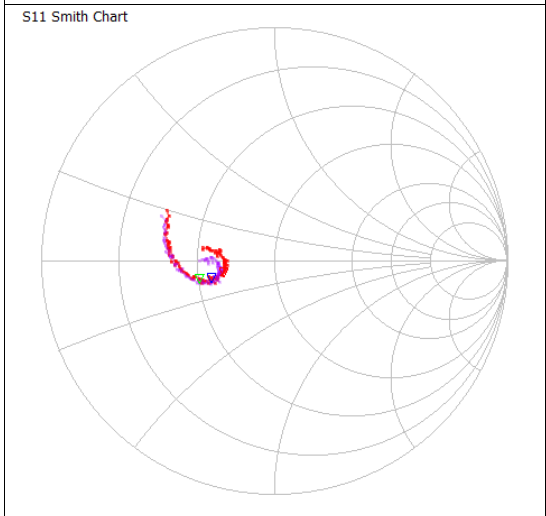
Compound	Weight
Salt (NaCl)	31.5 g
Sugar	245.7 g

Agar	2.25 g
Benzoic Acid	0.15 g
Distilled water	150 g

Voilà!

It is important to confirm that the RF characteristics of the solution match those that occur when the antenna is close to an actual body. To this end, the 90mm board was alternately placed 10mm above the phantom solution (poured into a household plastic box, whose RF characteristics are experimentally verified to be negligible), then on my thigh. The reflection coefficient was measured at all three frequencies of interest:

	
On phantom solution	On body (thigh)

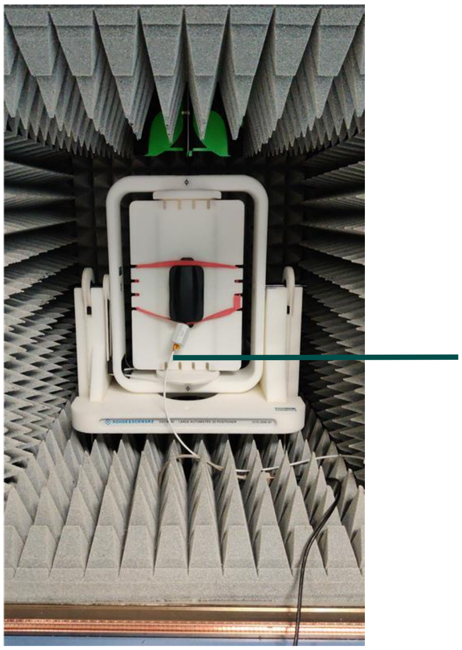
	LoRa Body (Pink) Phantom Solution (Red)
	GNSS Body (Red) Phantom Solution (Pink)
	Wi-Fi Body (Red) Phantom Solution (Pink)

These results indicate a reasonable fit of the recipe for all three frequency bands of interest.

A2: Active Antenna Testing Validates Passive Antenna Testing

As described above, in the section What Makes an IoT Device Radiate Properly?, improper load on an integrated power amplifier may reduce its performance. Hence, the natural step at the end of the design cycle is to run "Active Antenna Tests".

In a *passive* antenna test, the wireless transceiver used in the IoT device is replaced with lab equipment such as a signal generator:

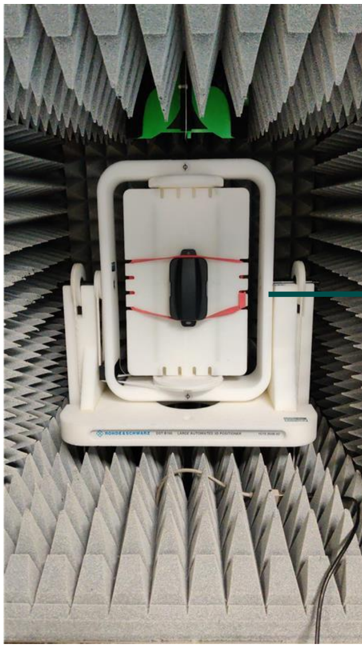


Passive Antenna Test Representation:
Coax to Test Equipment

This method, applied with all the relevant caution, gives good results, and a proper estimation of the antenna efficiency is possible.

However, when the objects to be measured become smaller, the test harness (sourcing equipment and its cable, temporarily attached to the IoT device) may significantly impact the results. On top of this, the effect of mismatch on the actual PA is not measured.

In an *active* antenna test, there is no test harness connected to the device. Instead, the active module on the test board, here the FMLR-1110-X-L07 module, generates the carrier used to measure the antenna performance in the chamber. Consequently, the results obtained in terms of efficiency, e.r.p., and radiation pattern will be 100% representative of the actual use of the device in the application.



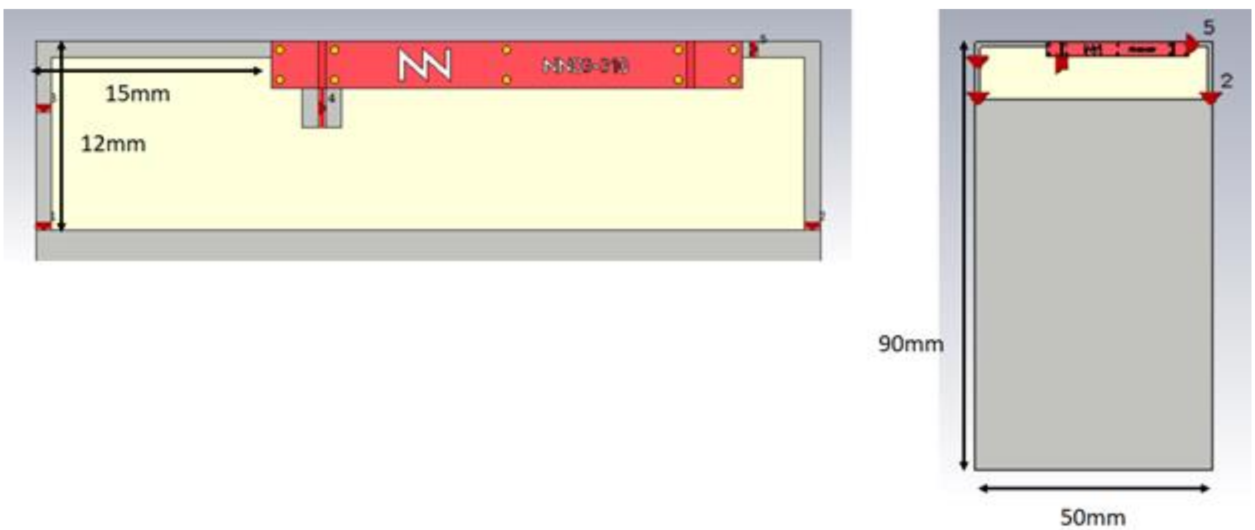
Active Antenna Test Representation:
Fully-Active Device

Although this paper does not cover this aspect, we are hoping to back-up these measurements with active antenna tests in some of the many conditions covered in this document.

A3: Results Obtained by Simulation

Fractus Antennas offers a free simulation service called Wireless Fastrack. This service consists of providing a proof-of-concept to the IoT designers, to give them an order of magnitude of the expected antenna performance for their PCB size. The service guides them in the proof phases of their projects to get the most efficient antenna designs that meet their expectations. It also includes the most appropriate Virtual Antenna component selection, together with design recommendations for its appropriate integration, recommended matching network topology, and bill of materials, as well as estimated antenna performance.

Illustrated below are the results obtained for the reference case study above (PCB of 90mm x 50mm) using the Wireless Fastrack service. Both simulations and measurements are in agreement for LoRa and GNSS. In the Wi-Fi bands some differences appear, mainly because, at these high frequencies any element can affect performance, this is the case for the cables and SMA connectors not modelled during the simulation process, but present in the measurement set-up. Nevertheless, the level of agreement is still good and provides a very fast preliminary analysis to have an order of magnitude of the expected performance in your device. The service is provided in 24 hours from the reception of the Wireless Fastrack request (subject to terms and conditions).



Images courtesy of Fractus Antennas

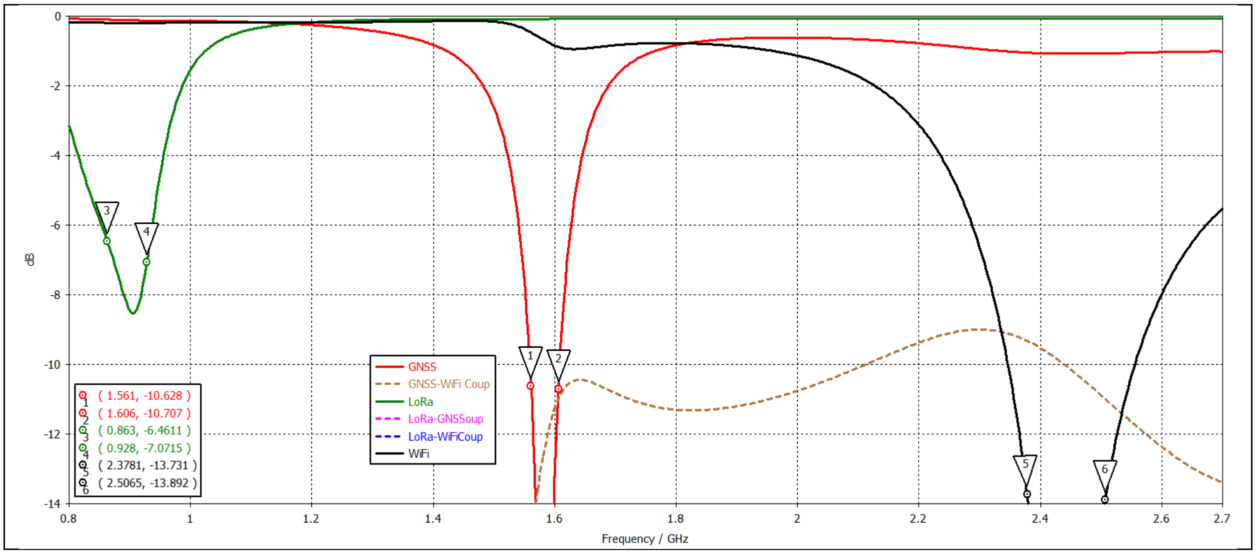


Image courtesy of Fractus Antennas

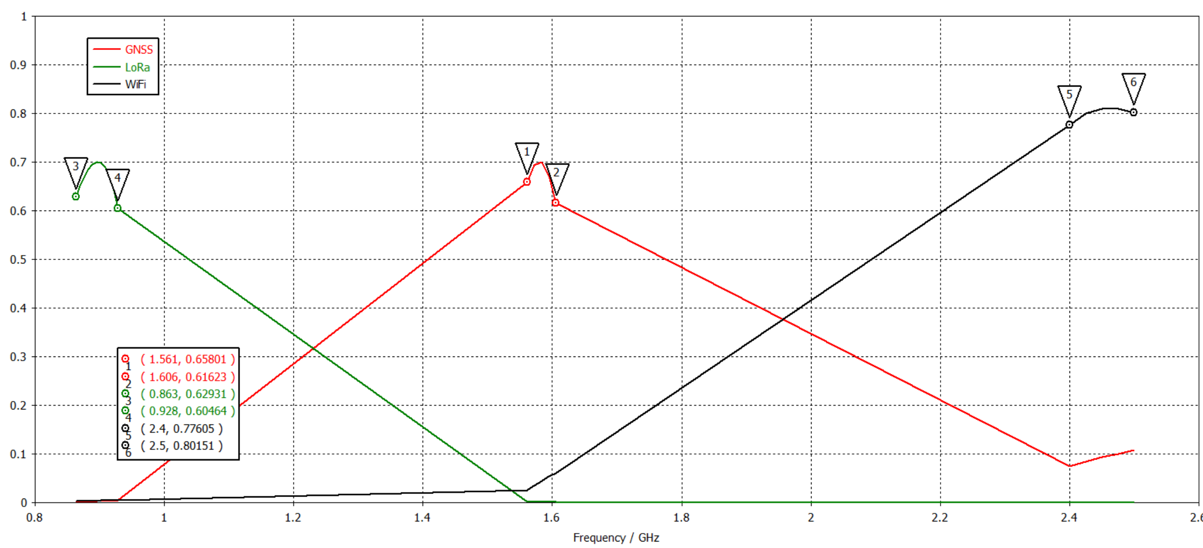


Image courtesy of Fractus Antennas

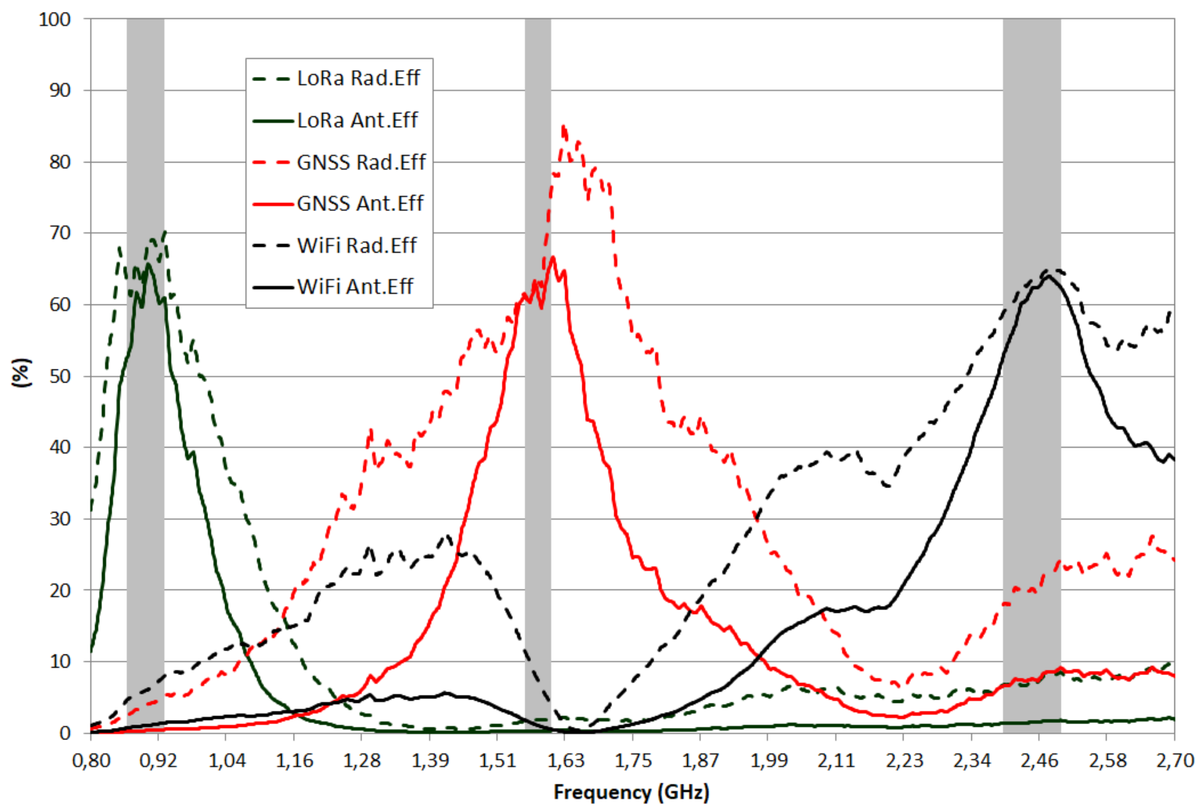


Image courtesy of Fractus Antennas

The table below shows the comparisons for simulated and measured results for the frequencies indicated.

	863 MHz	928 MHz	LoRa AVG	1561 MHz	1606 MHz	GNSS AVG	2400 MHz	2500 MHz	Wi-Fi AVG
Sim	62.9	60.5	66.7	65.8	61.6	66.8	77.6	80.2	80.0
Meas	52.4	60.9	60.6	61.1	65.8	61.9	52.9	62.4	60.5

A4: Passive Element Part Numbers

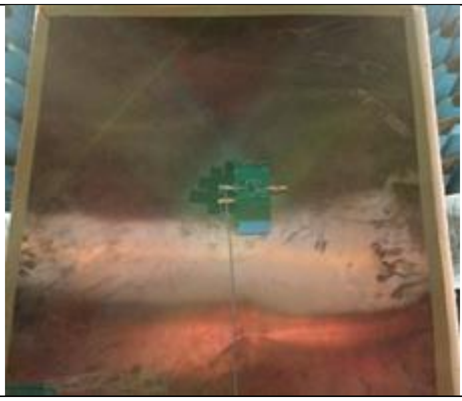
The following capacitors and inductors, from Murata, were used during the experiments:

L and C Commercial References:

Value Inductor	Part Number	Value Inductor	Part Number	Value Inductor	Part Number
28nH	LQW18AN28NG80	4.4nH	LQW15AN4N4G80	34nH	LQW18AN34NG80
16nH	LQW18AN16NG80	4.0nH	LQW15AN4N0G80	11nH	LQW18AN11NG80
15nH	LQW18AN15NG80	3.7nH	LQW15AN3N7G80	9.1nH	LQW18AN9N1G80
10nH	LQW18AN10NG10	3.5nH	LQW15AN3N5G80	8.4nH	LQW18AN8N4G80
9.1nH	LQW18AN9N1G80	3.2nH	LQW15AN3N2B00	5.0nH	LQW15AN5N0B80
8.7nH	LQW18AN8N7G80	2.8nH	LQW15AN2N8G80	2.5nH	LQW15AN2N5G80
8.4nH	LQW18AN8N4G80	2.3nH	LQW15AN2N3G80	2.2nH	LQW15AN2N2G80
7.5nH	LQW18AN7N5C80	2.2nH	LQW15AN2N2C10	34nH	LQW18AN34NG80
6.0nH	LQW5AN6N0B80	1.8nH	LQW15AN1N8C00	11nH	LQW18AN11NG80
5.6nH	LQW15AN5N6C10	1.3nH	LQW15AN1N3C10	0.8pF	GJM1555C1HR80WB01
2.1pF	GJM1555C1H2R1WB01	1pF	GJM1555C1H1R0WB01	8pF	GJM1555C1H8R0WB01
15pF	GJM1555C1H150FB01	9.1pF	GJM1555C1H9R1WB01		

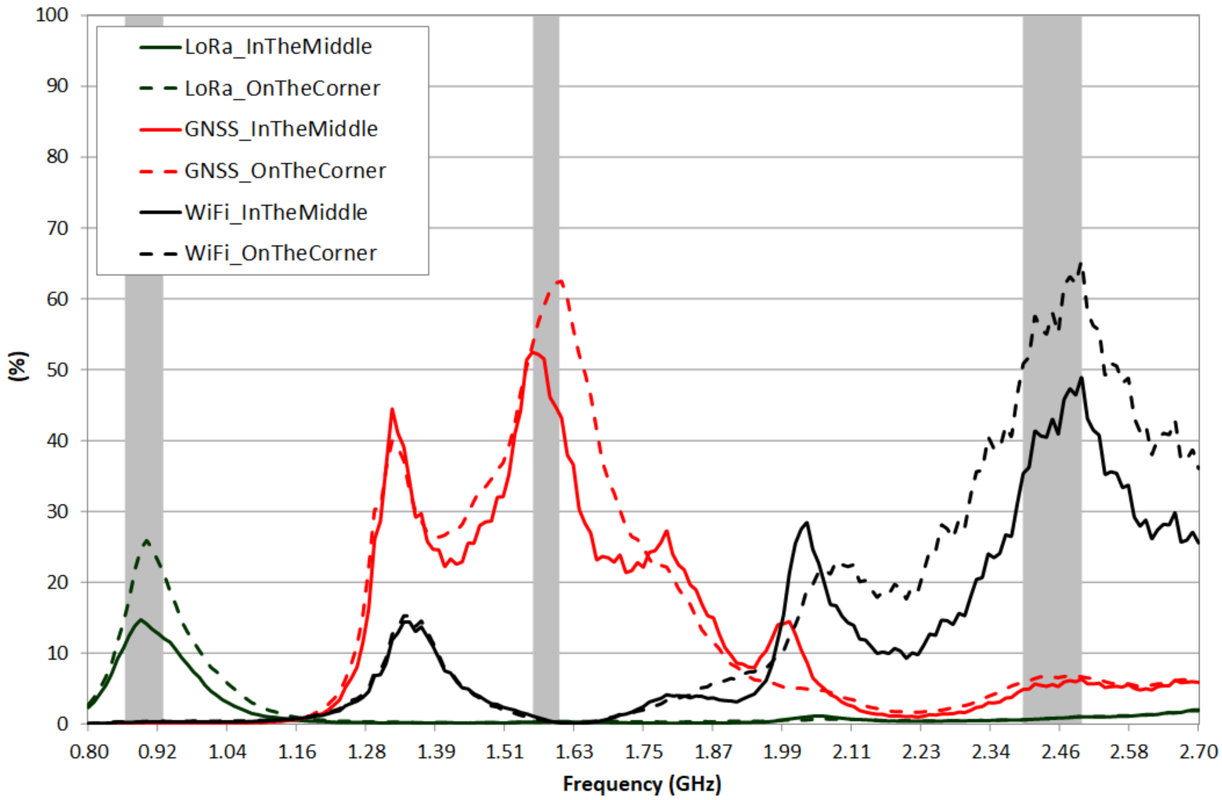
A5: 10mm Placement Tests for Metal Case

Although metal impacts performance, we can minimize this impact if the PCB is placed in the corner of the metal surface. In this experiment the PCB is 10 mm from the metal and the matching network used is the one shown the Board-size Impact: Matching and Resonance section. Results would be even better if the distance between the PCB and the metal surface was greater.

	
PCB in the middle	PCB on the corner

Images courtesy of Fractus Antennas

The following graph and table show the measured efficiency of the antennas for each of these placements.

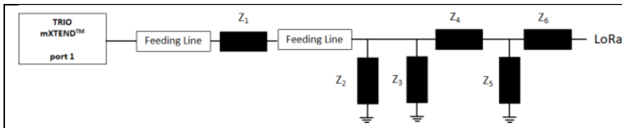


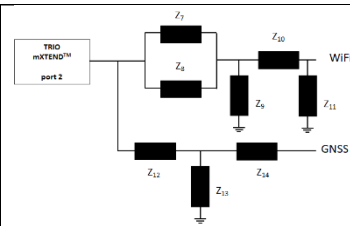
Images courtesy of Fractus Antennas

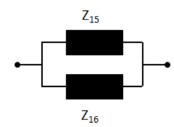
Ant. Eff	863 MHz	928 MHz	AVG LoRa	1561 MHz	1606 MHz	AVG GNSS	2400 MHz	2500 MHz	AVG Wi-Fi
PCB in the middle	11.2	12.2	13.3	52.4	43.8	48.8	35.2	48.8	42.4
PCB on the corner	15.2	21.4	22.4	53.8	62.4	59.3	50.7	65.2	57.9

A6: Alternative Matching for the 90mm Board

The following matching was used for the detuning experiments on the 90 mm board:







LoRa Matching Network	**GNSS & Wi-Fi Matching Network**	**Notch Filter**

	Z_1	Z_2	Z_3	Z_4	Z_5	Z_6	Z_7	Z_8	Z_9	Z_{10}	Z_{11}	Z_{12}	Z_{13}	Z_{14}	Z_{15}	Z_{16}
90x50	8.4nH	15pF	2.5nH	8pF	5nH	0Ω	8.4nH	1pF	9.1nH	2.2nH	OPEN	11nH	2.1pF	2.2nH	0.8pF	34nH

Images courtesy of Fractus Antennas

Important Notice

Contact Information

Semtech Corporation
200 Flynn Road, Camarillo, CA 93012
Phone: (805) 498-2111, Fax: (805) 498-3804
www.semtech.com