neo.cortec
Wireless connectivity made simple.

A STUDY FOR NEOCORTEC WWW.NEOCORTEC.COM

LOW COST DO IT YOURSELF PCB ANTENNAS **FOR WIRELESS IOT**

HARALD NAUMANN

Version 1.01
26.01.2022

Ludwig-Kaufholz-Weg 4, 31535 Neustadt, Germany
E-mail: harald.naumann@gsm-modem.de
Phone: +49-5032-8019985

TABLE OF **CONTENTS**

Author: Harald Naumann
https://www.linkedin.com/in/naumann/

LIST OF **ILLUSTRATIONS**

Illustration: page:

Author: Harald Naumann
https://www.linkedin.com/in/naumann/

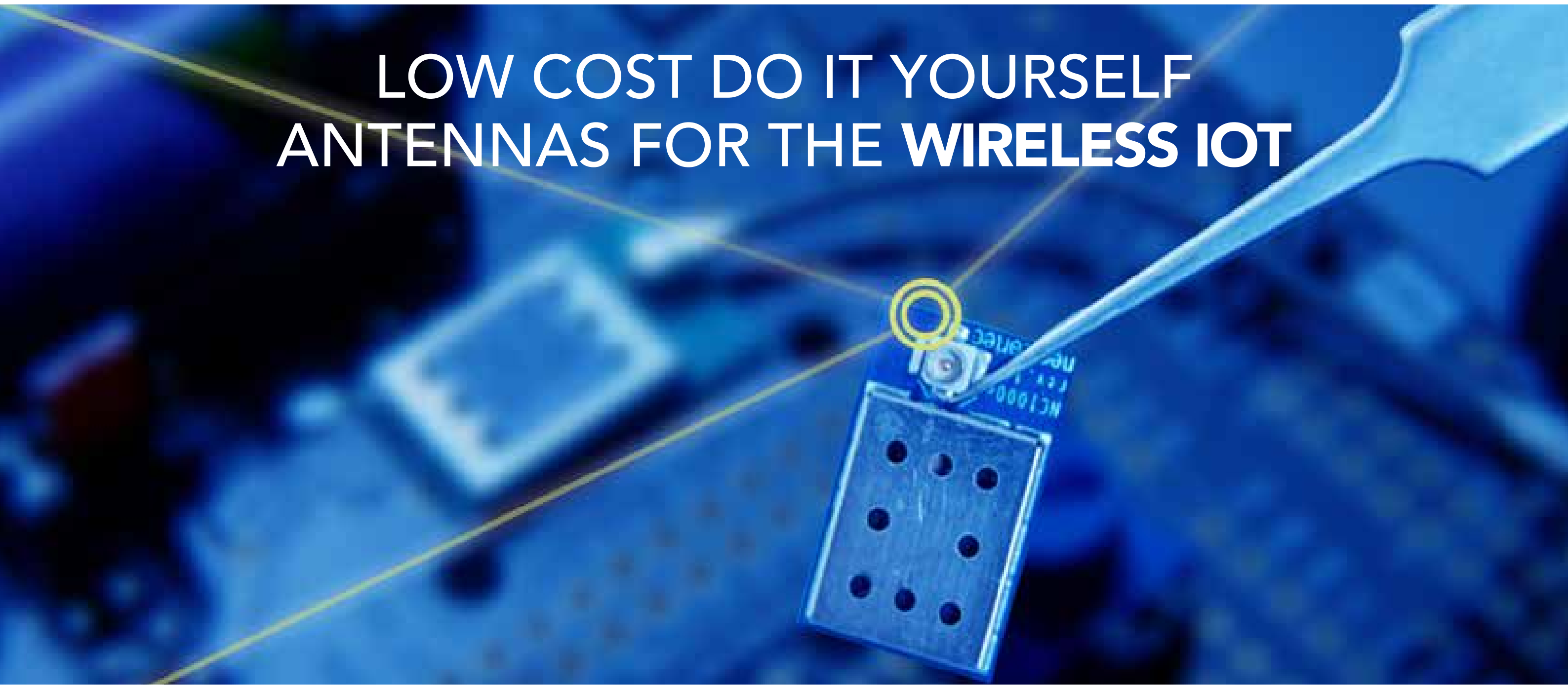
LIST OF **ILLUSTRATIONS**

LIST OF **TABLES**

LINKS TO DOWNLOAD THE ANTENNA FILES:

See Latest version at:
https://www.akoriot.com/white-papers/
http://www.neocortec.com
Gerber files of the PCB antennas: https://www.akoriot.com/white-papers/
DXF files files of the PCB antennas: https://www.akoriot.com/white-papers/

LOW COST DO IT YOURSELF ANTENNAS FOR THE **WIRELESS IOT**



With the Internet of Things, devices use embedded technologies and communicate over wired and wireless networks. Nobody wants to carry a cable around to transmit data from the sensor on their body or bike. The wire has to be replaced by something else. One possibility is infrared, which uses light signals for transmission. The disadvantage of light, however, is that it cannot penetrate a wall. Electromagnetic waves are more suitable, they can penetrate walls in buildings and offer a good range. These electromagnetic waves have different characteristics in different frequency bands. In the frequency range from 169 MHz to 3600 MHz, the radio waves propagate quasi-optically and so the range is basically limited to the line of sight. Reflections and refractions can, by contrast, help to increase the range, so that a signal can still be received behind a mountain or a skyscraper. In buildings, similarly, reflections and refractions can also extend the range.

Wi-Fi and Bluetooth are considered to be among the best-known wireless technologies in everyday life. They are now used almost everywhere in our smart phones, tablets, TVs, internet radios, kitchen machines, smart watches and sports equipment. Many of these devices or objects in daily use are connected to each other or to the cloud with Wi-Fi and Bluetooth. The connection from the device to the access point is star-shaped, one to many. "Meshed" wireless networks are an alternative approach offering extended range through the relay of signals by devices and are found in the implementations of NeoMesh, ZigBee, Thread, Z-Wave, and many other wireless protocols. In this article we focus on radio technologies in the frequency range below 1 GHz (Sub-GHz), because these low frequencies can penetrate obstacles more effectively. NeoMesh[1] , NB-IoT, LTE-M, LoRaWAN, Mioty, Sigfox and many other radio protocols operate in Europe in the frequency range from 798 MHz to 960 MHz. Migration from LoRaWAN, Mioty and Sigfox to NeoCortec is straightforward in Europe, North America and many other regions because the antennas are the same. With NB-IoT and LTE-M, the effort is a little higher due to the larger frequency bandwidth. The lowest common denominator of all radio protocols in the Sub-GHz range is the antenna. The findings in this paper are general and have broad practical application. At 433 MHz, the antenna and ground plane become twice as large as at 868 MHz. For Bluetooth and Wi-Fi at 2400 MHz, everything can be about three times smaller. The focus in this study is on NeoCortec with NeoMesh www.neocortec.com in the 868 MHz band in Europe and 915 MHz in the USA with a outlook for NB-IoT and LTE-M, even though NeoMesh is also available in the 2400 MHz band. Antenna designs for Sub-GHz are more complex than for Bluetooth/Wi-Fi. The goal of this study is to show every IoT-developer the pathway to an integrated antenna explaining how to avoid common pitfalls.

1 Cf. NeoMesh technology overview: in: NeoCortec, 24.04.2019, https://neocortec.com/technology/ (retrieved on 10.01.2022).

Author: Harald Naumann
https://www.linkedin.com/in/naumann/

TABLE 1: *Examples for SubGHz frequency bands*

	3GPP band 12 US	3GPP band 20 EU	3GPP band 8 EU	SRD 869 MHz EU	ISM 915 MHz US
Frequency range (MHz)	699 - 746	791 - 862	880 -960	863 - 870	902 - 928
Bandwidth (MHz)	47	71	80	7	26
NeoMesh				X	X
LoRaWAN				X	X
NB-IoT EU		X	X		
GSM EU			X		
LTE-M EU		X	X		
LTE-M US	X				

ANTENNA = ENERGY CONVERTER

Antennas are converters of electrical energy into an electromagnetic waveform. Passive antennas behave reciprocally and thus work as transmitting and receiving antennas at the same time. Active antennas, which contain a low-noise amplifier (LNA) for the receiving antenna, are non-reciprocal antennas. An example of this is an active GPS patch antenna.

Antennas are used to transmit information via electromagnetic waves. An antenna is a quadripole connected to the radio module by two terminals, the other two have no physical connection and sit in free space. Without a fixed physical connection into free space, this part of the antenna is strongly influenced by its environment. The size of an antenna is primarily determined by the wavelength (λ). The lower the frequency, the larger the dimensions of the antenna.

ILLUSTRATION 1: *Antenna as quadripole*

A so-called Hertzian dipole[2] consists of two elements in the length of/. In a monopole, part of the dipole is removed. The missing part of the dipole is replaced by the mass surface (ground plane).

The minimum size of the mass surface is determined by the lowest frequency in the application. For this reason, devices with integrated antennas cannot be reduced in size at will. The migration of a PCB that was developed for higher frequency ranges, such as Bluetooth, to the lower frequency of 868/915 MHz used by NeoCortec[3] or NB-IoT/LTE-M is therefore not straightforward.

[2] Cf. Ellingson, Steven W.: 9.4: Radiation from a Hertzian Dipole, in: Physics LibreTexts, 09.05.2020, https://phys.libretexts.org/Bookshelves/Electricity_and_Magnetism/Book%3A_Electromagnetics_II_(Ellingson)/09%3A_Radiation/9.04%3A_Radiation_from_a_Hertzian_Dipole (retrieved on 10.01.2022).

[3] Cf. The NeoCortec wireless ad hoc network: in: NeoCortec, 24.03.2021, https://neocortec.com/ (retrieved on 10.01.2022).

A PCB that was designed for a Bluetooth radio module (2400 MHz) cannot simply be redesigned with a NeoCortec radio module (868/915 MHz). For NB-IoT in the 698 MHz to 960 MHz range, adapting a PCB designed for Bluetooth Low Energy or Wi-Fi is further complicated by the frequency bandwidth. The bandwidth of an antenna (the range of frequencies over which it operates correctly) in percent is calculated from the used bandwidth/centre frequency x 100%. The greater the bandwidth required and the greater the lambda/4 of the lowest frequency, the more difficult it is to develop or integrate the antenna.

TABLE 2: *Bandwidth of frequency bands*

	f1 (MHz)	f2 (MHz)	Bandwidth (MHz)	Centre frequency (MHz)	Bandwidth (%)	Lambda/4 fu1 (cm)
Bluetooth	2402	2480	78	2441	3,20	3,12
ISM 915 MHz	863	870	7	866,5	0,81	8,69
ISM 868 MHz	902	928	26	915	2,84	8,31
NB-IoT Band 8 & 20	880	960	80	920	8,70	8,52
NB-IoT Band 20	791	862	71	826,5	8,59	9,48
NB-IoT Band 8 & 20	791	960	169	875,5	19,30	9,48

HOW DO YOU CHOOSE A SUITABLE **ANTENNA?**

ANTENNA **PARAMETERS**

Antenna data sheets list various electrical and physical parameters in addition to the mechanical dimensions and the type of connection. There is no technical difference between chip antennas and self-constructed PCB track antennas. Even a piece of wire can act as an antenna. Regardless of how the antenna is shaped, the following parameters can be measured for all antennas.

Author: Harald Naumann
https://www.linkedin.com/in/naumann/

Antenna gain

The antenna gain is a relative value that refers to a reference antenna. The reference value is the received field strength of the selected antenna in the direction of reception relative to the received field strength of the reference antenna. The reference antenna is either a so-called isotropic antenna or a half-wave dipole. The isotropic antenna is an imaginary antenna which transmits uniformly in all directions (sphere). The gain is given in dBi. The "i" indicates the isotropic antenna as a reference.

The isotropic antenna can be compared to an incandescent lamp without a screen. The lamp would shine almost uniformly in all directions: It cannot emit any light in the direction of its socket. There it has a zero point. The incandescent lamp without a lamp shade, however, comes very close to the idealised isotropic radiator.

The second known reference antenna is the half-wave dipole. In contrast to the isotropic antenna, this can actually be constructed. The half-wave dipole has two zero points and does not radiate energy in these directions. If it is taken as a reference, the gain of an antenna is given in dBd. The "d" added to the unit dB indicates the half-wave dipole.

TABLE 3: *Antenna gain of different antennas*

Antenna	Gain [dBi] related to the isotropic antenna	Gain [dBd] related to the half-wave dipole
Monopole / Dipole	1,6	-0,6
λ/2 rotary radiator	3	1
Yagi antenna	5 - 15	3 - 12
Parabolic antenna	15 - 25	13 - 23

Values in dBi can be converted directly into dBd and vice versa. 0 dBd corresponds to 2.15 dBi. The confusion between dBi and dBd is the first pitfall awaiting the designer when comparing data sheets. If one antenna looks 2 dB better, this may only be due to comparison with the isotropic antenna.

An antenna is a passive component and cannot amplify. The gain of an antenna is always due to its directivity. The gain of the λ/2 omnidirectional antenna is due to the small beam angle of the antenna. With the 5/8 radiator, the gain is even greater and the beam angle even smaller. The directional effect can be seen most clearly with the Yagi antenna or parabolic antenna. Here, the energy is directed in one direction and almost nothing is radiated to the rear. However, the gain is always given in the main beam direction. The parabolic antenna is similar to the street lamp with reflector. The light is bundled and directed downwards.

Since this study considers portable devices or small devices with integrated antennas, the data sheets of the antennas offered always contain values around approximately 0 dBi or -2.15 dBd.

Antennas for mobile radio (GSM, LTE, LTE-M,NB-IoT) are always designed as antennas with multi-resonance. Good data sheets list the gain in the bands individually and not just the peak value in one of the bands. Even better is a graphical representation of the gain across all bands. A peak with a lot of gain in the middle of a band is of little use, because an IoT device should be able to transmit and receive approximately equally throughout the frequency range. That is where the next pitfall can be found. Some manufacturers state the peak value of the antenna gain in the data sheet without showing it as a peak value. A high peak value with a poor average antenna gain is not desirable for a mobile device. With a fixed sensor in the NeoMesh from NeoCortec, a high gain in one direction is also not useful because you do not know in which direction the next node is located that you will need to communicate with.

Beam angle of the antenna

The beam angle is specified for λ/2 antennas and other omnidirectional antennas or for directional antennas. It results from the points in the antenna diagram at which the gain decreases by 3 dB compared to the maximum in the main beam direction.

ILLUSTRATION 2:
Antenna gain and beam angle

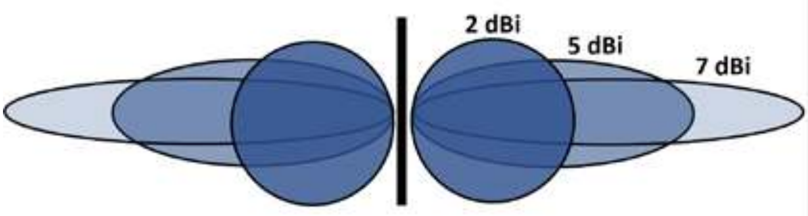
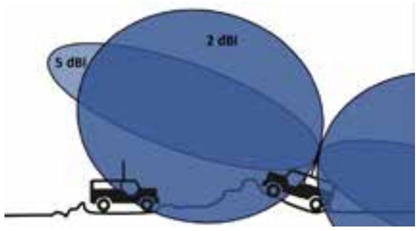


ILLUSTRATION 3:
Wrong beam angle



For integrated antennas, it is unusual to specify the beam angle. With IoT devices, the aim is generally to achieve the most uniform radiation possible in all directions. GPS patch antennas with their extreme directivity are an exception. Some antenna manufacturers show the directional pattern in 3D in their data sheets. Beam angle, directivity and antenna gain belong together. An antenna is a passive component and therefore cannot amplify, but only focus the light like a lens or a refractor in a lamp and direct it primarily in a preferred direction.

Standing wave ratio

The voltage standing wave ratio (VSWR) was previously used in high-frequency technology as a parameter to evaluate antennas, among other things. A low standing wave ratio value indicates that the antenna is sending little energy back to the generator (radio module). Standing wave ratio and return loss can be converted directly. The change of the standing wave ratio from 1.5 to 2 is often difficult to read in a diagram. The change of the value by 0.5 linearly is equal to the change of approximately 4.5 dB in the return loss. The delta of 4.5 dB is much easier to read. In this paper we will therefore primarily show the return loss in dB.

4 Cf. VSWR to Return Loss Conversion Chart: in: Everything RF, n.d., https://www.everythingrf.com/tech-resources/vswr (retrieved on 11.01.2022).

TABLE 4: *Comparison of standing wave ratio and return loss[4] .*

VSWR (:1)	Return Loss (dB)	Reflection Coefficient(Γ)	Mismatch loss (dB)	Reflected Power (%)	Mismatch loss (dB)
1.001	66.025	0.0005	0	0	99.99998
1.065	30.04	0.0315	0.00431	0.0992	99.90078
1.118	25.081	0.0557	0.01349	0.3102	99.68975
1.5	13.979	0.2	0.17729	4	96
2	9.542	0.3333	0.51142	11.1089	88.89111
3	6.021	0.5	1.24939	25	75
4	4.437	0.6	1.9382	36	64
6	2.923	0.7142	3.09876	51.0082	48.99184

Return loss

When an RF signal is fed to an antenna, part of the wave is reflected. The return loss (R) in the antenna data sheet indicates how much energy is lost in the reflection.

For antennas for NB-IoT, LTE-M, GSM, UMTS or LTE, a return loss of -6 dB at the bandedges is the goal. At -6 dB, 25 % of the energy is reflected from the antenna to the gener ator. For narrow band antennas, e.g. for NeoCortec, Sigfox, LoRaWAN orGPS/GLONASS, a return loss of -9.54 dB is aimed for and usually rounded to -10 dB.

The power that an antenna actually radiates is influenced by its return loss. With a return loss of -4.4 dB, 1.94 dB is reflected. If this 1.94 dB is only achieved with a complex matching network, this will add further losses to the 1.94 dB due to thermal losses in the matching network. On top of this, some of the real radiated energy will then be converted to heat by the plastic enclosure. Because all losses add up, a return loss of -6 dB is targeted for broadband antennas and a mismatch loss of 1.24 dB is accepted. The sum of all losses totalling 3 dB and more is not unusual.

This 3 dB more or less - and thus more or less range for the antenna - is in the hands of every IoT developer with the choice of antenna and its integration into the overall design. Internal antennas for NeoCortec in the 868 / 915 MHz band 20, on the other hand, often offer a return loss of better than -15 dB in almost the entire band.

Bandwidth of the antenna

The bandwidth of an antenna results from the delta between the lowest frequency, at which a return loss of -6 dB or -10 dB for the lowest and the highest frequency is achieved. The return loss curve shown below is a measurement of the PCB antenna of the Gillette order button listed in the IoT M2M Cookbook[5] . This button was designed for GSM, and the antenna also covers NB-IoT/LTE-M in band 8 and band 20. It shows that developers can build their own broadband antennas that have good performance characteristics.

[5] Naumann, Harald: IoT / M2M Cookbook, in: akorIoT, 10.01.2014, https://www.akoriot.com/iot_books/ (retrieved 12.12.2021).

ILLUSTRATION 4: *Bandwidth with -6 dB return loss of the GSM / NB-IoT / LTE-M PCB antenna at Gillette order button. Source: IoT / M2M Cookbook.*

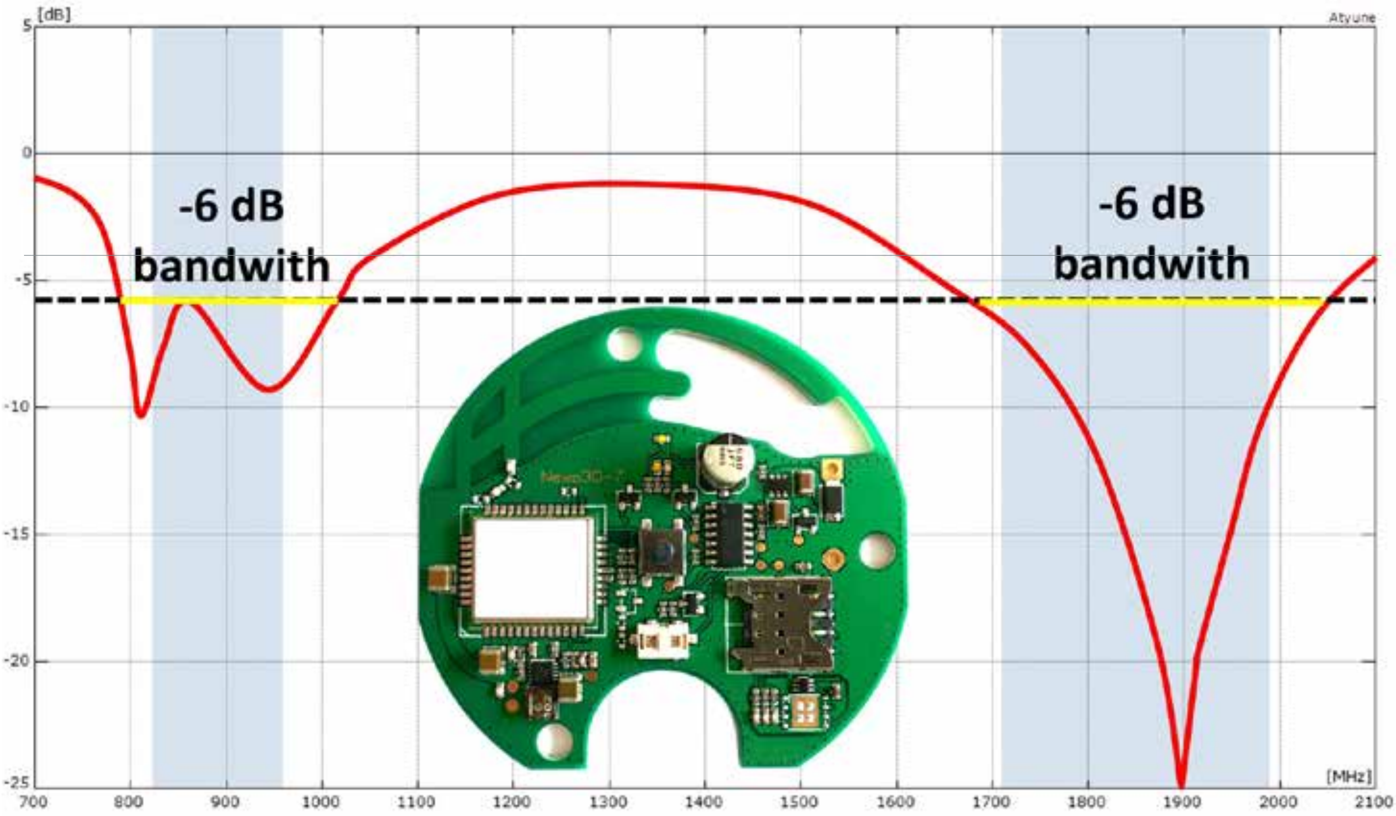
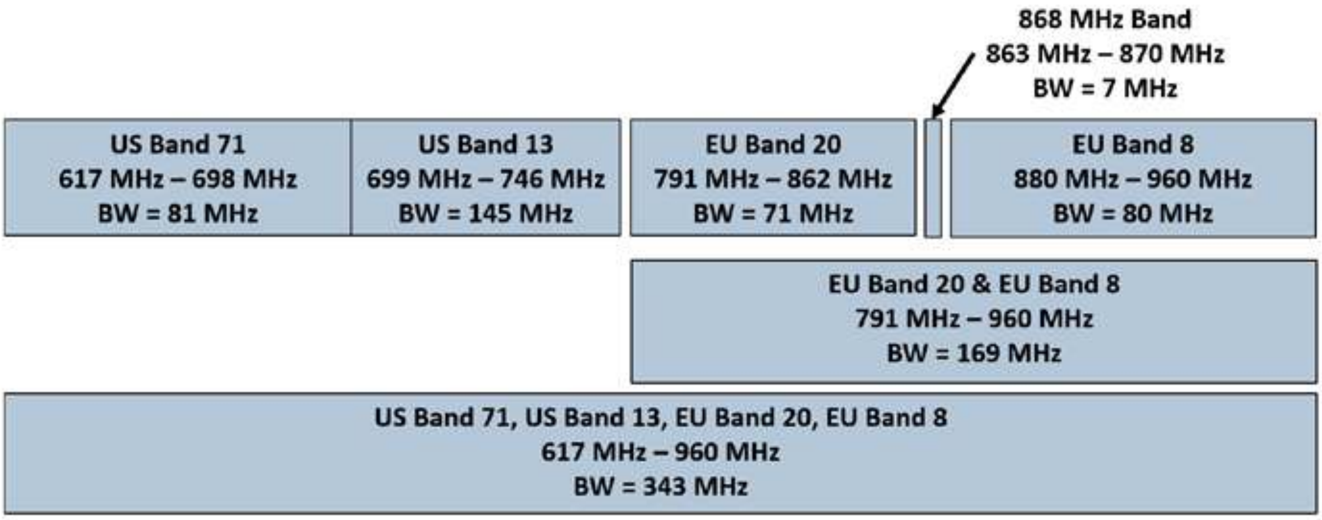


ILLUSTRATION 5: *Frequency range and necessities for NB-IoT in USA/ Europe and licence-free 868 MHz band for Neo-Cortec, LoRaWAN, Sigfox in Europe. Source Harald Naumann.*



Antenna efficiency

The efficiency of an antenna is the ratio of the output power delivered to the antenna to the output power radiated by the antenna. Good return loss does not necessarily mean that the power that is not reflected is actually radiated. If the antenna is replaced by a 50 Ω resistor, then nothing is reflected and the RF energy is completely converted into heat. Since antennas are also lossy, part of the supplied energy is not radiated but converted into heat in the antenna. In the simulation of the NB-IoT/ LTE-M, this is also referred to as Total Efficiency and Radiated Efficiency.

"Radiated efficiency is the ratio of the power radiated by the antenna to the power that gets into the antenna. The power not radiated is dissipated in conductor and dielectric losses.

Total efficiency is the ratio of the radiated power to the power incident from the network; it includes both the reflection loss and dissipation of power energy in the antenna." [6]

[6] NCf. AWR Microwave Office Measurement Catalog: Radiation, Mismatch, or Total Efficiency: Efficiency: in: AWR, n.d., https://awrcorp.com/download/faq/english/docs/Measurements/efficiency.htm (retrieved 10.01.2022)

Antenna diagram

Even if the specifications of an antenna look good in the data sheet, the antenna does not automatically deliver those good results in a real application. The evaluation boards of antenna manufacturers are always measured without an enclosure and on a reference ground plane. If the ground plane is shortened, the bandwidth of the antenna in the Sub-GHz range is drastically reduced. Plastic near the antenna also affects the bandwidth. The battery used in the circuit also has an influence.

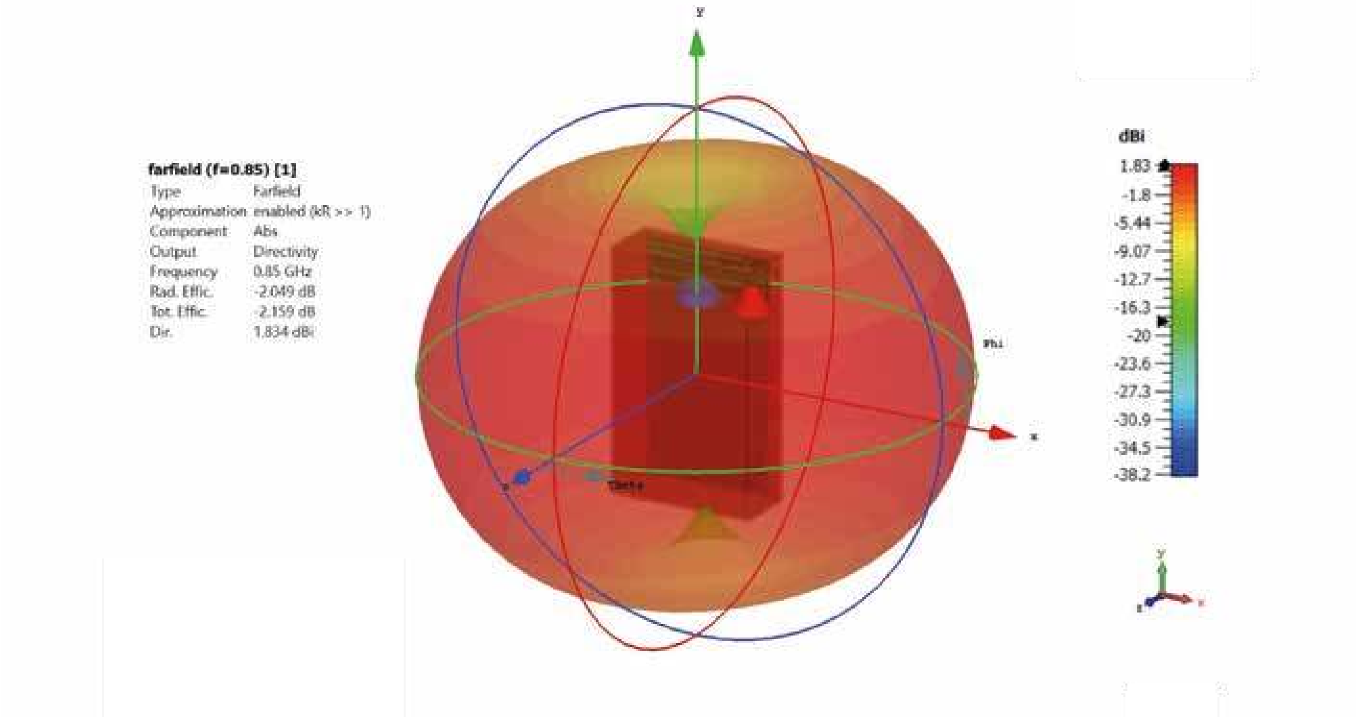
The actual propagation of the waves depends on many parameters and can only be estimated approximately with a lot of experience. If you want to know exactly, you can also measure the antenna pattern of your device. For this purpose, it is not necessary to install or rent an expensive anechoic measuring chamber, there are also measuring methods, e.g. the Radiation Measurement System (RMS) by MegiQ, which can be purchased at much lower cost and which also require less space.

Size of the reference ground plane

In a dipole, one part of the antenna points to the left and the other to the right. The length of the two parts is given by the transmitting frequency. With a monopole, one part of the dipole is missing. The ground plane replaces the missing part. The length of the PCB used for the ground plane is also dictated by the target transmission frequency. If the area or the length of the PCB for the ground plane is too small, the bandwidth of the monopole decreases.

Data sheets from well-known antenna manufacturers show the data of monopole antennas with the reference ground plane and a shortened ground plane. However, shortening should be avoided if possible. A close look at the manufacturer's specifications makes it clear that a large PCB leads to good results in antenna efficiency. The size of the test boards is certainly not chosen randomly by the manufacturers. Sometimes a very long PCB is chosen in order to achieve good return loss at low frequencies.

ILLUSTRATION 6: *Simulation of an antenna for a NeoMesh sensor at 868 MHz*



Summary of antenna parameters

Developers have to consider many antenna parameters, depending on the target application. The highest possible antenna gain is not always an advantage. Especially for mobile applications where a wide beam angle or omnidirectional radiation is necessary for a reliable function. Permanently installed sensors using a mesh networking approach such as NeoMesh from NeoCortec do not know in which direction the next sensor is located and should therefore not have a preferred direction for most applications. The simulation of a trace antenna for NeoMesh was carried out in the European licence free band at a frequency of 868 MHz. The gain is mostly around 0 dBi in all directions. The maximum reaches 1,89 dBi. The antenna is based on a typical monopole with 1.6 dBi gain. The maximum of 1,89 dBi is caused by the overall construction, which leads to a maximum in directivity in the red area of the graph (Dir = Directivity in the diagram).

The bandwidth of an antenna is an important parameter. If the data sheet of the antenna does not show enough bandwidth, then it is technically not possible to achieve good radiation. If the return loss is too high, this can lead to harmonics. Harmonics then lead to a product not being able to achieve CE/RED certification. An antenna with too low a bandwidth must not be considered a candidate during selection. The antenna efficiency stated in the data sheet is only a theoretical value without the losses in the enclosure. The manufacturer cannot know which material is used and what the consequent losses will be. If the efficiency of the antenna is poor without an enclosure, it will not be better with an enclosure. A good return loss indicates that not much energy is reflected, however this does not mean that all the energy is also radiated. The antenna effectiveness of the IoT device can only be determined with measurements.

Evaluating antenna data sheets and application notes correctly

The first thing to look for in the data sheet, application note or a series of measurements is always the bandwidth. The developer must determine for themselves whether they are aiming for -6 dB or -10 dB return loss. If the bandwidth according to the data sheet is too small, then the data sheet can be safely filed away.

If -6 dB return loss was selected, then the second target should be at the lowest frequency of the antenna. If this is already too low for the application, then it is necessary to shorten the antenna. However, it is impossible to shorten the structure of purchased chip antennas, for example so such an antenna could not be used. In the case of self-

Author: Harald Naumann
https://www.linkedin.com/in/naumann/

built PCB antennas, a scalpel can be used on prototype to scrape away some of the ground plane to shorten the antenna to the correct size. For mass production, the antenna structure can then be correctly printed as part of the layout.

However, care should be taken when evaluating the data sheet. The antenna gain is defined at the point of maximum performance and usually looks good. If the antenna manufacturer tricks a little, then an antenna that was originally developed for GSM quad band, with the lowest frequency of 824 MHz may be declared to be an antenna for NB-IoT or LTE. However, the return loss of the antenna might be high at 798 MHz meaning that only a small part of the transmission energy is radiated, effecting the range and power consumption of the final product.

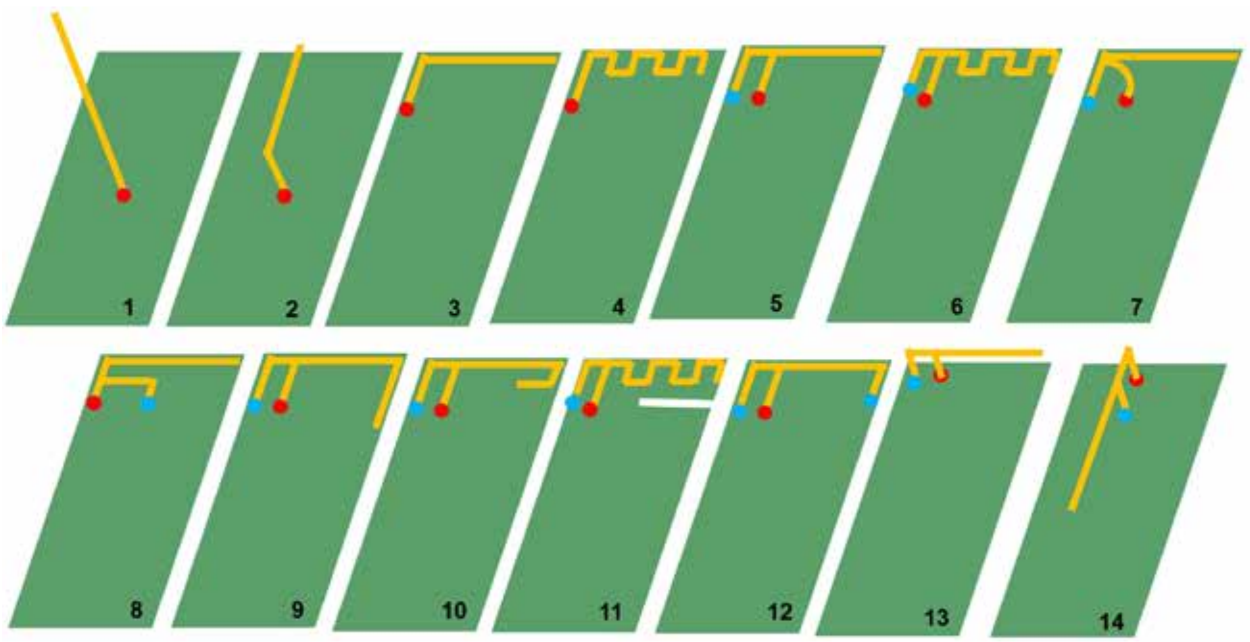
What is much worse, is that when the return wave hits the amplifier output of the radio module the harmonics generated there can easily exceed the limits of the Radio Equipment Directive, meaning that the final design cannot legally be sold, resulting in delays and expensive redesign of the antenna.
When selecting antennas, developers should also bear in mind that the enclosure with its plastic slightly shifts the centre frequency of the antenna and also usually increases the bandwidth a little.

Once an antenna has been selected based on the data sheet, its return loss should be measured on the evaluation board in the enclosure of choice. If this test is also completed satisfactorily, the antenna is then mounted on an empty pre-production PCB in the plastic housing. If this test is also positive, the chip antenna or also the PCB antenna can be adopted in the layout of the PCB for the circuitry of the device.

A network analyser (VNA - Vector Network Analyser) is needed to measure the antenna parameters. In addition to the classic design as a laboratory measuring device, PC-based measuring devices are also offered for this purpose, which are not quite as expensive.

DEVELOPMENT OF **A PCB TRACK ANTENNA**

ILLUSTRATION 7: *Overview of different L- and F antennas*



This section explains how to migrate a design from a dipole to a monopole antenna. A dipole antenna (from Latin di 'two') is an antenna that often consists of two straight metal rods. A monopole antenna, also called a Marconi antenna after its inventor Guglielmo Marconi, is a vertical antenna above a large metal surface called a ground plane. Unlike a dipole antenna, it is fed asymmetrically. The integrated antennas in our smart phones, tablets, TVs, internet radios, food processors, smart watches, sports equipment and also IoT devices are almost always monopole antennas. A straight stretched antenna above the ground plane as shown in number 1 above is rather rare, because the necessary installation space is missing. The red dot symbolises the feed point of the antenna and the blue dot the short circuit point of the antenna. This text serves as an introduction and versions 3 to 10 are explained in more depth in further sections. Version 11 to 14 and many more antennas are planned for the updoming "IoT Antenna Cookbook".

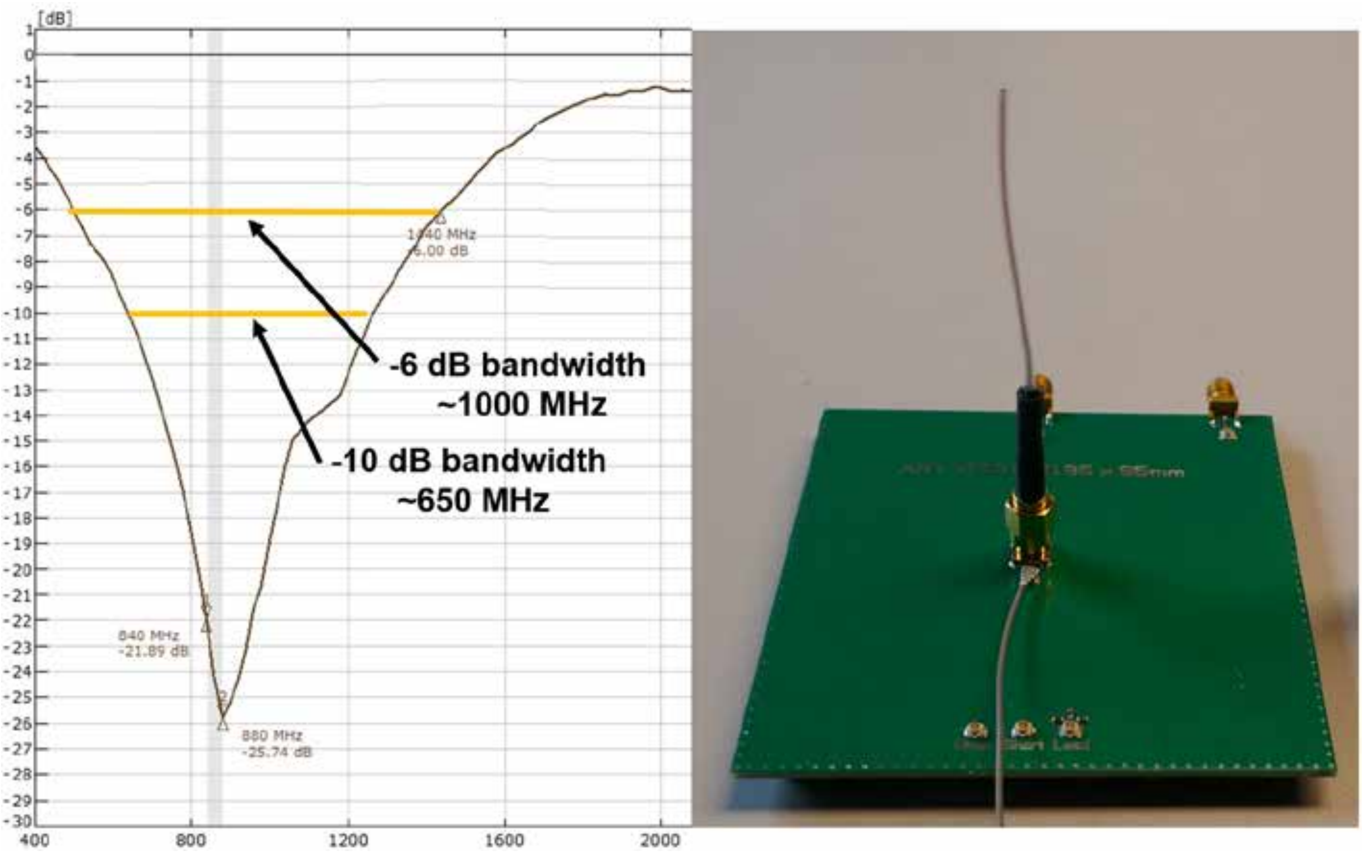
Number 1 was implemented in the measurement setup below. The test board with an edge length of 85 mm x 85 mm was used as a reference board to measure and compare antennas with SMA connectors. In this case, the shield of an RF cable with SMA connector was removed and the inner conductor was shortened so that a resonance frequency with a centre frequency of 880 MHz was created. The bandwidth of the antenna is approximately 1000 MHz at -6 dB bandwidth and approximately 650 MHz at -6 dB. The antenna thus covers all cellular bands worldwide for NB-IoT with 617 MHz to 960 MHz. The peak return loss is 25.74 dB.

The bend in the radiator of antenna number 2 means that is termed an L-antenna, and this angle leads to the reduction of the antenna bandwidth. This effect is not explained further in this study.

Antenna 3 shows the L-antenna integrated into the PCB. The L-antenna is a very simple antenna structure. Antenna 4 shows an L-antenna with a meander structure to shorten the radiator as more bends reduce the bandwidth again. Any reduction in the installation space of the antenna automatically leads to a reduction in the bandwidth. Chu already specified in 1947 in his antenna theorem that the reduction of installation space leads to a reduction of the bandwidth.

Antennas 5 to 10 show different versions of inverted F antennas (IFA) or IFA with meander (MIFA). Version 11 shows an inverted F antenna again. Version 12 is an IFA short-circuited at the end and is called a loop antenna and therefore shows two short-circuit points. Version 13 is an IFA brought into the third dimension. Version 14 again shows an IFA rotated 90 degrees. Most chip antennas use the principle of F-antennas. This can be recognised by the short-circuit point of the antenna, often via a coil to ground.

ILLUSTRATION 8: *Testing of DIY wire antenna on test PCB*



Author: Harald Naumann
https://www.linkedin.com/in/naumann/

COMPARISON OF THE DESIGN NOTES **WITH PCB ANTENNAS FROM TEXAS INSTRUMENTS**

We limit the comparison of the antennas in this study to the antennas in the Design Notes from Texas Instruments. Any reader is welcome to fill the empty columns with other antennas. We compare the technical parameters and address the missing references. Afterwards we explain step by step the missing hints with our own series of antenna simulations. The goal is that the wireless IoT developer can take any L or F antenna from this study and adapt and optimise it according to their wishes.

TABLE 5: *Comparison of the parameters of the design notes of Texas Instruments*

	Antenna 1	Antenna 2	Antenna 3	Your antenna
	TI DN038 [7]	TI DN023 [8]	TI DN024 [9]	
Type	L antenna with helical structure	Inverted F antenna wwith meander	L antenna with S structure	
Centre frequency	868 MHz	868, 915, 955 MHz	868, 915, 955 MHz	
Impedance	~10 Ω	~50 Ω	~50 Ω	
Return Loss peak				
- 10 dB bandwidth @ 868 MHz	40 MHz	40 MHz	88 MHz	
Length of radiator	+++	+++	+++	
PCB thickness	0.8 mm	0.8 mm	0.8 mm	
PCB size	Missed	31 mm x 45 mm	43 mm x	
63 mm		0.0992	99.90078	
Antenna area with space to GND	12 mm x	0.3102	99.68975	
19 mm	20 mm x 43 mm	25 mm x	96	
38 mm		11.1089	88.89111	
Value Epsilon R FR4	Missed	Missed	Missed	
Efficiency	-1.83 dB	Missed		
Efficiency	66.55%	Missed		
Smith Chart	Given	Missed	Given	
Gerber files	+++	+++	+++	
Effect: type of FR4	Missed	Missed	Missed	
Effect: thickness of FR4	Missed	Missed	+	
Effect: distance to enclosure	+	+	+	
Effect: size of ground plane	+	+	++	
Effect: length of radiator	+	+	+	
Effect: width of radiator	Missed	Missed	Missed	
Effect: type of plastic material	Missed	Missed	Missed	
Hand effect	Missed	Missed	Missed	
Release date	16.04.2007	17.11.2012	16.04.2007	

The parameters in the table are briefly explained below. +++ means very good. ++ means good. + means could be better.

7 Cf. Wallace, Richard: Design Note DN038 Miniature Helical PCB Antenna for 868 MHz or 915/920 MHz, in: Texas Instruments, 16.04.2007, https://www.ti.com/lit/swra416 (retrieved 10.01.2022).

8 Cf. Kervel, Fredrik: Design Note DN023 868 MHz, 915 MHz and 955 MHz Inverted F Antenna, in: Texas Intruments, 17.11.2017, https://www.ti.com/lit/pdf/swra228 (retrieved 10.01.2022).

9 Wallace, Richard: Design Note DN024 Monopole PCB Antenna with Single or Dual Band Option, in: Texas Instruments, 16.04.2007a, https://www.ti.com/lit/swra227 (retrieved 10.01.2022).

Type of antenna
In this study, only L-antennas, inverted F antenna (IFA), S-antennas and a few combinations of these are considered. The inverted-F antenna is a further development of the quarter-wave monopole antenna. The S-structure is an L-structure which has been shortened by the serpentine lines in the necessary area. In the respective pictures, the letters L, F and S are visible from the shape of the antenna. All three TI documents specify that nothing should be changed. This leads to the fact that the structures are usually not changed by IoT developers. However with the right knowledge, explained in further sections of this study, changes can be made to improve the performance of the antennas to better suit real-world applications.

Centre frequency
The focus in this paper is on the 868 and 915 MHz frequencies. In every antenna data sheet or application note, you will find the centre frequency. Sometimes you have to read it from the graphs themselves.

Impedance
The impedance can now be read from the Smith chart. Antenna 1 shows only 10 Ω impedance and therefore needs a matching network to transform to 50 Ω. This is associated with high losses and is reflected in the efficiency of -1.83 dB which is equivalent to 66.55 %. An antenna with an impedance of 50 Ω shows a peak value of -25 dB return loss and better. The two values are therefore connected.

Peak Return Loss
This value must usually be read from the diagram. Whether it is -25 dB or -35 dB is no longer important for the amount of energy radiated.

Frequency bandwidth
This value is very important. The 866 MHz band in the EU is only 7 MHz wide. The 915 MHz band in the USA is much wider at 26 MHz. The selected antennas cover the required bandwidth of 7 MHz for Europe. If the design is for both US and European markets then cover is critical across both bands and it is only possible with the TI DN024.

Length of the radiator
The length of the radiator is well documented. The length determines the centre frequency.

Thickness of the PCB
The thickness is mentioned several times as 0.8 mm. The standard is 1.55 mm. The effect of a change in thickness is not explained in detail for all antennas in the table.

Size of the PCB
The size of the PCB is not specified for the first antenna. The size of the PCB influences, among other things, the centre frequency of the antenna because of the size of the ground plane.

Installation space of the antenna
The necessary space can be easily seen in the drawings. Antenna 1 was designed to use as little space as possible.

Epsilon R of the FR4
The value is not mentioned and has an influence on the centre frequency and the strip line.

Efficiency
The antenna effectiveness is mentioned in dB and in percent for antenna 1 and not mentioned for the others. As noted above, 66.55 % or -1.83 dB is a very poor value.

Smith Chart
The Smith Chart is only shown for antenna 1.

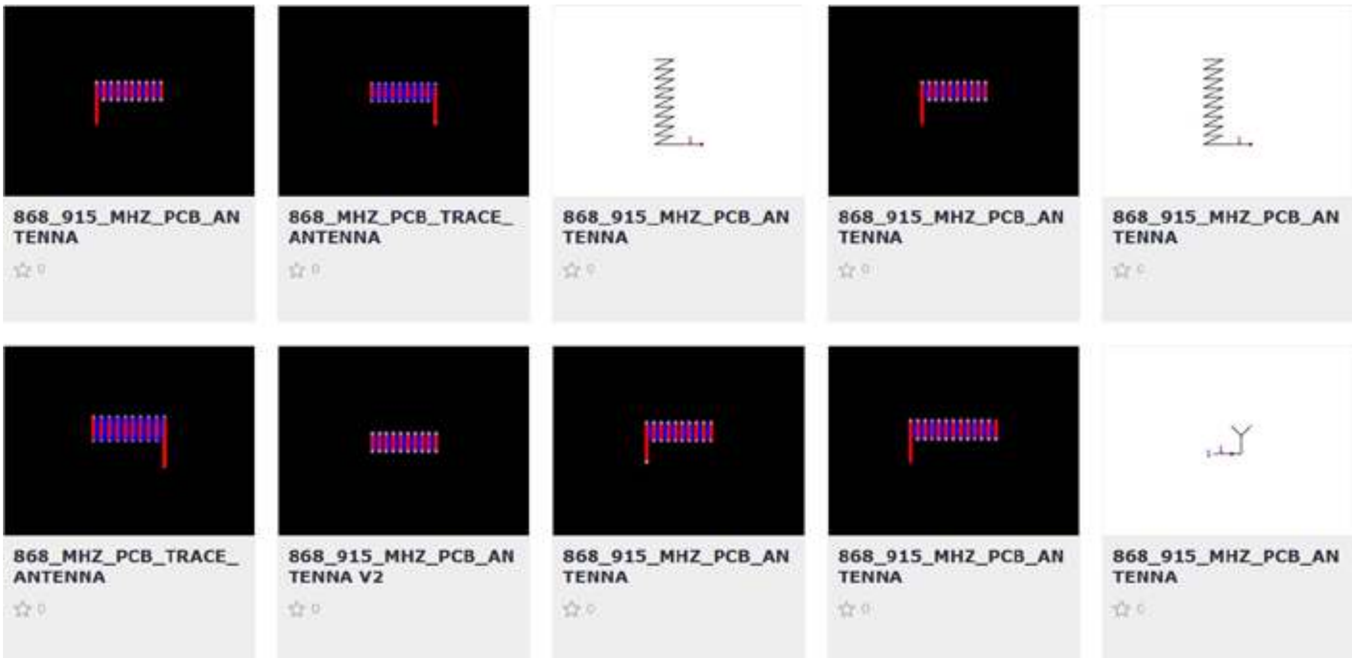
Gerber files
The Gerber files are available for download.

Effects influencing the antenna
The effects that influence the antenna are mentioned only slightly or not at all. All three PDFs say not to change the antenna structure but at the same time they say to change the antenna. Any modification is limited to lengthening or shortening the radiator. There is no mention of adjusting the impedance or the frequency bandwidth.

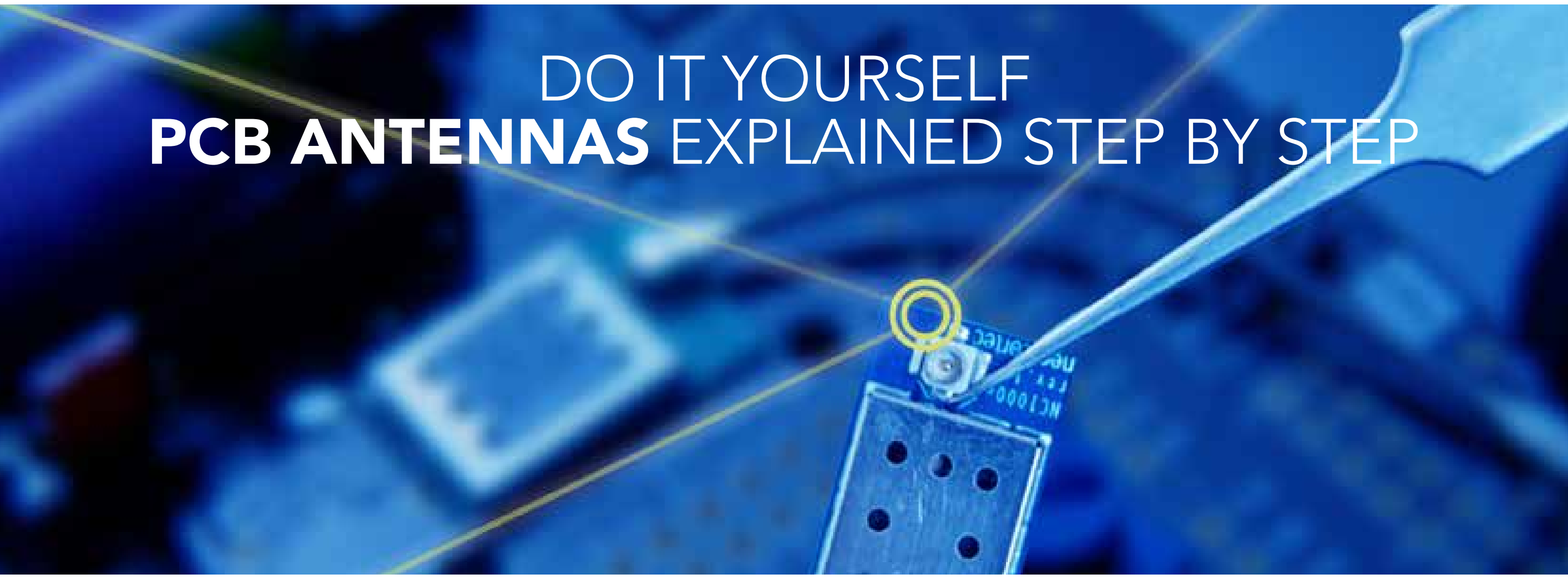
Results based on the three PDFs
The result is that hardware developers publish toothless copies of the three antenna layouts on the Easyeda website without making any change to the layout. The author of antenna 1 (TI DN038) has written that nothing should be changed. These sentences have been copied by the authors of TI DN023 and TI DN024. Hardware developers follow the instructions like lemmings and wonder why antenna 1 (TI DN038) works badly or not at all. The screen shot from EasyEDA[10] shows nine 1:1 copies of the antenna from the design note DB038. The keywords for the search were 868, MHz, PCB and antenna. If you open other pages you will find even more copies. None of the developers have made any changes. The whole thing is repeated with antenna 2 and 3.

[10] Cf. EasyEDA - Online PCB design & circuit simulator: in: EasyEDA, n.d., https://easyeda.com (retrieved 10.01.2022)

ILLUSTRATION 9: *L-antennas with helix structure based on DN038.*



DO IT YOURSELF **PCB ANTENNAS** EXPLAINED STEP BY STEP



In order to better understand the antenna structures of the Design Notes from Texas Instrument (TI), we break down the antennas into as many components as possible in this secsion, and explain each change to the antenna structure or boundary conditions step by step.

TABLE 6: *Parameters of the materials in the antenna simulations*

	Specification	Remark
Size of the PCBs	55 mm x 85 mm	Size of a credit card
Free space for the antenna	14 mm x 55 mm	
Distance of the antenna to the edge of the PCB	2 mm	12 mm x 51 mm net area for the antenna
Distance of the antenna to the edge of of the board	0 mm	
Thickness of PCBs	1.55 mm	
Epsilon R FR4	4.3	3.8 - 4.5 is possible
Tan Delta FR4	0,025	
Epsilon R plastic ABS	2.8	
Tan delta plastic ABS	0.008	
Thickness of copper	0.35 mm	
Solder resist	-	Not used in the simulation

The size of the PCBs was set to the size of a credit card (business card) for two reasons. Everyone can imagine 55 mm x 85 mm because it is such a familiar shape. 85 mm minus 16 mm for the free space results in a length of only 69 mm for the ground plane. Lambda/4 of the considered frequency ranges, however, is in the range from 83 mm to 95 mm. With a length of only 69 mm, the ground plane is already shorter than Lambda/4. That this is already critical will become clear in the following sections.

In each section, only one parameter is usually changed to look at the effect of this single change in more detail. The effect on return loss, antenna impedance, bandwidth, radiated power and antenna efficiency is explained. In order for the chosen antenna structures to work, a certain distance between the antenna structure and the edge of the enclosure must be maintained. If the plastic enclosure were to come too close to the antenna structure, then this would lead to a massive detuning of the antenna. We address the influence of the enclosure on any antenna structure at the very end of the multiple simulations.

L-ANTENNA WITH CHANGE OF DISTANCE OF RADIATOR TO GROUND PLANE (A1)

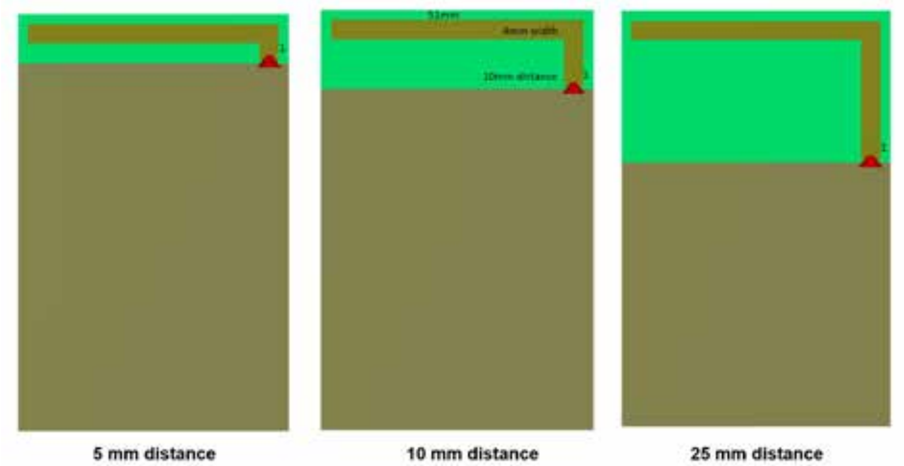
The extremely small helix antenna in TI's Design Note is based on an L-antenna integrated in the PCB. To understand TI's antenna structure, we first look at an L-antenna without the shortening resulting from a helix structure.

In the first simulation, we change the distance of the antenna radiator to the ground plane. Since the size of the PCB should not be changed, the mass surface below the antenna must inevitably become smaller. Changing the mass surface also has an effect on the antenna's centre frequency. Furthermore, the length of the radiator parallel to the ground plane was not changed. This means that with increasing distance, the effective antenna radiator becomes longer and longer and thus the centre frequency of the antenna becomes lower. Lengthening the antenna radiator inevitably leads to a lower frequency for all antenna structures. We will not go into this effect in this simulation.

In this simulation we explain that the effect of changing the distance between the antenna radiator and the ground plane strongly affects the impedance of the antenna.

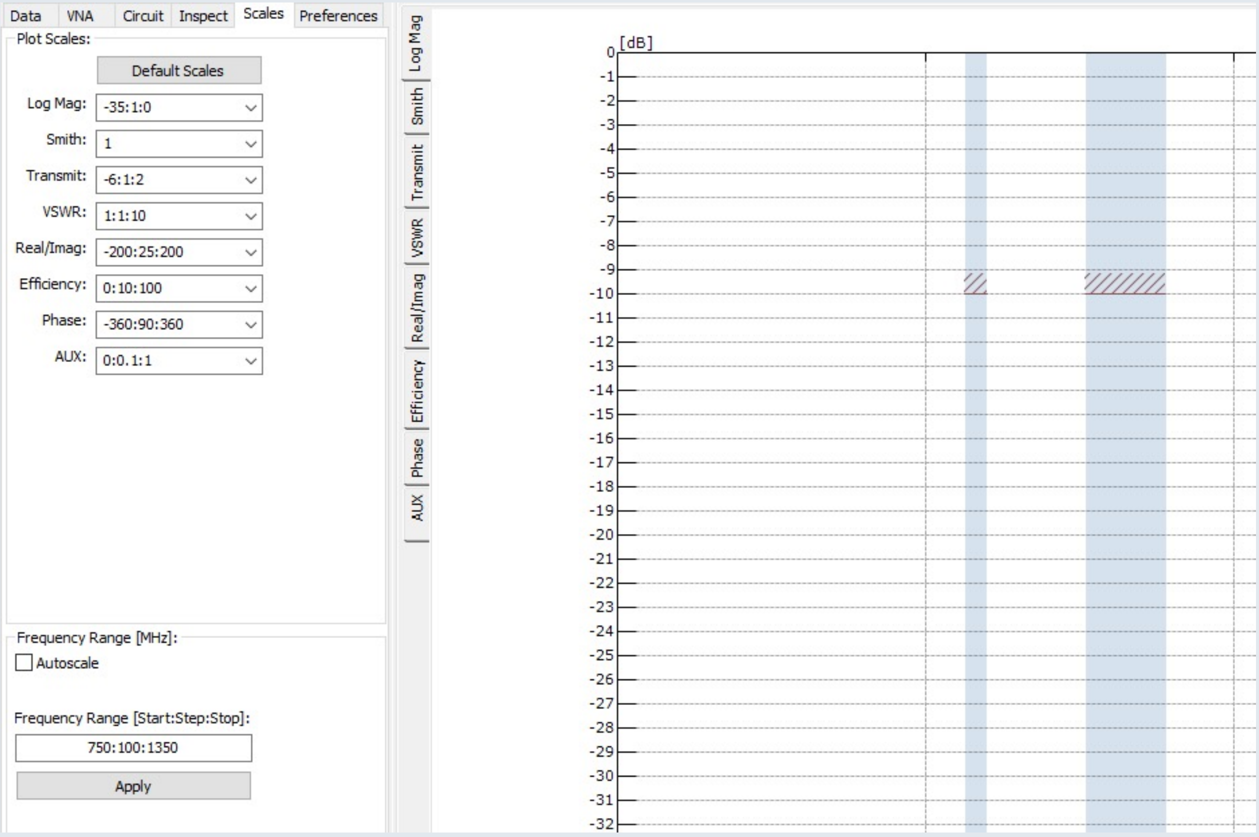
Before we explain the effect in more detail, let's look at the choice of colours. The colours were chosen to create the highest possible contrast. The distance of the radiator to the ground plane was changed in the illustration in steps of 5 mm. The largest distance, 25 mm, is shown in the red curve. The colours green, blue, black and pink show the distances 20 mm, 15 mm, 10 mm and 5 mm. The chosen colours will be repeated in the same order in the following simulations. If more than five curves are required for explanation, additional colours will be added.

ILLUSTRATION 10: *L-antenna with change of distance of radiator to ground plane (A1)*



Author: Harald Naumann
https://www.linkedin.com/in/naumann/

ILLUSTRATION 11: *Setup of the scales at software Atyune*

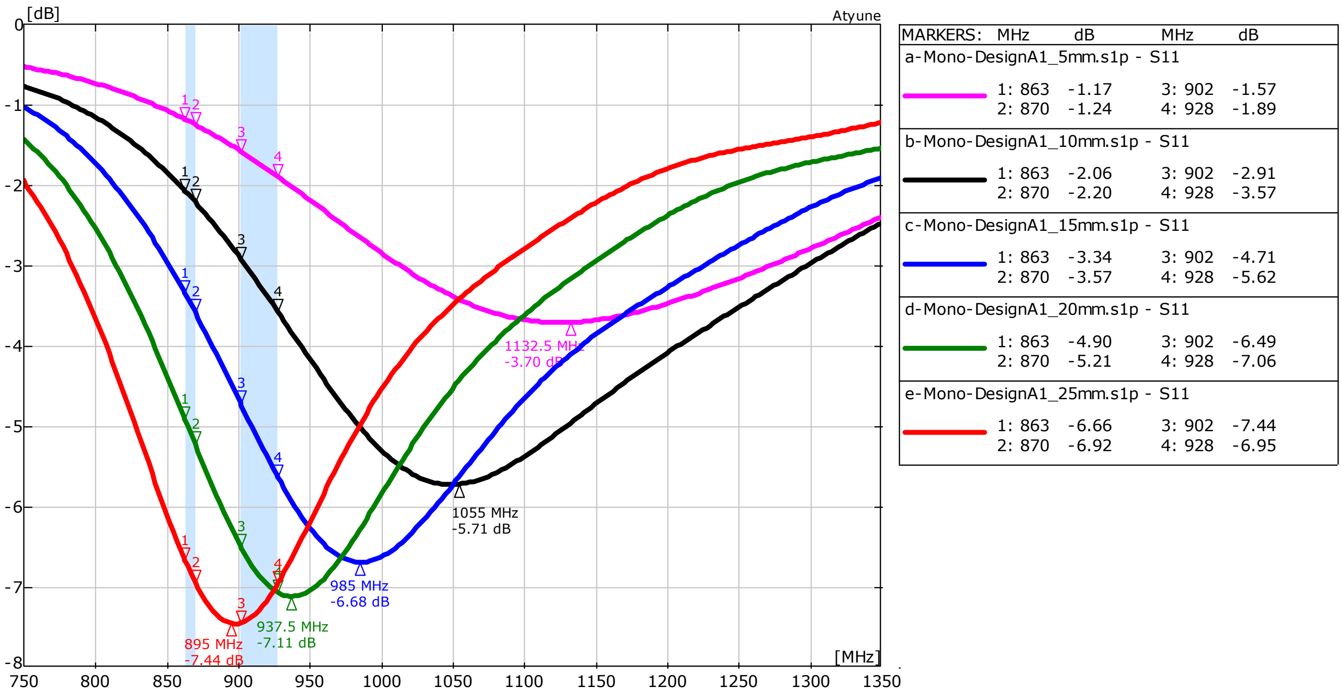


The two areas marked in light blue show the frequency range for 868 MHz (863 - 870 MHz) in Europe and 915 MHz (902 - 928 MHz) in the USA. From the two marked areas it is clear that the bandwidth for an antenna in the licence-free band near 900 MHz in the USA must be significantly higher than in Europe. We will discuss the frequency ranges for NB-IoT and LTE-M later. The findings from the simulations in the two licence-free bands also apply to the licence-required bands. The greater the bandwidth required in a frequency range, the more difficult it is to achieve the necessary bandwidth on a small PCB. Antenna designs for the USA are therefore somewhat more complicated than for Europe. If one antenna structure targets the range for both regions, then this structure must reach from 863 MHz to 928 MHz and thus cover 65 MHz. However, an antenna design that covers both frequency ranges at once is ruled out in the design note from Texas Instruments for the L antenna with helix structure.

The screen shot shows one of the many menus under Atyune[11] . By default, Atyune uses auto scale. The frequency range in the display is adjusted to the range in the Touchstone file. The smaller the range, the better you can read the values. If you choose auto scale, it starts at 0 MHz. However, we are looking at antennas in the range of 750 MHz to 1350 MHz. When the return loss curve approaches 0 dB, a lot of energy is reflected and not radiated. In the graph below, the range was limited to 750 to 1350 MHz. Log-Mag can also display values above 0 dB. Since this is impossible with antennas, and the maximum value can be 0 dB, we have limited it to 0 dB. In the negative range -35 dB is not unusual. Since the L-antenna only has a maximum of approximately -7 dB, we have limited it to -8 dB. We always adjust the frequency range and Log-Mag in the following simulations. The priority is the readability of the curves after printing in PDF format.

[11] Cf. Atyune - Home: in: Atyune, n.d., https://www.atyune.com/ (retrieved 10.01.2022).

ILLUSTRATION 12: *Return loss of the L-antenna with change of distance of radiator to ground plane (A1)*

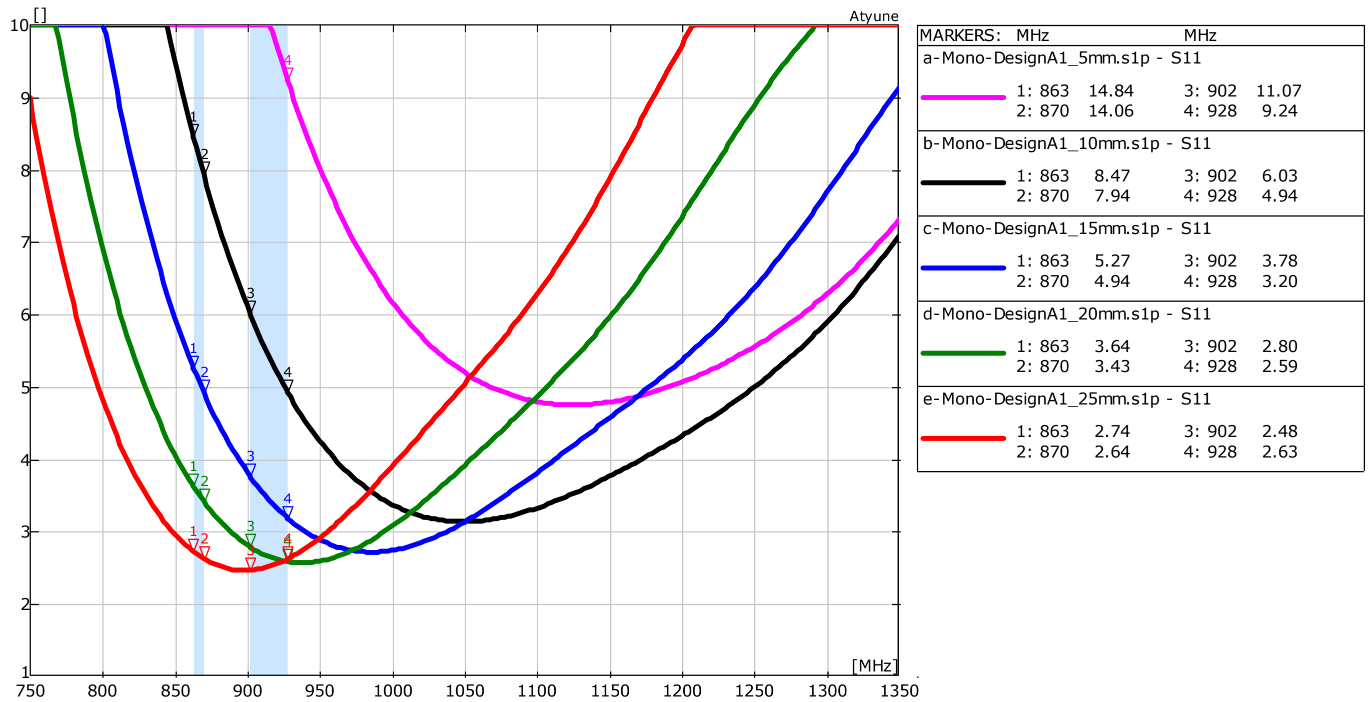


The Atyune software automatically places the numbers 1, 2, 3 and 4 on the corners of the selected frequency bands. Since we have selected the frequency band for the USA and Europe, there are automatically four corner frequencies which are marked with numbers. These markings are not important for the first considerations. Later we will use the software to simulate a matching network for the antennas.

The figure shows the return loss of the simple L-antenna. The return loss and the standing wave ratio (VSWR) of an antenna are equivalent, however because the standing wave ratio is shown with a linear curve, it is much more difficult to read than the return loss which is logarithmic. The illustration of the standing wave ratio is therefore only shown once at this point in this study.

All simulations are available at www.akoriot.com as a download in Touchstone format. The Touchstone file can be visualised differently with Atyune. With a small-band antenna for 868 or 915 MHz, a return loss of -25 dB at the peak is not unusual. The more negative the value in dB for the return loss, the closer we are to the desired 50 Ω impedance. With a large distance of 25 mm from the ground plane, only -7.44 dB can be achieved as a peak value for the return loss. If the distance is reduced in 5 mm steps, the return loss of the antenna deteriorates step by step. A value of -7.44 dB indicates that the impedance of the antenna is definitely far away from the requested 50 Ω.

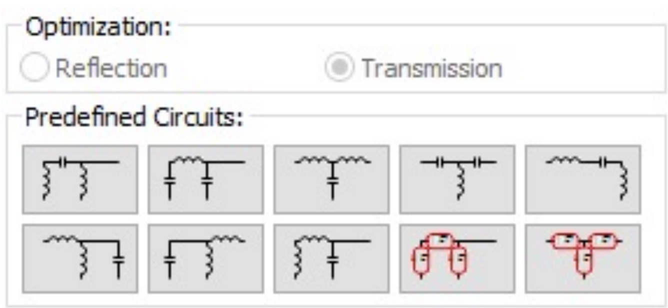
ILLUSTRATION 13: *VSWR of L-antenna with change of distance of radiator to ground plane (A1)*



The simulation software CST Studio Suite[12] used in this study or a good Vector Network Analyser allows the export of data in the Touchstone exchange format. Touchstone files have the extension .sNp, where N indicates the number of ports. The measurement results of an antenna or even the simulation of an antenna ends with ".s1p" because antennas have only one port. The data of a measurement object with two ports, such as an attenuator, has the ending "s2p". The data of an object with three ports, such as a directional coupler, has the ending "s3p". The names for the files have been chosen appropriately. "Mono_DesignA1" indicates that it is antenna A1 in the long list of antennas in this discussion. "5mm", "10mm", "15mm", "20mm" and "25mm" in the file name names the distance of the radiator from the ground plane. From the original 16 simulations with 16 distances, only 5 were visualised. The mechanical change to the antenna structure or PCB is documented in the name of the S1P file. The (A1) in the heading shows the name of the order A1. A1 is also found in the name of the S1P file. This ensures that readers with access to all simulations can later visualise the files themselves. If the simulations are updated or supplemented, they can be easily sorted and compared. The Atyune software is also able to automatically calculate a matching network for the antenna and visualise the result. Atyune knows two types of matching.

12 CF. CST Studio Suite 3D EM simulation and analysis software, in: Dassault Systèmes, n.d., https://www.3ds.com/products-services/simulia/products/cst-studio-suite/ (retrieved on 20.01.2022).

ILLUSTRATION 14: *Atyune: selection of reflection and transmission*

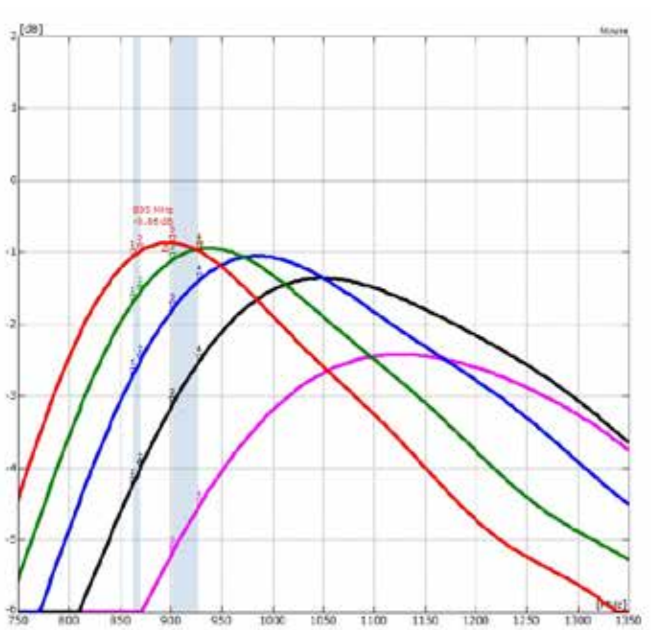


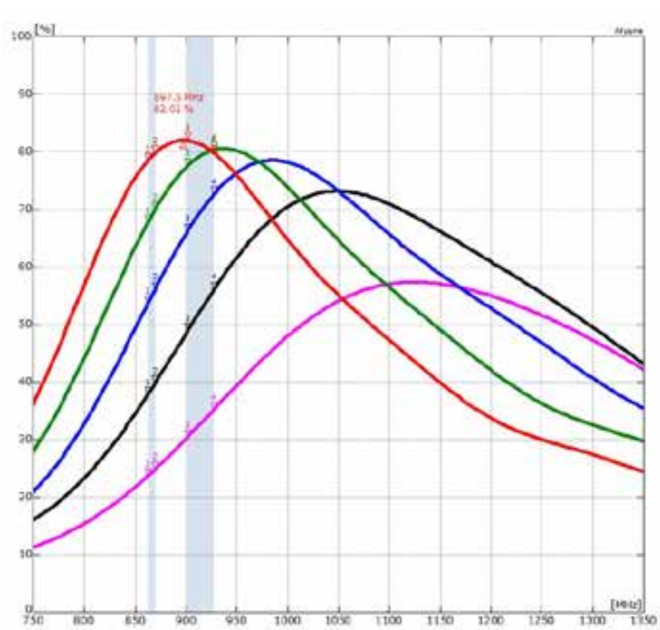
Author: Harald Naumann
https://www.linkedin.com/in/naumann/

Reflected:
In this case, the automatic matching routines try to minimise the reflection parameter in the selected frequency bands. This method is equivalent to the one typically used when optimising by hand with a VNA. However, one must be very careful when doing so. If you are not careful you will reach a perfect 50 Ohms impedance, but at the same time most of the power will be lost in the matching network. The antenna will be fed with very little power and the efficiency will be poor.

Transmission:
This is the default option. Atyune tries to optimise the power delivered to the antenna. Attention has been paid to this in the following simulations. Atyune has limitations. The PCB layout is ignored. Atyune does not simulate the layout of the matching circuit. The software ignores the effects of connections between components in the matching network. In addition, the impedance of ground paths (vias, thermal reliefs) is ignored as are parasitic effects of solder pads. The impact of all these limitations can be reduced by designing matching circuits where components are very close together and ground paths are kept as short as possible. This is not a handicap because it is a requirement for good RF designs. More about the details of Atyune can be found in the manual.

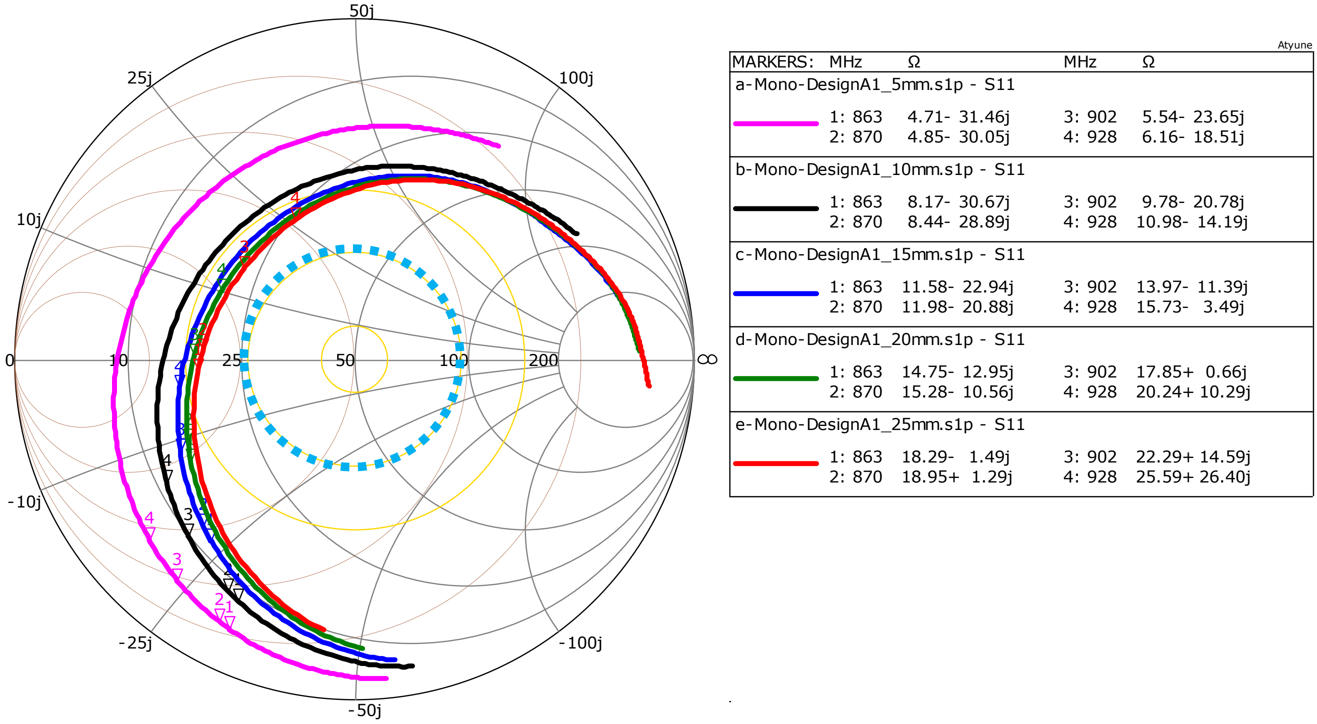
ILLUSTRATION 15: *Gain in dB and efficiency of L-antenna with change of distance of radiator to ground plane (A1)*





The two figures show the possible radiated power of the antenna in dB on the left and the efficiency of the antenna in percent on the right. It is important to note that the curves do not show the radiated energy but the loss in the matching network. Atyune cannot know or detect what happens to the transferred RF energy. In the worst case, a large part is absorbed in the plastic of the enclosure and therefore not radiated into the air. On the following pages we primarily look at the matching at the feed point. The radiated power is displayed at the end of these basic considerations. The curve in pink shows that the curve approaches a loss of -3 dB at the centre frequency before approximately 1100 MHz. At the same time, the right pink curve shows that the efficiency is approaching approximately 50 %. A loss of three dB means a halving of the transmission power or a loss of 50 %. The simulation of the L-antenna was made without an enclosure or batteries nearby. Either of these will add further losses. With such a narrow band antenna, the loss should be around 0 dB at the peak or the antenna efficiency should be close to 100 %. A possible optimisation of the antenna will be discussed in the next steps.

ILLUSTRATION 16: *Smith Chart of L-antenna with change of distance of radiator to ground plane (A1)*



The illustration shows the Smith Chart of the antenna. The exact 50 Ω impedance can be found in the middle of this chart to the right of the number 50. Exactly 50 Ω is the maximum an antenna can reach at any one point. Anything between 25 Ω on the left side and 100 Ω on the right side of the dotted circle is considered a 50 Ω antenna. An impedance of 25 Ω or an impedance of 100 Ω generates exactly the same loss due to the mismatch. However, it can be seen in the diagram that none of the five curves touches the dotted blue area or even runs close to the point for 50 Ω. As explained in detail earlier, an antenna with a return loss of -7.44 dB must have an impedance that is far from 50 Ω. The Smith Chart clearly shows the faulty impedance of the antenna.

ILLUSTRATION 17: *Gain, efficiency, return loss and Smith Chart of the L-antenna with change of distance of radiator to ground plane, unmatched and matched version 1 (A1)*

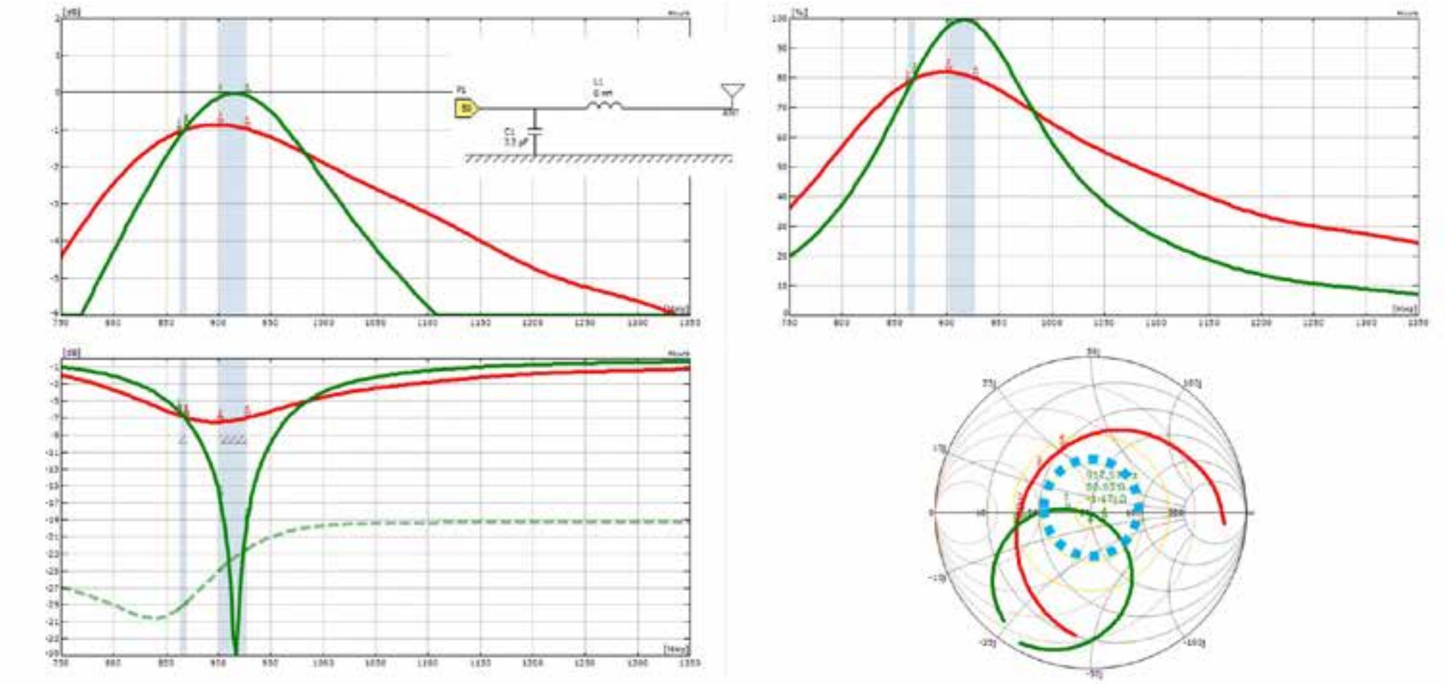
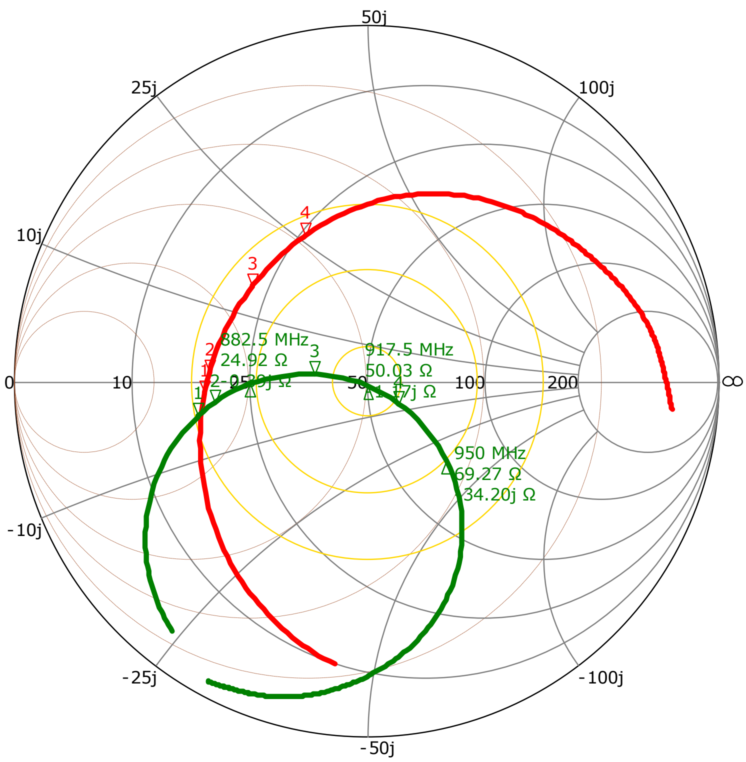


ILLUSTRATION 18: *Smith Chart of the L-antenna with change of distance of radiator to ground plane, unmatched and matched version 1 (A1)*

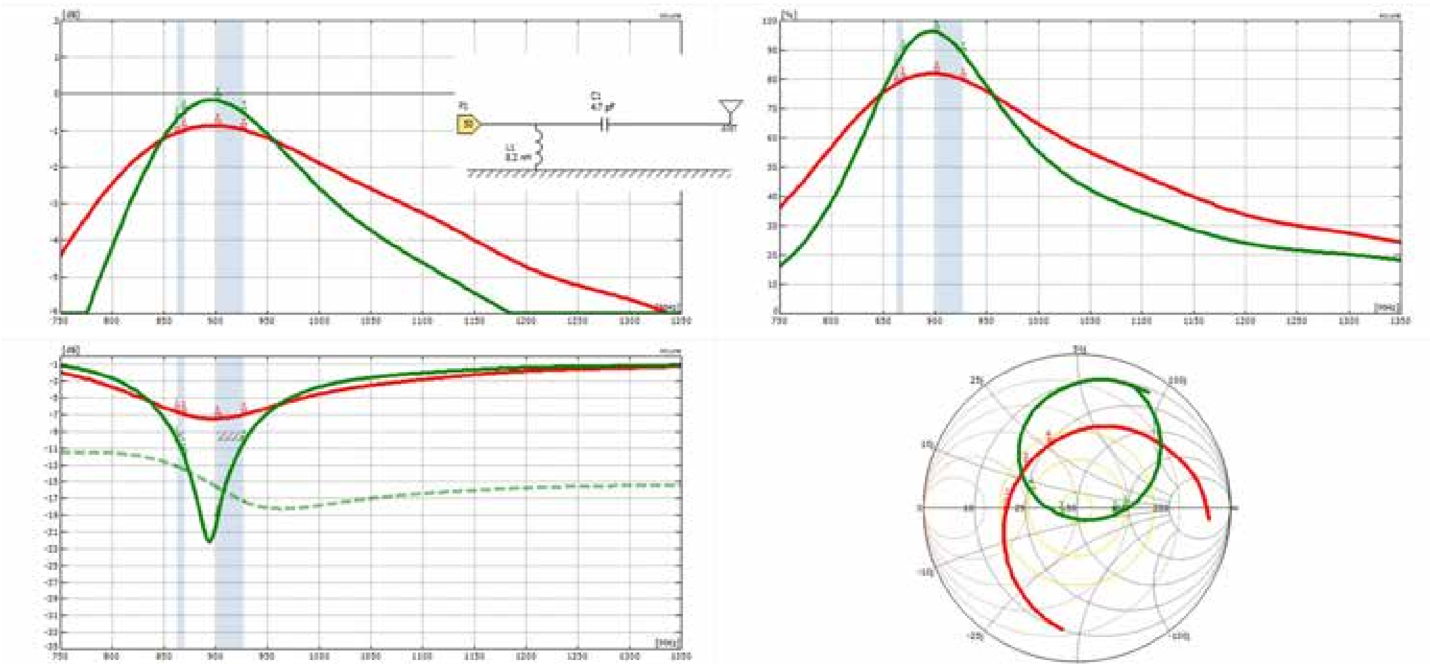


Atyune

MARKERS: MHz	Ω	MHz	Ω
e-Mono-DesignA1_25mm.s1p - S11			
1: 863	18.29- 1.49j	3: 902	22.29+ 14.59j
2: 870	18.95+ 1.29j	4: 928	25.59+ 26.40j
Matched Data - S11			
1: 863	17.28- 4.40j	3: 902	36.89+ 1.70j
2: 870	19.63- 2.89j	4: 928	59.55- 7.64j

In the five diagrams above it is shown that the antenna can be optimised with only one capacitor with a value of 3.3 pF. For this purpose, automatic matching with two components was selected in the Atyune software. The default was a return loss of -10 dB for the American frequency band from 902 MHz to 928 MHz. The Smith Chart was displayed a second time in a larger resolution so that the values can be read better. In the second Smith Chart it can be seen that at 917 MHz the green curve with the matched antenna almost passes through at the 50 Ω point. The values in the table with marker 3 and 4 are generated automatically by the software. The other markers near 25 Ω -0.34 jΩ and 67 Ω 34 jΩ were set manually. The L-antenna becomes very wide band with only one component. You will observe that the European frequency range is not covered with one capacitor. For this we do another simulation.

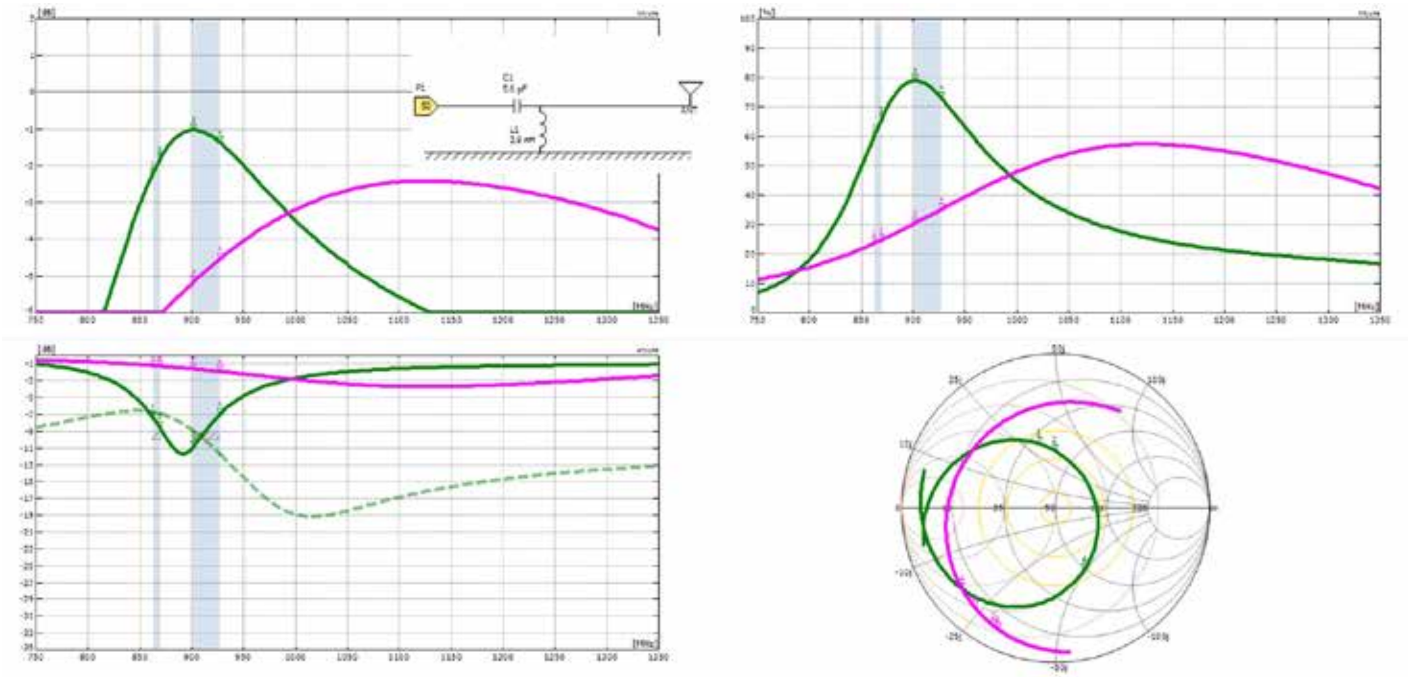
ILLUSTRATION 19: *Gain, efficiency, return loss and Smith Chart of the L-antenna (A1) with change of distance of radiator to ground plane, unmatched and matched version 1*



Author: Harald Naumann
https://www.linkedin.com/in/naumann/

The four illustrations show the matching of the L-antenna with two components to cover the frequency range for 868 MHz in Europe and 915 MHz USA. The compromise with two components shows that losses are to be expected. As noted above, in addition to the losses shown in the simulation, there are also losses in the plastic housing. The goal of a return loss of -10 dB on the band edges could not quite be achieved.

ILLUSTRATION 20: *Gain, efficiency, return loss and Smith Chart of the L-antenna (A1) with change of distance of radiator to ground plane, unmatched and matched version 2*

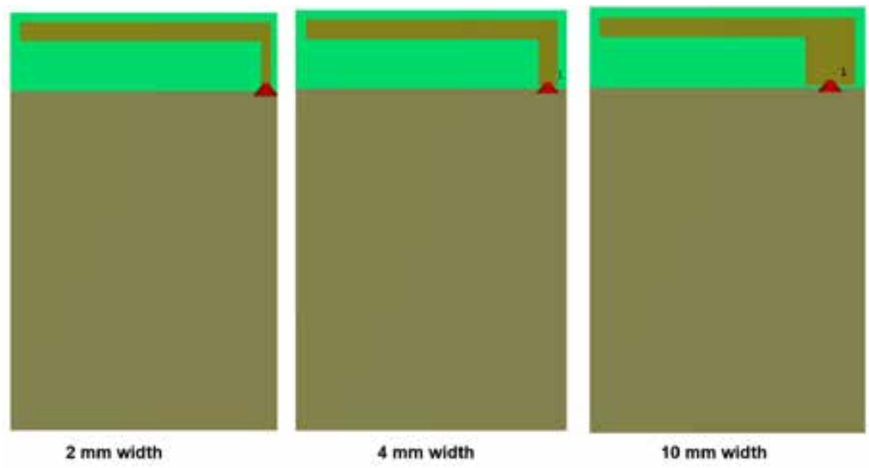


In the illustrations, the antenna with only 5 mm distance to the ground plane was optimised with an adapted network of two components. It can be seen that the maximum return loss value for the antenna with 5 mm distance is significantly worse than for the antenna with 25 mm distance. However, the greater distance to the ground plane also means that the area for components on the PCB becomes smaller. This compromise between more space for the antenna and better antenna performance versus less space for the antenna and thus more space for the other components must be made again and again for all PCB antennas. The more space you invest in the antenna, the better the antenna performance in general. Compared to the antenna proposed by TI, you can see that our alternative L-antenna without meander or helix structure is better. We will discuss the disadvantages of the meander structure in subsequent simulations.

The simulation of the simple L-antenna did not take into account that L-antennas have a strong hand effect (as change in the antenna's performance caused by the capacitive effect of the human body). The narrow bandwidth after the antenna has been adjusted by one or two components means that objects (or even a hand) in the vicinity of the antenna can cause a strong change in the centre resonance frequency, which means that the antenna can no longer receive. An L-antenna is therefore unsuitable for a hand-held remote control or for a tracking device in a handbag or on a dog's collar. This effect of strong interference with the centre frequency is also repeatedly criticised by IoT developers, who opt for the L antenna with the helix structure from Texas Instruments. The risks of an extreme hand effect is not mentioned in TI's design note.

L-ANTENNA
WITH CHANGE OF TRACE WIDTH AT FEED POINT

ILLUSTRATION 21: *L-antenna with change of trace width at feed point*



In this series of simulations we change the width of the feed point. We keep the width of the radiator parallel to the ground plane at 4 mm in all five simulations. The distance of the antenna radiator to the ground plane also remains the same. The fact that the centre frequencies of the five simulations are far away from 868 or 915 MHz is not important in this consideration. Without further measures such as bending the radiator or meandering the radiator, it is not possible to achieve the 868 or 915 MHz resonance frequency on a PCB that is only 55 mm wide.

Changing the width of the conductor path at the feed point of the antenna leads to a strong change in the impedance of the antenna. Looking at the return loss, it can be seen that the antenna with the 10 mm wide trace (red line) has a return loss of -9.84 dB, which is five dB better than the antenna with the 2 mm wide trace (pink line). Looking at the Smith Chart, we see that the red curve is closer to the 50 Ω in the middle of the diagram. The insight in this simulation is that a wider trace at the feed of the antenna leads to an improvement of the impedance. It is therefore to be expected that a widening of the traces at the helix antenna from Texas Instruments also leads to an optimisation of the impedance. We do not simulate a matching network in this simulation because the antenna radiators are very far away from 868/915 MHz in their centre frequency. A simulation would result in extending the length of the radiator with the help of a coil. However, an inductance in series with the radiator inevitably leads to losses in the passive component. It would therefore be better to mechanically extend the antenna radiator and bring it closer to the requested centre frequency. The optimisation of the antennas for requested frequencies is carried out in the following simulations.

ILLUSTRATION 22: *Return loss of the L-antenna with change of trace width at feed point*

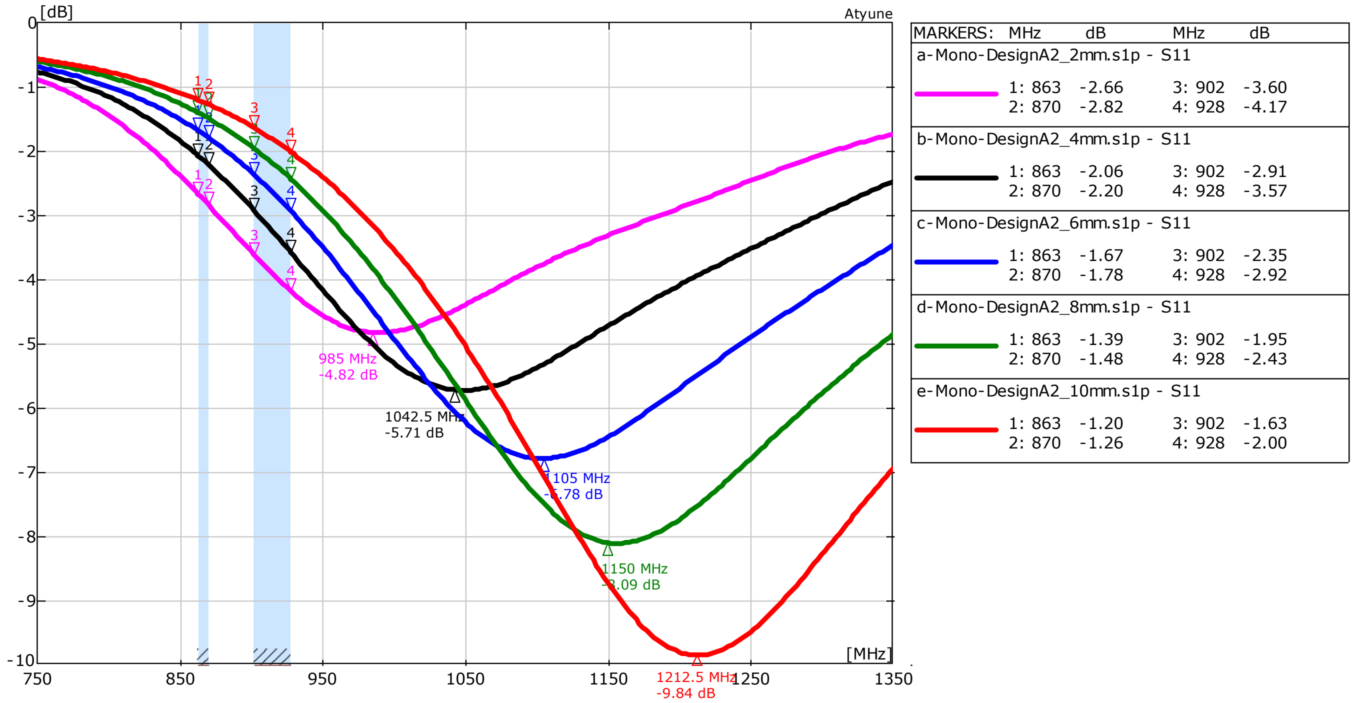
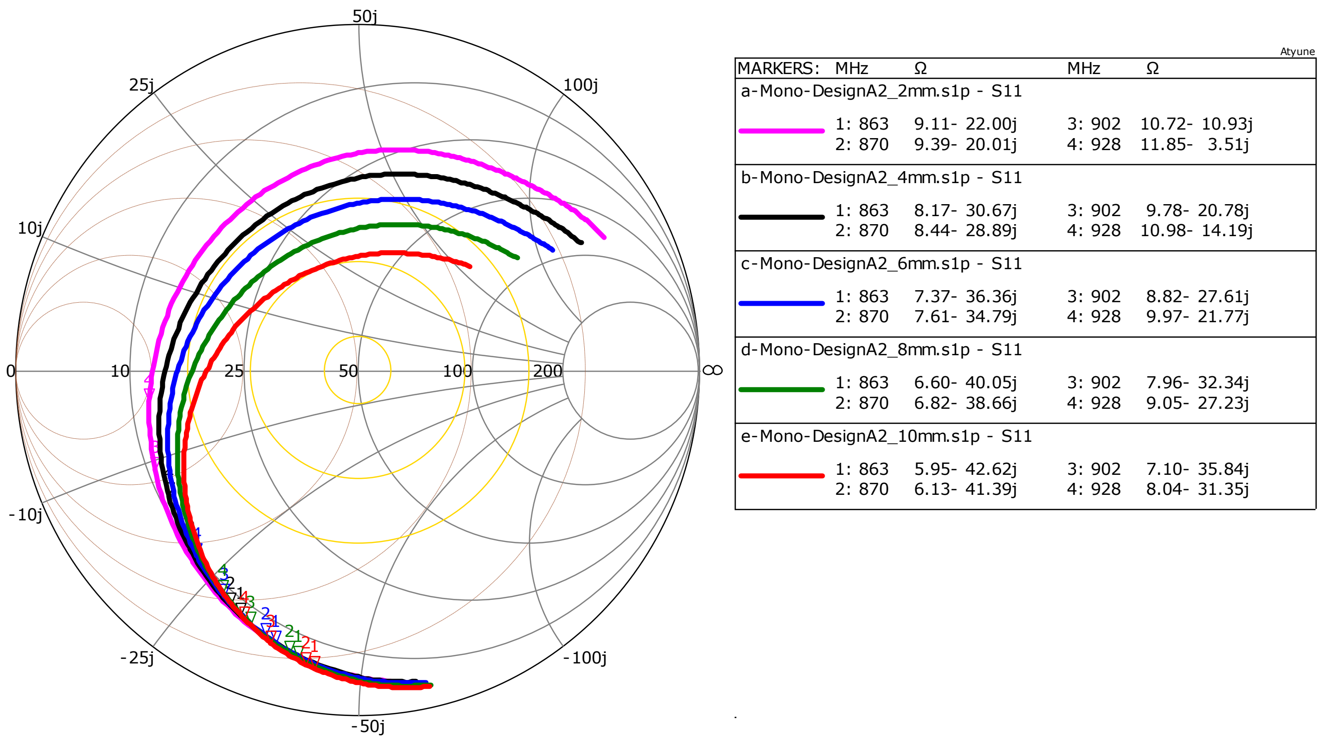
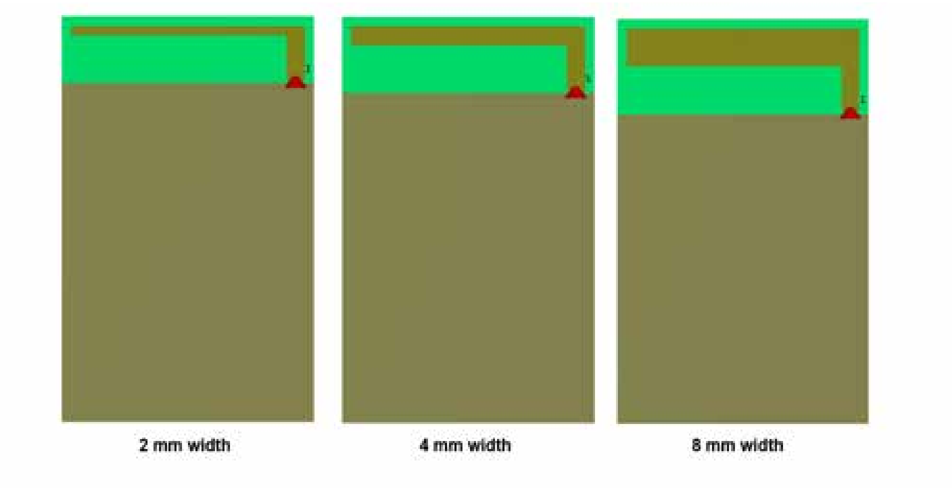


ILLUSTRATION 23: *Smith chart of the L-antenna with change of trace width at feed point*



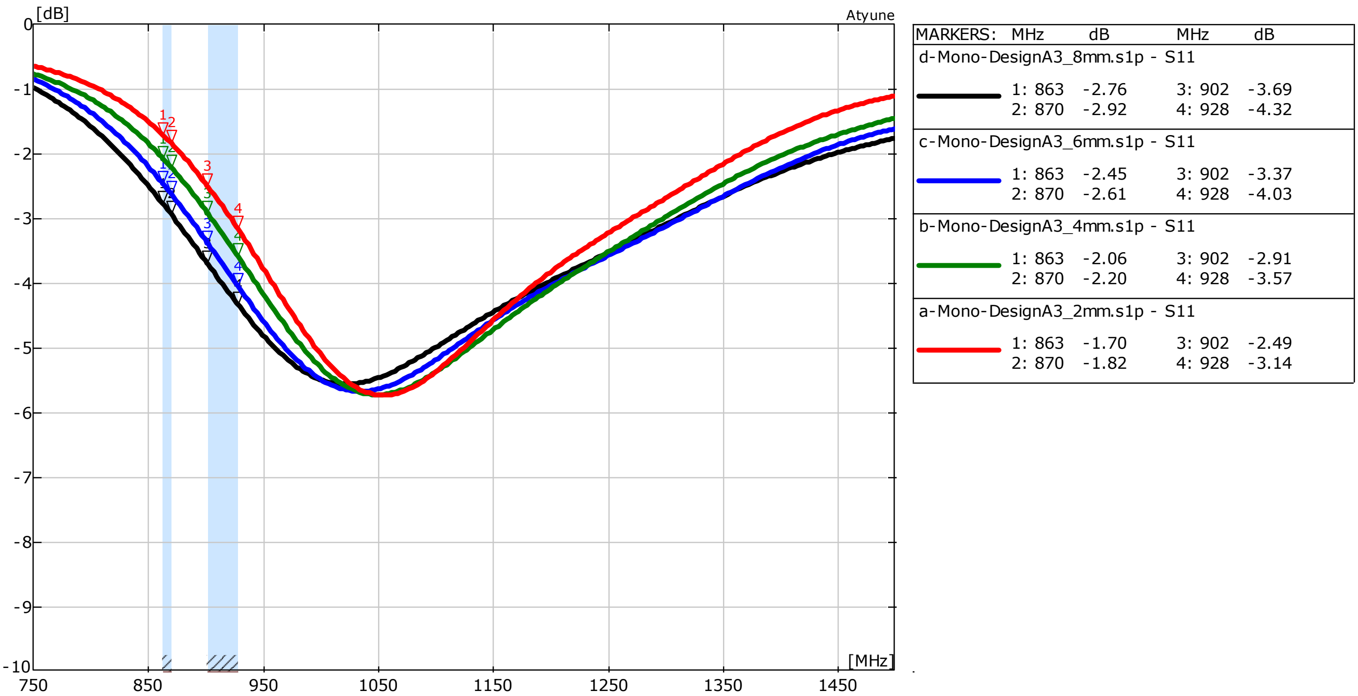
L-ANTENNA
WITH CHANGE OF RADIATOR TRACK WIDTH

ILLUSTRATION 24: *L-antenna with change of radiator track width*



In this series of simulations, we keep the width of the track at the feed point at 4 mm. This time we change the width of the radiator parallel to the ground plane from 2 mm in steps to 8 mm. The finding is that 2 mm, 4 mm, 6 mm and also 8 mm wide traces do not make much difference in return loss and also in impedance. The Smith Chart is not shown in this simulation.

ILLUSTRATION 25: *Return loss of L-antenna with change of radiator track width*



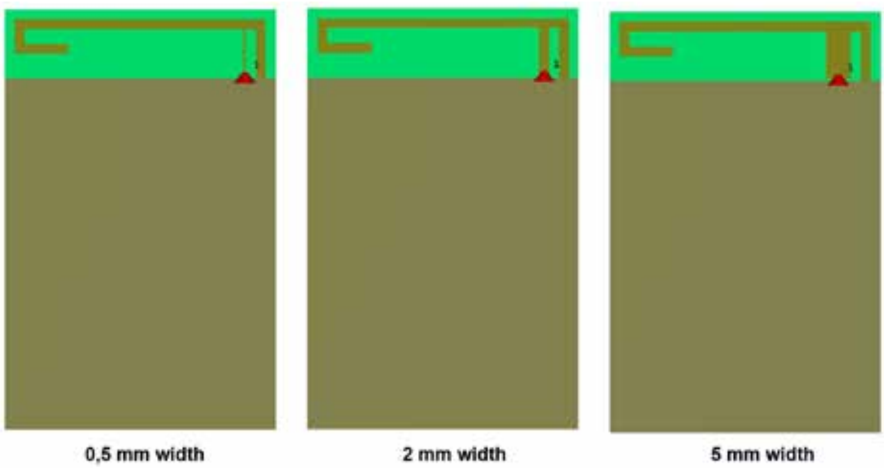
F ANTENNA general distances and dimensions

ILLUSTRATION 26: *F antenna general distances and dimensions*

Before we now explain the simulations with the inverted F-antennas in more detail, we mention again the mechanical dimensions for the basic model. The distance of the radiator or shorting arm to the edge of the PCB is set to 2 mm. This distance of 2 mm ensures that the influence of the plastic enclosure causes the antenna to be completely out of tune. In the following simulation, a plastic enclosure is not used for the time being. The reference designs from Texas Instruments are also documented without a plastic housing. This makes the results of the simulations comparable with the design notes from TI. The standard width of the radiator and shorting arm is also set at 2 mm. After wrapping, the radiator has a distance of 5 mm to the ground plane. The long radiator running parallel to the ground plane has a distance of 10 mm to the PCB. The space between the supply line at the feed point and the shorting arm is also 2 mm. The width of the PCB corresponds to the width of a credit card and is therefore 55 mm. The entire PCB is 85 mm long and thus corresponds to the length of a credit card. If you now add the distance of the radiator to the ground with 10 mm, the width of the radiator 2 mm and the distance at the edge of the PCB, you get 14 mm. If you subtract the 14 mm from the 85 mm total length, you get 71 mm for the length of the mass surface.

F ANTENNA with change of trace width at feed point (A2withA8)

ILLUSTRATION 27: *F antenna with change of trace width at feed point (A2withA8)*



In this simulation, we consider an inverted F antenna for the first time. This type of antenna provides a strong magnetic field between the feed point of the antenna and the shorting arm. In the vicinity of the short-circuit, larger currents are allowed on the PCB. If the PCB is to have several layers with ground, the high short-circuit current near the short-circuit should be distributed to the different ground layers. This is achieved by multiple vias near the shorting arm.

The centre frequency of the F antennas shown is close to the requested resonant frequency for the licence-free band in Europe or in the USA. The length of the folded radiator is not changed in this simulation. The feed line for the RF signal has a width of 0.5, 1, 1.5, 2 and 5 millimetres. Although the length of the radiator is not changed, the frequency at the peak of the return loss for the radiator with a width of 0.5 mm shifts from 858 MHz to 902 MHz with a width of 5 mm. The delta from the best return loss of approximately -34 dB to the worst return loss of approximately -11 dB is therefore approximately 23 dB. The finding in this simulation is that the width of the feed line for the high-frequency signal has a strong influence on the return loss and also on the centre frequency of the resonance bodies. In our chosen configurations, the best return loss results from a feed line width of 1 mm.If we look at the curve for the losses in dB on the left and the curve for the efficiency on the right, we see that the worst return loss of -16 dB and the best return loss of -33 dB have similarly low losses and similarly good efficiency. The second finding in this simulation is that a return loss better than -15 dB leads to a hardly measurable better efficiency of the antenna. Even with the curve in pink, the peak loss is less than half a dB. This 0.5 dB is also difficult to measure.

ILLUSTRATION 28: *Return loss F antenna with change of trace width at feed point (A2withA8)*

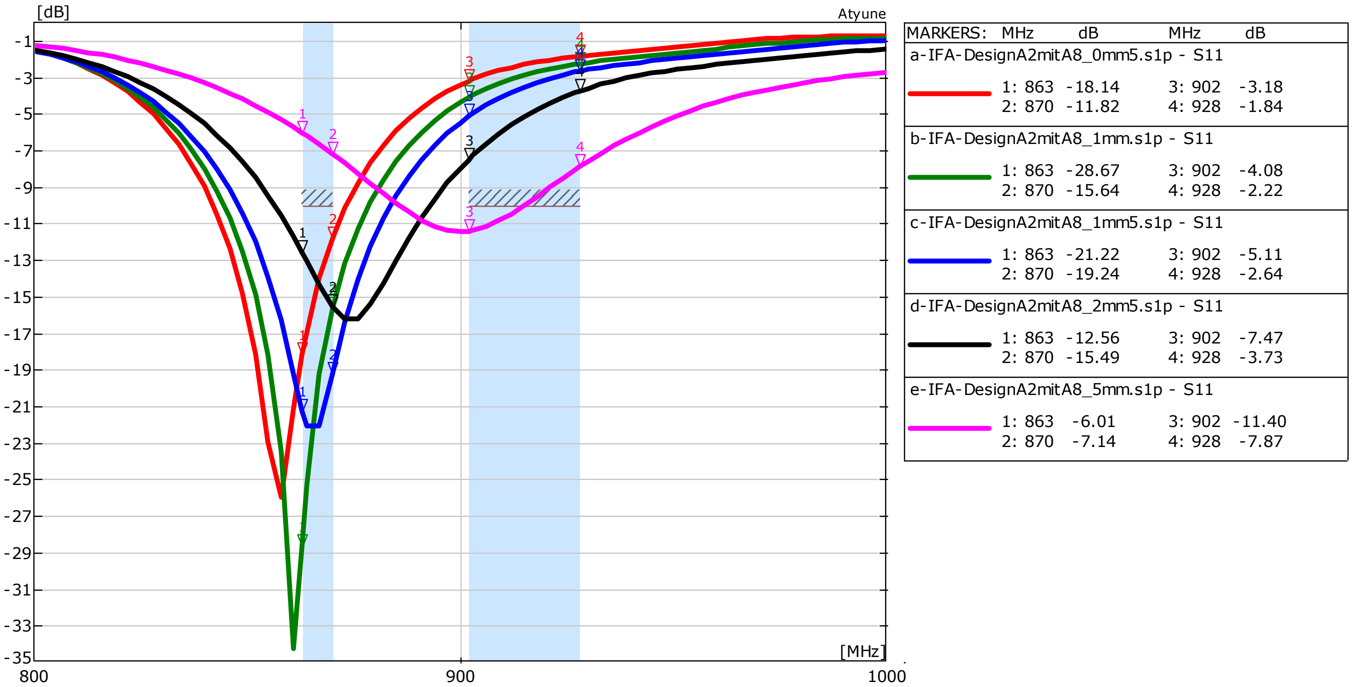
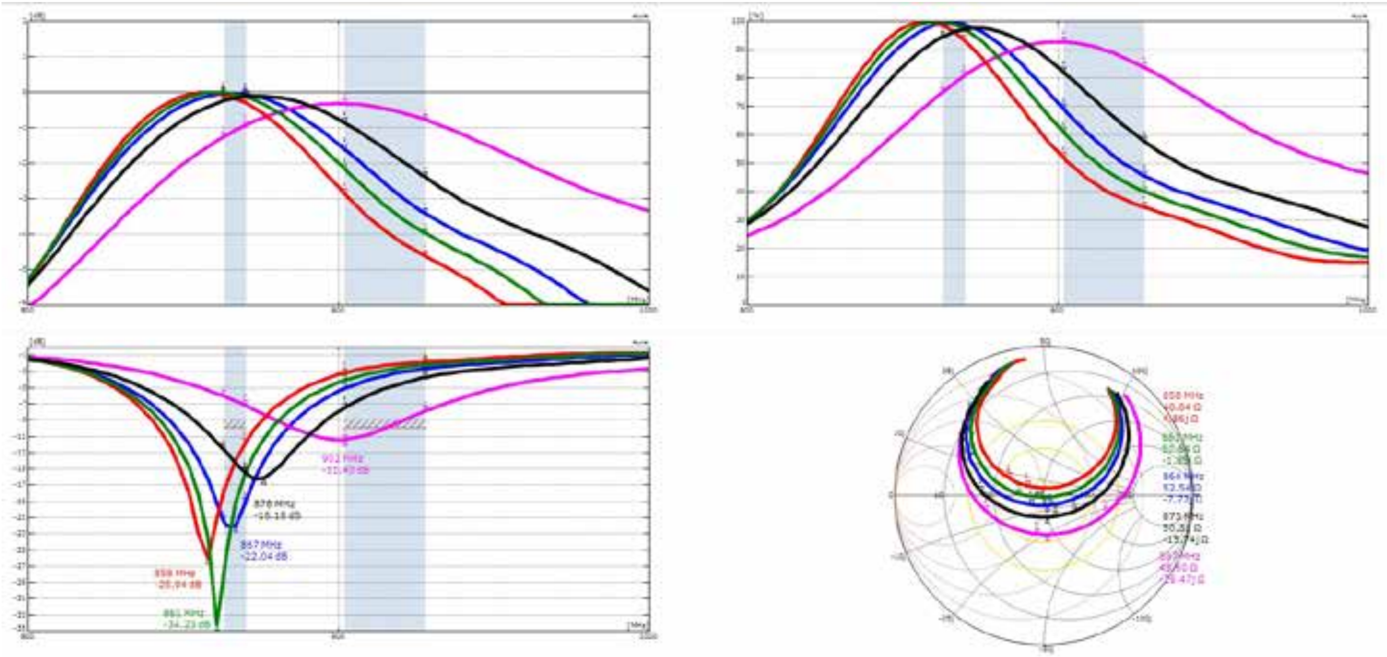


ILLUSTRATION 29: *Gain, efficiency, return loss and Smith Chart of F antenna with change of trace width at feed point (A2withA8)*



Author: Harald Naumann
https://www.linkedin.com/in/naumann/

-10 dB Return Loss Bandwidth

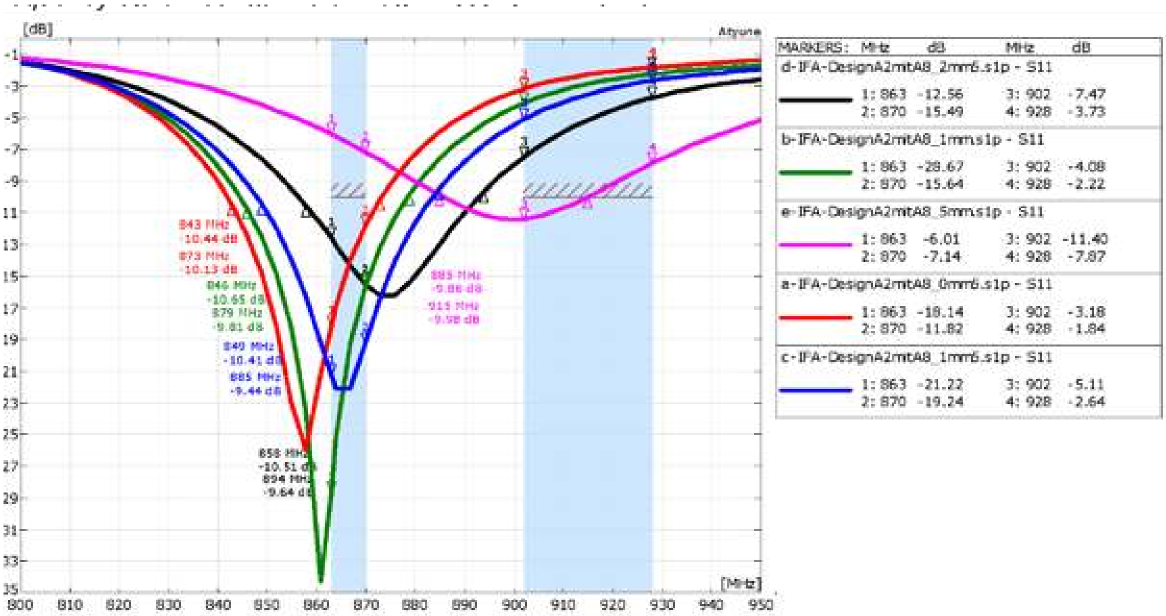
In the following diagram we look at the frequency bandwidth of the five antennas for the first time. The bandwidth of an antenna is evaluated at -6 dB or -10 dB return loss. For antennas with a lower frequency bandwidth, such as in the 868 MHz or 915 MHz band, we aim for a return loss of approximately -10 dB. With wide band antennas for NB-IoT or other cellular antennas for multi band, one aims for a return loss of -6 dB at the band corners. Even -5 dB is still tolerated for multi band antennas. Since we are only looking at small bandwidth antennas in the current simulation, our goal is to reach -10 dB or at least be close to it. Therefore, in the diagram below we have marked one value close to -10 dB at the lower band corner and another value at the upper corner. It is not always possible to mark exactly the -10 dB point. The marker can only be set to a value that was actually simulated. If there is no measured value at exactly -10 dB, then one must choose a value as close to -10 dB as possible. To make it easier to read the value on the lower and upper band corner, we visualised the measured value of the upper corner directly below the value of the lower edge. The readings were then transferred to the table and the bandwidth of the five different antennas was made visible. In this case we do not consider the centre frequency but the achieved frequency bandwidth. For Europe we need 7 MHz bandwidth and for USA we need 26 MHz bandwidth. All five antennas achieve better than 26 MHz. The green antenna with a peak in return loss gives us only 33 MHz bandwidth. The blue and black antennas give us 36 MHz bandwidth. It must be remembered that this 36 MHz bandwidth has been achieved without a matching network and only by the correct placement of the shorting arm.

The insight here is that it is not the antenna with the highest peak return loss that is the better antenna, but the antenna with the highest bandwidth.

TABLE 7: *Frequency bandwidth at - 10 dB return loss for A2withA8*

	f1 (MHz)	f2 (MHz)	Bandwidth (MHz)	Centre frequency (MHz)
Red	843	873	30	858
Green	846	879	33	862.5
Blue	849	885	36	867
Black	858	894	36	876
Pink	885	915	30	900

ILLUSTRATION 30: *Frequency bandwidth at - 10 dB return loss for A2withA8*



Author: Harald Naumann
https://www.linkedin.com/in/naumann/

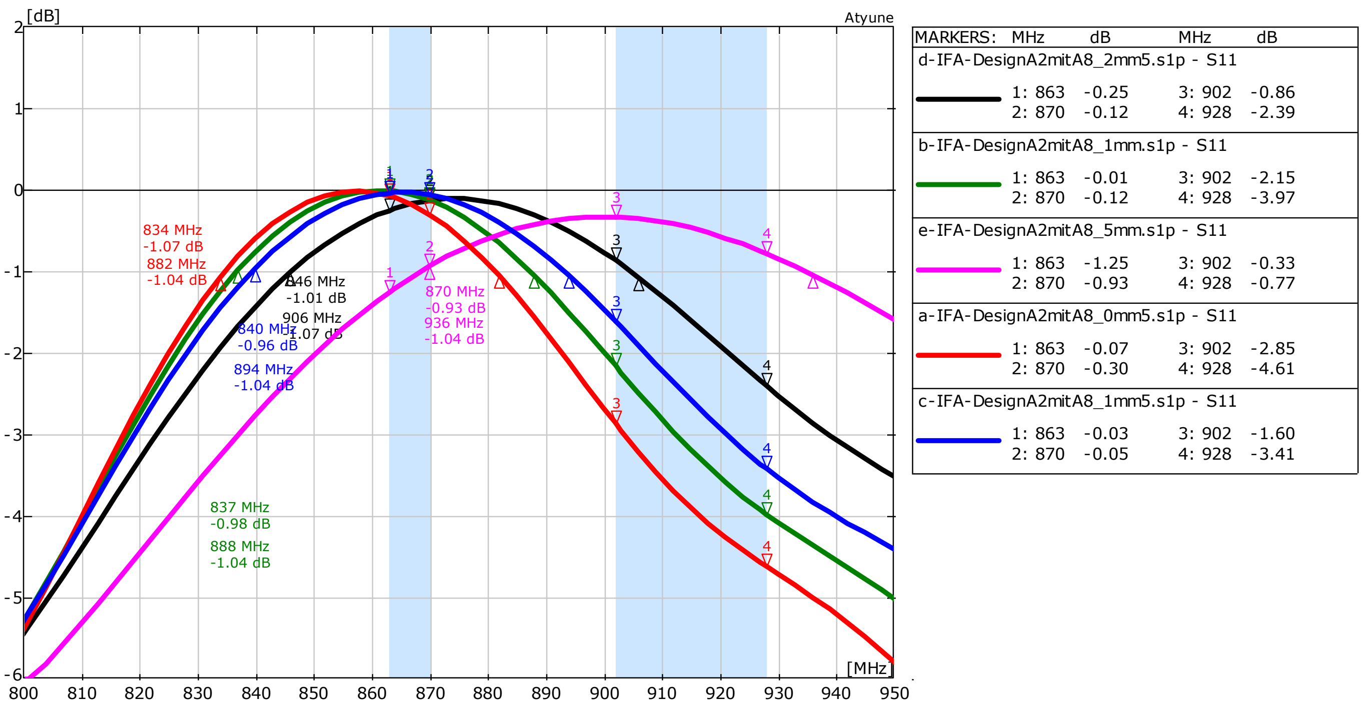
Bandwidth at the -1 dB Transmit evaluation

The lowest frequency in the European band is 863 MHz and the highest frequency in the American band is 928 MHz. If you want to design an antenna that covers both bands, it must have a frequency bandwidth of 65 MHz. If we accept minus 1 dB of radiated power at the band corners, the ranking of the five antennas shifts again. The antenna with the pink colour suddenly becomes the best antenna because it has a bandwidth of 66 MHz. However, this 66 MHz bandwidth is also due to a loss of approximately 0.5 dB at the peak. In the end, it is always a compromise between bandwidth and radiated power. The lower the bandwidth, the higher the radiated power can be on the band corners. The best radiated power is achieved by choosing two different antennas for the European and American bands. If you want to use only one antenna for both bands, you can switch between the two bands. We will discuss frequency switching in further sections.

TABLE 8: *Drop of -1 dB by mismatch with F antenna with change of trace width at feed point (A2withA8)*

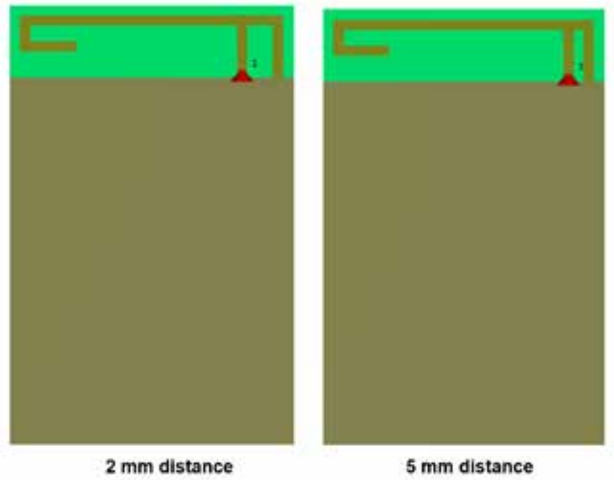
	f1 (MHz)	f2 (MHz)	Bandwidth (MHz)	Centre frequency (MHz)
Red	834	882	48	858
Green	837	868	31	852.5
Blue	840	894	54	867
Black	846	906	60	876
Pink	870	936	66	903

ILLUSTRATION 32: *Analysis of the loss of F antenna with change of trace width at feed point (A2withA8)*



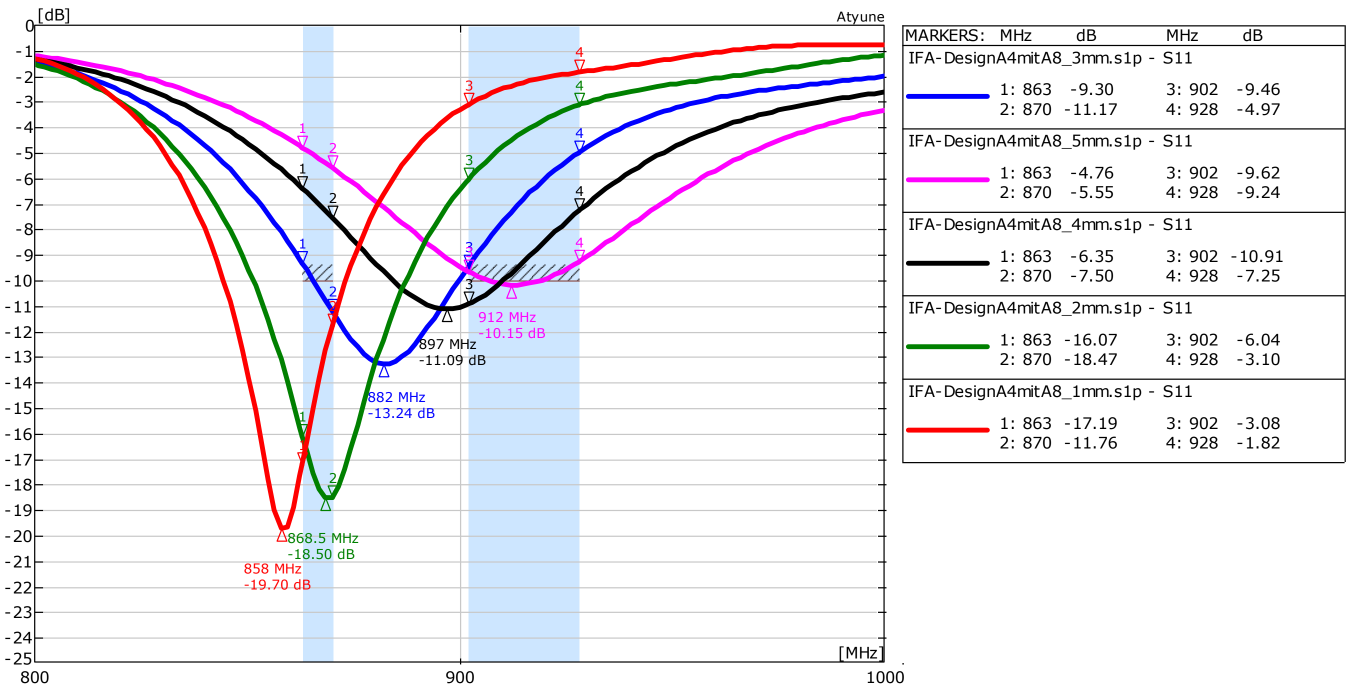
F ANTENNA WITH CHANGE OF DISTANCE TO SHORT-CIRCUIT POINT (A4WITHA8)

ILLUSTRATION 33: *F antenna with change of distance to short-circuit point (A4withA8)*



In this simulation we observe the change of the impedance or return loss of the antenna depending on the distance of the shorting arm to the feed point. The distance was increased in 1 mm steps from 1 mm to 5 mm. It can be seen that the return loss deteriorates from approximately -20 dB to approximately -10 dB. Depending on whether you are aiming for a -10 dB or a -6 dB bandwidth for the antenna, the red antenna or the pink antenna is the better one. If one strives for the widest possible bandwidth at a return loss of -10 dB without further components in the matching network, the blue-coloured curve shows the best result. The insight in this simulation is that the impedance can be changed with the distance of the shorting arm to the feed point.

ILLUSTRATION 34: *Return loss of F-antenna with change of distance to short-circuit point (A4withA8)*



Author: Harald Naumann
https://www.linkedin.com/in/naumann/

ILLUSTRATION 35: *Gain, efficiency, return loss and Smith Chart of F-antenna with change of distance to short-circuit point A4withA8)*

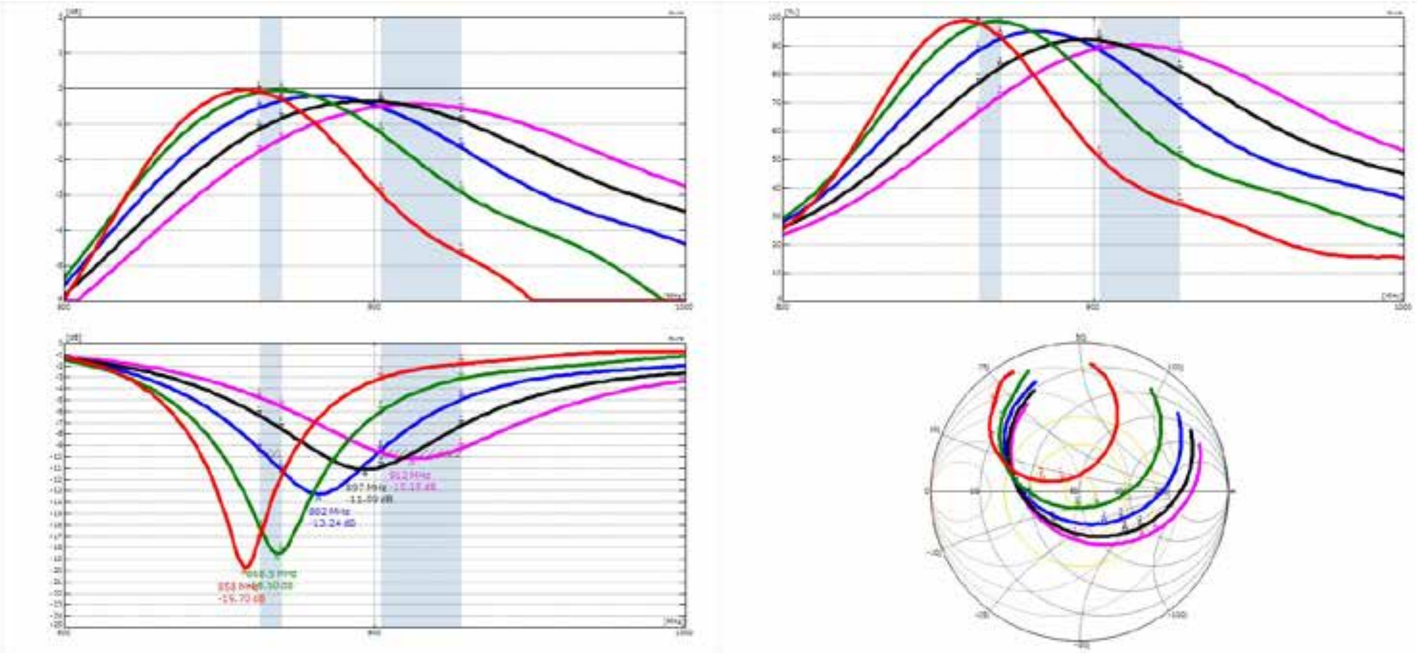
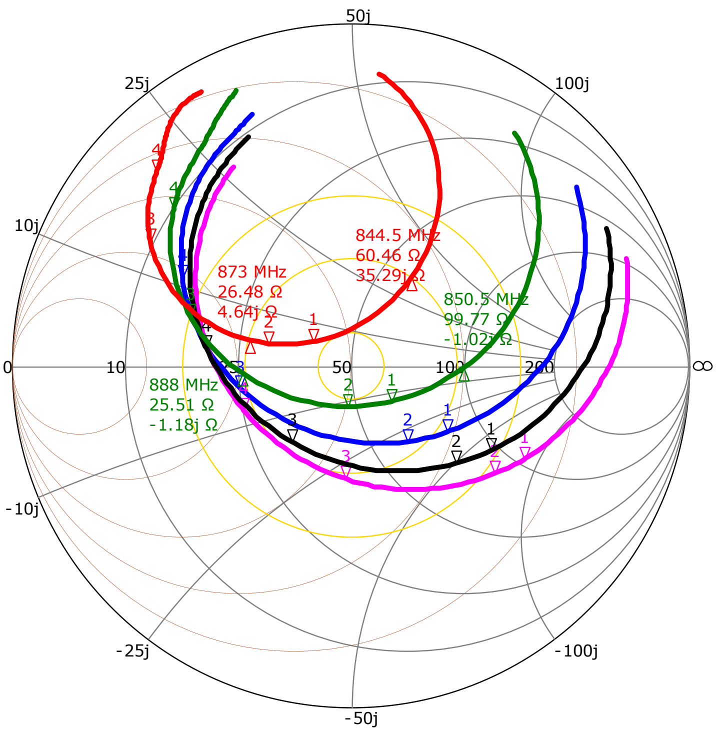


ILLUSTRATION 36: *Smith Chart of F-antenna with change of distance to short-circuit point (A4withA8)*

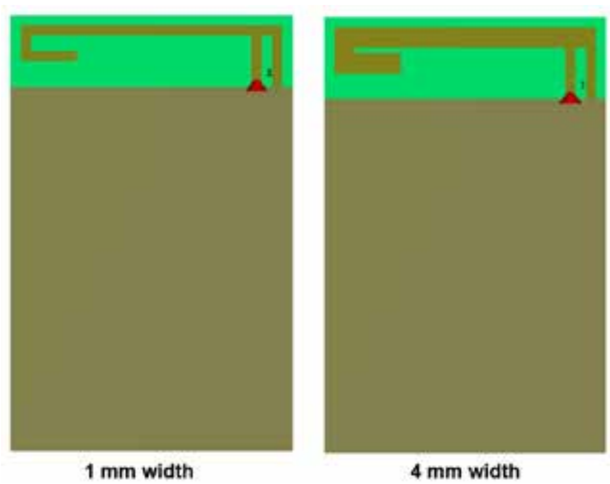


Atyune

MARKERS: MHz	Ω	MHz	Ω
IFA-DesignA4mitA8_3mm.s1p - S11			
1: 863	80.05- 35.05j	3: 902	25.01- 3.68j
2: 870	62.10- 29.69j	4: 928	14.68+ 11.22j
IFA-DesignA4mitA8_5mm.s1p - S11			
1: 863	105.95- 86.63j	3: 902	38.68- 28.62j
2: 870	83.82- 73.01j	4: 928	25.03- 7.32j
IFA-DesignA4mitA8_4mm.s1p - S11			
1: 863	94.70- 60.91j	3: 902	31.99- 15.51j
2: 870	73.97- 51.21j	4: 928	19.81+ 2.70j
IFA-DesignA4mitA8_2mm.s1p - S11			
1: 863	61.83- 13.19j	3: 902	17.05+ 6.66j
2: 870	47.25- 11.35j	4: 928	10.04+ 18.13j
IFA-DesignA4mitA8_1mm.s1p - S11			
1: 863	39.14+ 5.86j	3: 902	9.47+ 13.75j
2: 870	29.83+ 4.43j	4: 928	6.09+ 20.30j

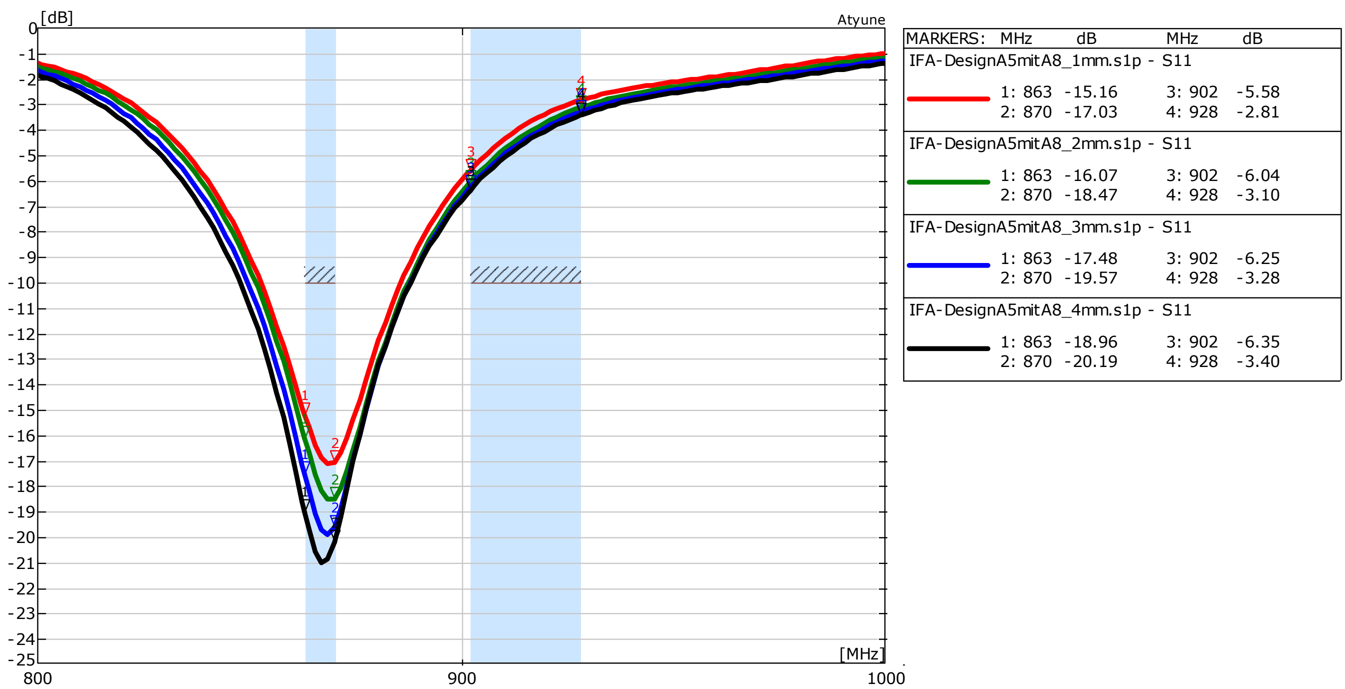
F ANTENNA
WITH CHANGE OF RADIATOR WIDTH (A5WITHA8)

ILLUSTRATION 37: *F antenna with change of radiator width (A5withA8)*



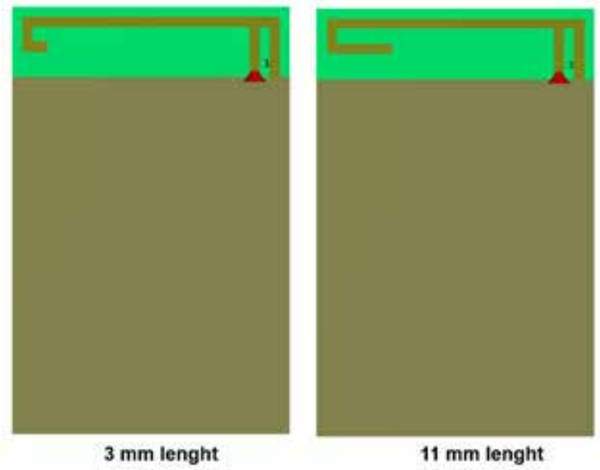
In this simulation, the distance from the supply to the short circuit was kept constant. Only the width of the radiator was changed in steps of 1 mm from 1 mm to 4 mm. It can be observed that the centre frequency is not changed by the change in width. The return loss attenuation changes from approximately -17 dB to approximately -21 dB. The conclusion is that by changing the width of the radiator, the return loss can be optimised a little.

ILLUSTRATION 38: *Return loss F antenna with change of radiator width (A5withA8)*



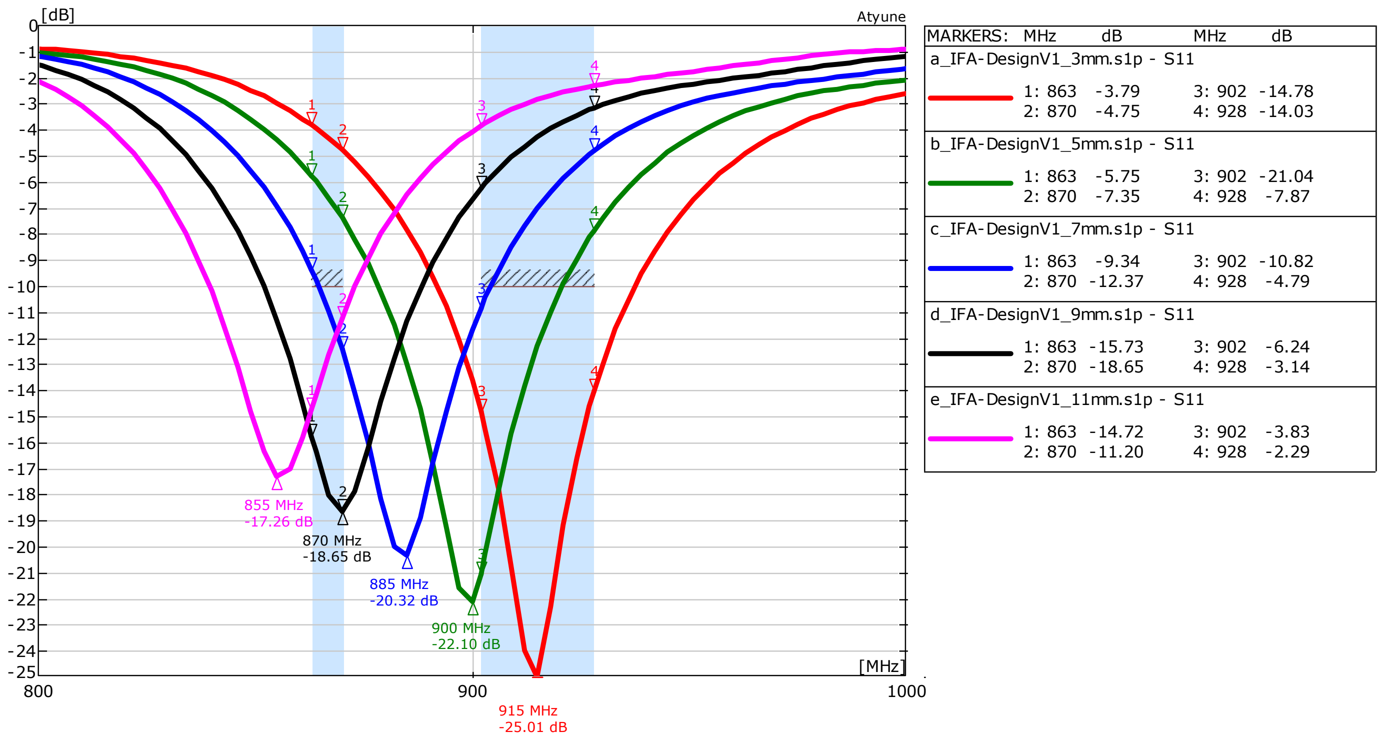
F ANTENNA
WITH CHANGE OF RADIATOR LENGTH (V1)

ILLUSTRATION 39: *F antenna with change of radiator length (V1)*



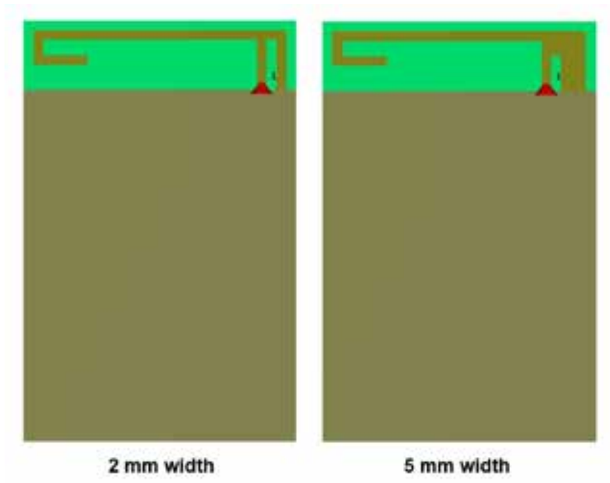
In this simulation, only the length of the radiator was increased in several steps from 3 mm to 11 mm length. In all five simulations the peak value of the return loss is between -17 dB and -21 dB. The high return loss indicates that the antenna must be very close to the target 50 Ω. As the radiator lengthens, the centre frequency of the antenna decreases. At the same time, the maximum value of return loss is also reduced. The simulation shows that by changing the length of the radiator, the centre frequency of the antenna can be adjusted.

ILLUSTRATION 40: *Return loss F antenna with change of radiator length (V1)*



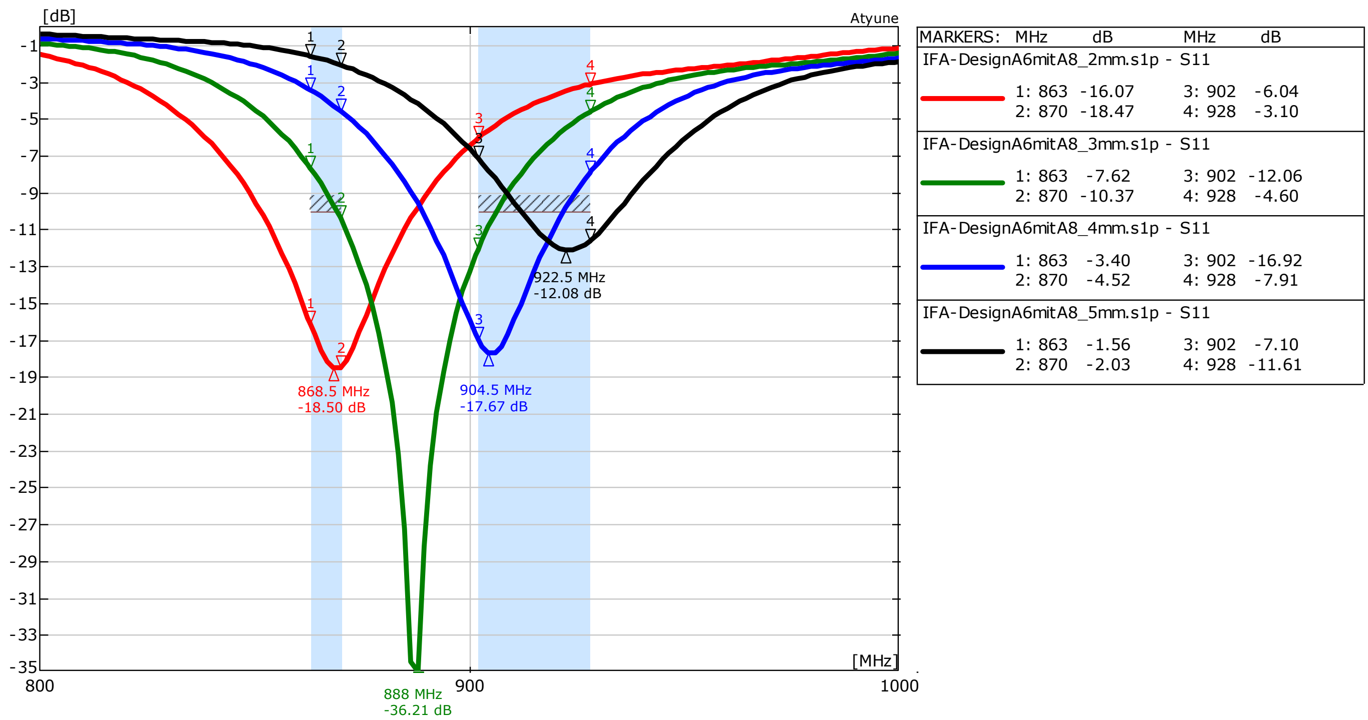
F ANTENNA WITH CHANGE OF THE WIDTH OF THE SHORT-CIRCUIT POINT (A6WITHA8)

ILLUSTRATION 41: *F-antenna with change of the width of the short-circuit point (A6withA8)*



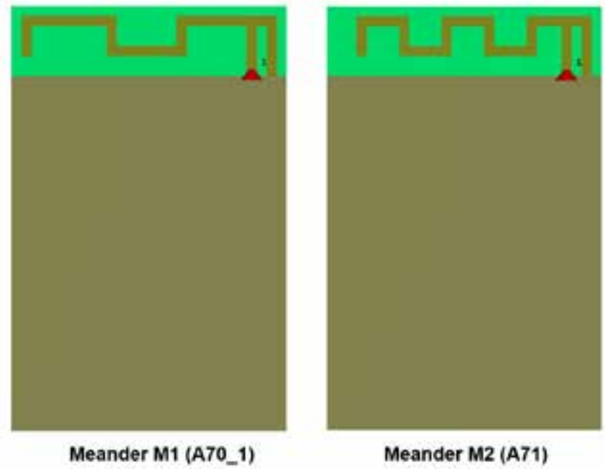
In this simulation, only the width of the shorting arm was changed. The width was 2, 3, 4 and 5 mm. At 2 and 4 mm, a similar value is achieved with -17 and -18 dBm return loss, respectively. At 5 mm width, the return loss changes to approximately -12 dB. At 3 mm width, the best peak value so far is reached with -36 dB. The conclusion of this simulation is that by changing the width of the shorting arm, the return loss can be adjusted.

ILLUSTRATION 42: *Return loss of F-antenna with change of the width of the short-circuit point (A6withA8)*



F ANTENNA WITH MEANDER (A70&A71)

ILLUSTRATION 43: *F antenna with meander (A70&A71)*



In this simulation only the meander has changed. Although the right antenna has a longer path and thus a longer radiator due to its multiple meanders, this is not reflected in the centre frequency of the antenna. Although the two antennas have different lengths, the centre frequency is very similar. It is also noticeable that the right antenna with its multiple meander has a significantly worse return loss than the left antenna. Furthermore, you can see that both antennas show losses in the diagram for transmit. The antennas do not reach 100 % peak efficiency.

The finding of this simulation is that meandering structures perform significantly worse compared to the folded antenna structures used in the previous simulations. The insight is therefore that designs should seek to avoid antenna structures with meanders.

ILLUSTRATION 44: *Return loss F antenna with meander (A70&A71)*

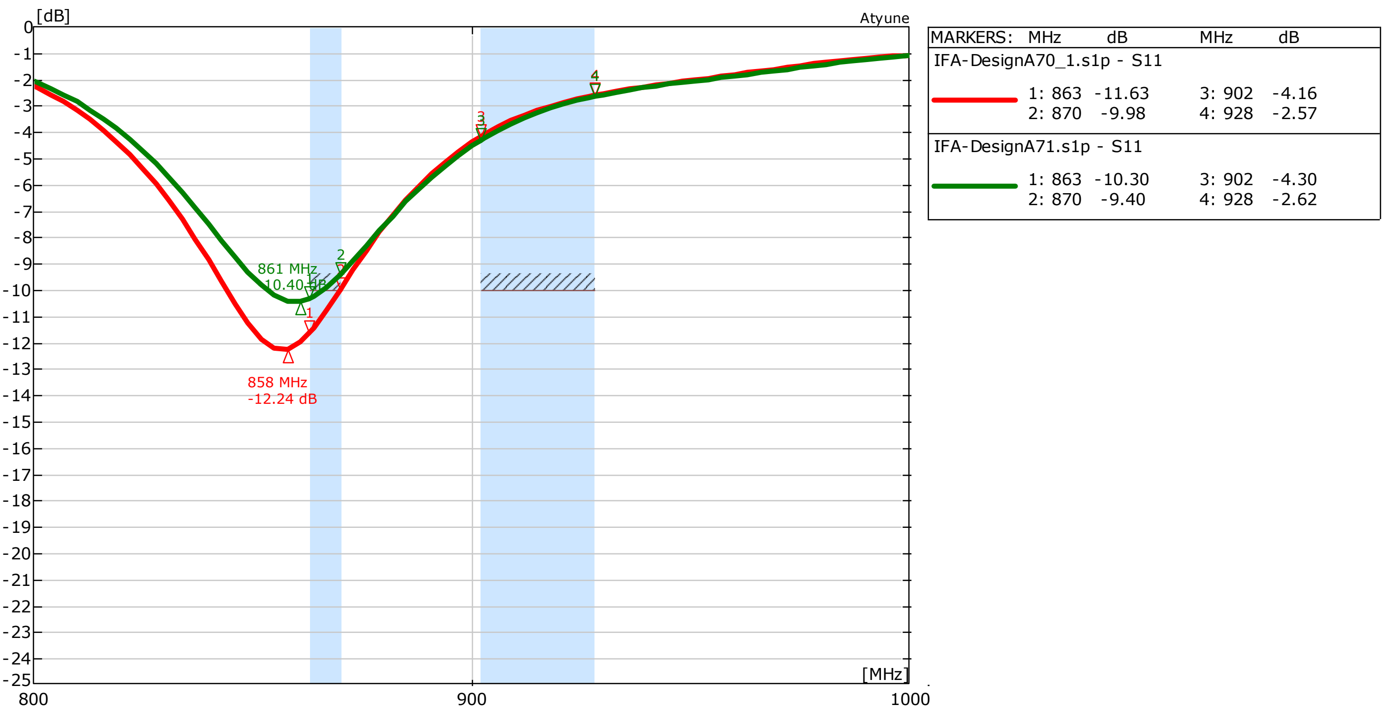
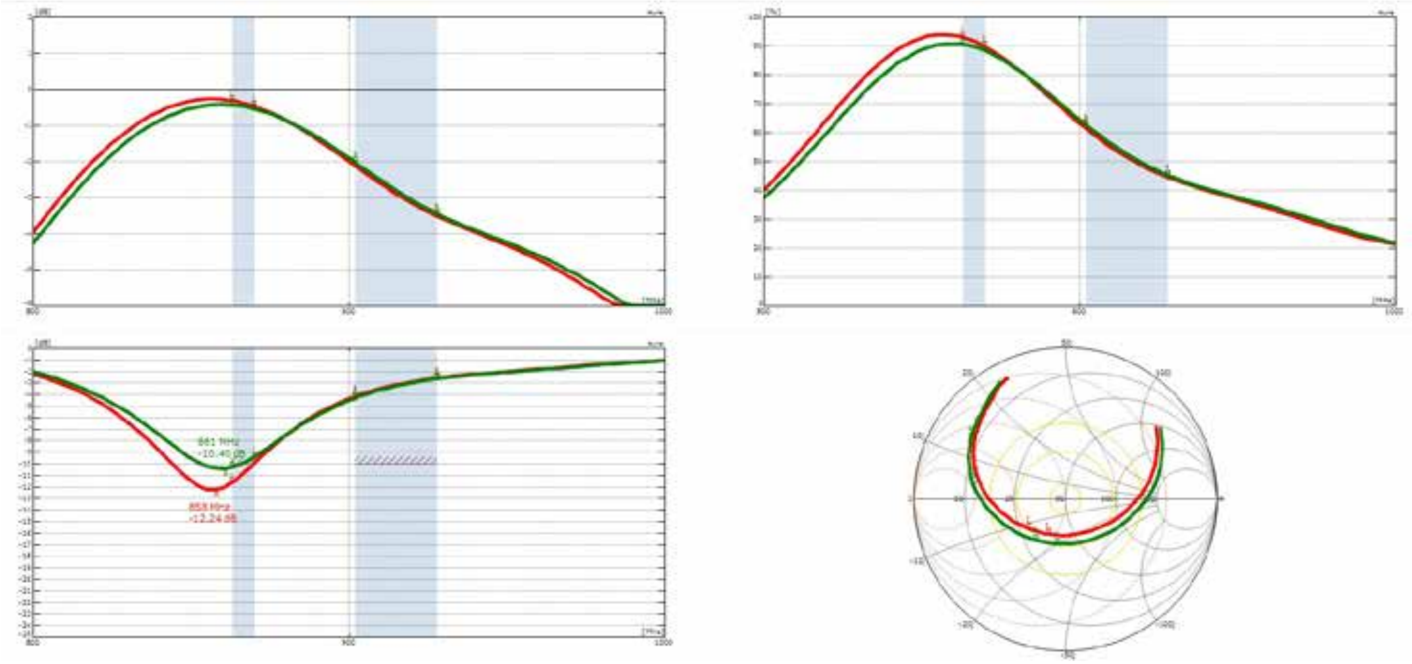
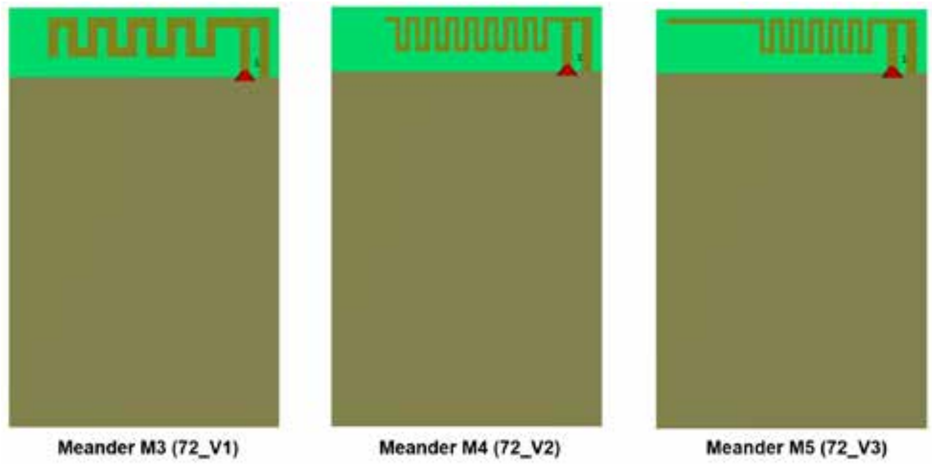


ILLUSTRATION 45: *F antenna with meander (A70&A71)*



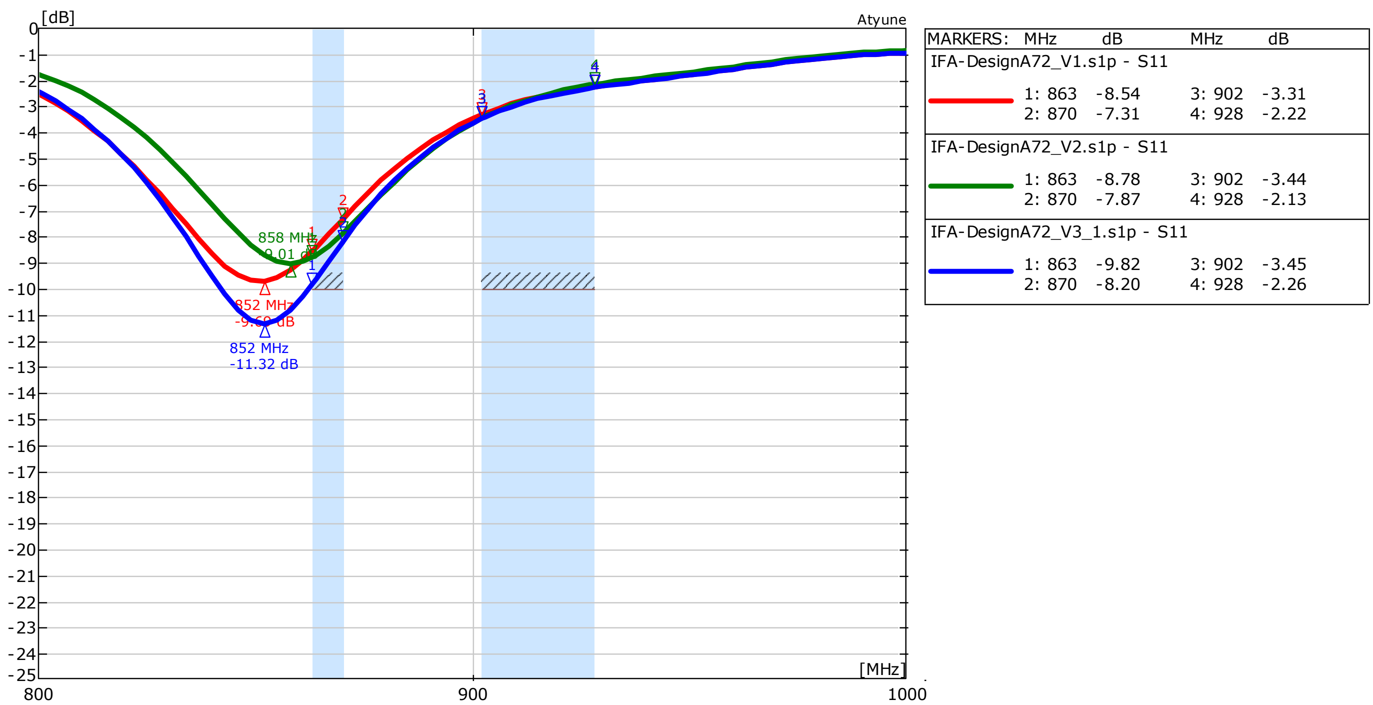
F ANTENNA WITH CHANGE OF MEANDER STRUCTURE (A72)

ILLUSTRATION 46: *F antenna with change the meander (A72)*



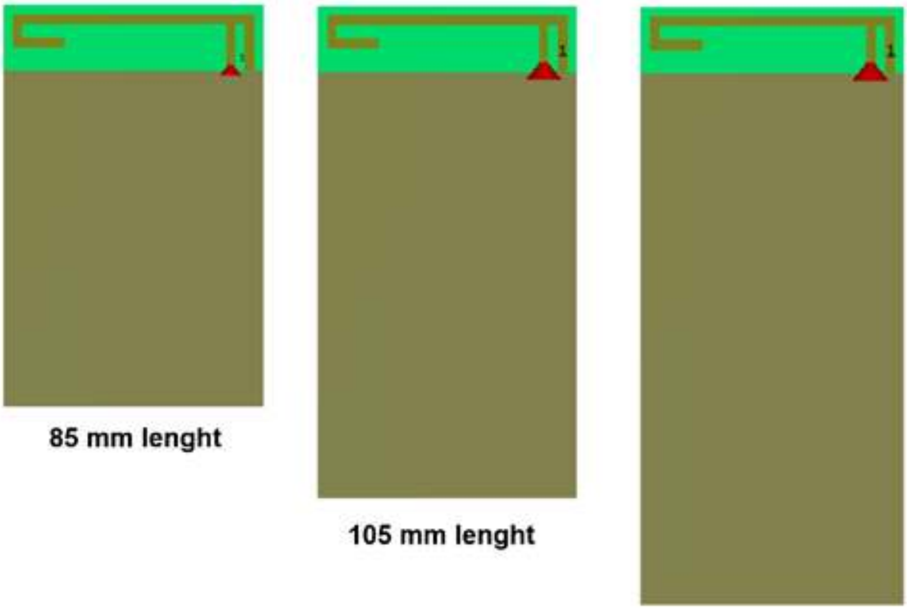
In this simulation, meander structures were used again. The green curve shows the antenna A72_V2. This structure has the closest meander. There, the antenna structures running up and down are closest to each other. This structure comes nearest to the helix structure proposed by Texas Instruments in the design note DN038. Here, too, it can be seen that the significantly longer distance of the multiple meanders of antenna A72_V2 does not shift the centre frequency any further downwards. The previously shown bent antennas layouts were much better ways of altering the centre frequency and optimising the return loss. The findings of this simulation again show that antenna structures with meanders should be avoided.

ILLUSTRATION 47: *F antenna with change of PCB length (A72)*



F ANTENNA WITH CHANGE IN LENGTH OF PCB (A8)

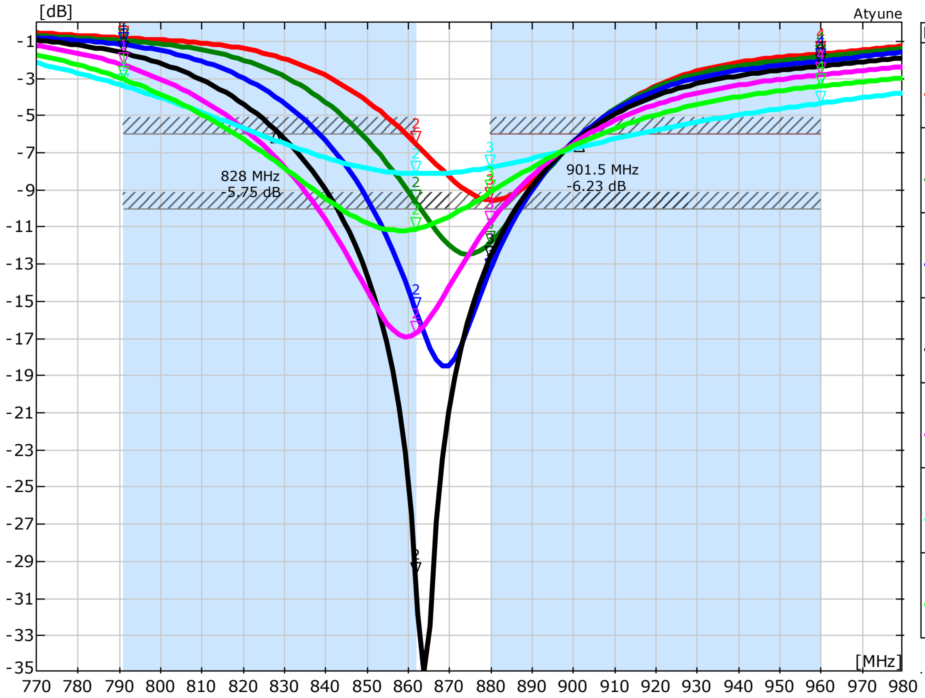
ILLUSTRATION 48: *F antenna with change in length of PCB (A8)*



In this simulation the antenna structure and the shorting bracket was not changed. The only change in this simulation was to change the length of the PCB from 65 mm in 10 mm steps to 125 mm. 65 mm is already a very small or short ground plane for a frequency of approximately 900 MHz. If the PCB is extended in 10 mm steps up to 95 mm, the return loss reaches a peak value of -35 dB. This means that the length of the PCB and the maximum return loss, and thus also the maximum bandwidth of the antennas, are directly related. The data sheets of well-known manufacturers of chip antennas show the same fact. There you will see a relationship between the length of the PCB, the return loss and the bandwidth. If you increase the length of the PCB from 95 mm to 105 mm and beyond, you will notice that the return loss decreases and at the same time the centre frequency decreases minimally. The change of the centre frequency is not very strong, but the change in return loss is dramatic. From this simulation it can be seen that importance of the length of the PCB cannot be over stressed. This is generally not mentioned in the documentation of the chip antennas of the well-known manufacturers.

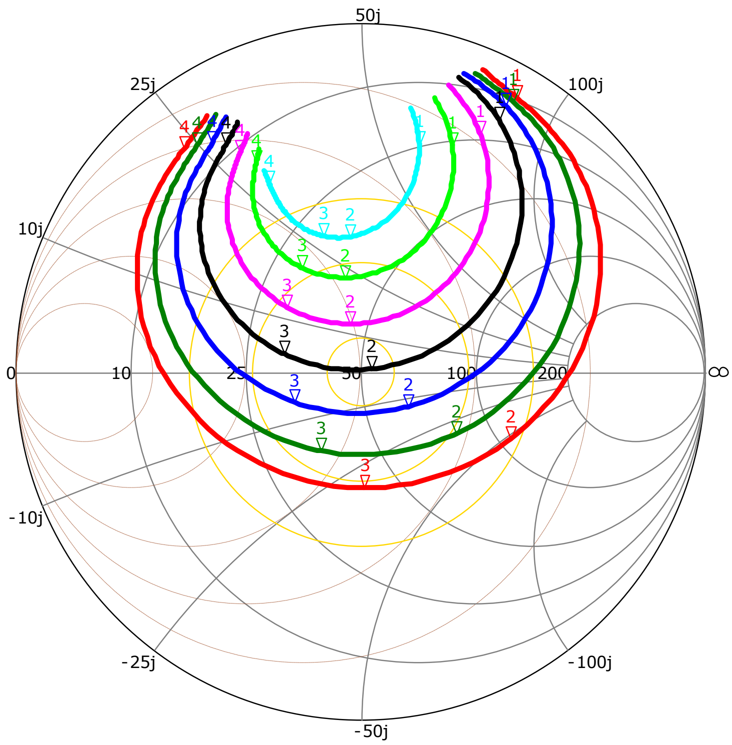
The insight in this simulation is that a PCB that is too small will give poor bandwidth and poor maximum return loss. The extended finding of this simulation is that a PCB that is too large also results in poor bandwidth and poor maximum return loss. All the previous simulations demonstrated clearly that changes to one of the many possible layout parameters can change the antenna performance. Even if a perfect antenna optimised for a certain PCB ends up being copied to a PCB that is too big, then in the worst case the perfect antenna becomes a bad antenna. This fact applies not only to the simulated PCB track antenna discussed here but also to the many chip antennas on the market.

ILLUSTRATION 49: *Return loss of F antenna with change in length of PCB (A8)*



MARKERS:	MHz	dB	MHz	dB
a_IFA-DesignA8_65mm.s1p - S11				
	1: 791	-0.82	3: 880	-9.55
	2: 862	-6.49	4: 960	-1.68
b_IFA-DesignA8_75mm.s1p - S11				
	1: 791	-0.96	3: 880	-11.87
	2: 862	-9.65	4: 960	-1.84
c_IFA-DesignA8_85mm.s1p - S11				
	1: 791	-1.18	3: 880	-13.34
	2: 862	-15.45	4: 960	-2.06
d_IFA-DesignA8_95mm.s1p - S11				
	1: 791	-1.63	3: 880	-12.69
	2: 862	-29.69	4: 960	-2.33
e_IFA-DesignA8_105mm.s1p - S11				
	1: 791	-2.27	3: 880	-10.80
	2: 862	-16.74	4: 960	-2.80
e_IFA-DesignA8_125mm.s1p - S11				
	1: 791	-3.39	3: 880	-7.78
	2: 862	-8.13	4: 960	-4.34
f_IFA-DesignA8_115mm.s1p - S11				
	1: 791	-3.03	3: 880	-9.15
	2: 862	-11.11	4: 960	-3.41

ILLUSTRATION 50: *Smith chart of F antenna with change in length of PCB (A8)*



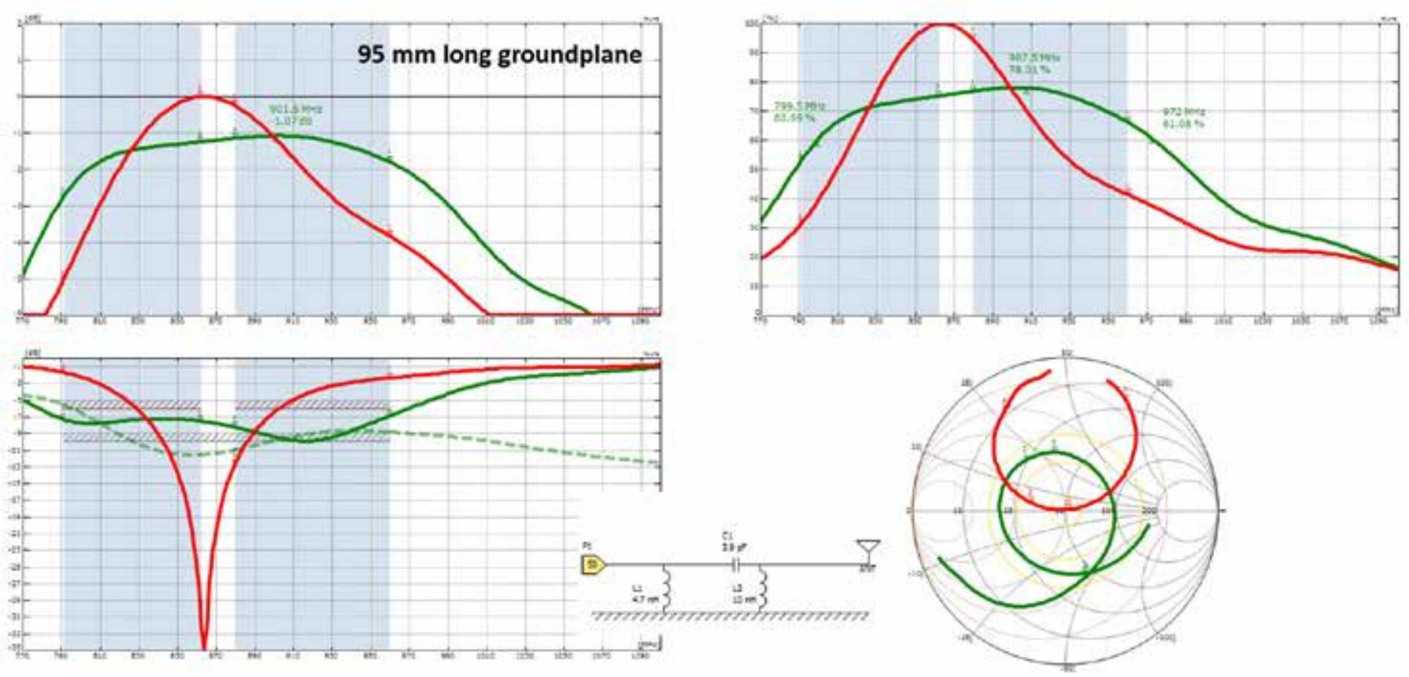
Atyune

MARKERS:	MHz	Ω	MHz	Ω
a_IFA-DesignA8_65mm.s1p - S11				
	1: 791	9.28+ 85.34j	3: 880	40.57- 30.37j
	2: 862	108.37- 53.43j	4: 960	5.91+ 23.77j
b_IFA-DesignA8_75mm.s1p - S11				
	1: 791	10.82+ 84.65j	3: 880	35.94- 17.40j
	2: 862	80.71- 31.91j	4: 960	6.63+ 25.06j
c_IFA-DesignA8_85mm.s1p - S11				
	1: 791	12.87+ 82.90j	3: 880	33.08- 5.96j
	2: 862	64.31- 13.16j	4: 960	7.59+ 26.37j
d_IFA-DesignA8_95mm.s1p - S11				
	1: 791	17.63+ 81.85j	3: 880	31.44+ 3.66j
	2: 862	53.12+ 1.29j	4: 960	8.77+ 27.63j
e_IFA-DesignA8_105mm.s1p - S11				
	1: 791	22.60+ 76.27j	3: 880	30.18+ 12.46j
	2: 862	44.92+ 12.98j	4: 960	10.68+ 28.41j
e_IFA-DesignA8_125mm.s1p - S11				
	1: 791	24.16+ 58.53j	3: 880	30.01+ 28.30j
	2: 862	34.57+ 31.91j	4: 960	16.56+ 28.56j
f_IFA-DesignA8_115mm.s1p - S11 -				
	1: 791	25.89+ 67.53j	3: 880	29.89+ 20.56j
	2: 862	39.11+ 23.21j	4: 960	13.15+ 29.09j

The following simulation was optimised with 85 mm, 95 mm and 105 mm long ground plane with a matching network containing 2-3 passive components. The focus was on the best performance in dB or antenna efficiency. With the 95 mm PCB, an efficiency of better than 50 % is possible with three components. If the centre frequency of the antenna is shifted by 10 MHz, an efficiency of 60 % is possible. The peak value would then be 78 % efficiency. Compared to chip antennas, this is a similar value or even a better value. With the user-designed F antenna, the radiator can easily be changed by 10 % to achieve the requested centre frequency.

With a 105 mm ground plane, an efficiency of 67 % and 77 % is possible on the corner frequencies. The peak value is 83.62 % antenna effectiveness. With the 85 mm long ground plane, the efficiency drops to 45 %. Just keep in mind that the simulated structures were not optimised in impedance by changing the shorting arm. It is therefore likely that a PCB with a length of 85 mm can still be optimised for an efficiency of better than 50 %.
Since an antenna for the licence-free band in Europe at 868 MHz and USA 915 MHz only requires a bandwidth of 65 MHz, an 85 mm long ground plane can cover both bands at the same time.

ILLUSTRATION 51: *Gain, efficiency, return loss and Smith Chart of F antenna a PCB length of 95 mm(A8)*



Author: Harald Naumann
https://www.linkedin.com/in/naumann/

ILLUSTRATION 52: *Gain, efficiency, return loss and Smith Chart of F antenna a PCB length of 105 mm(A8)*

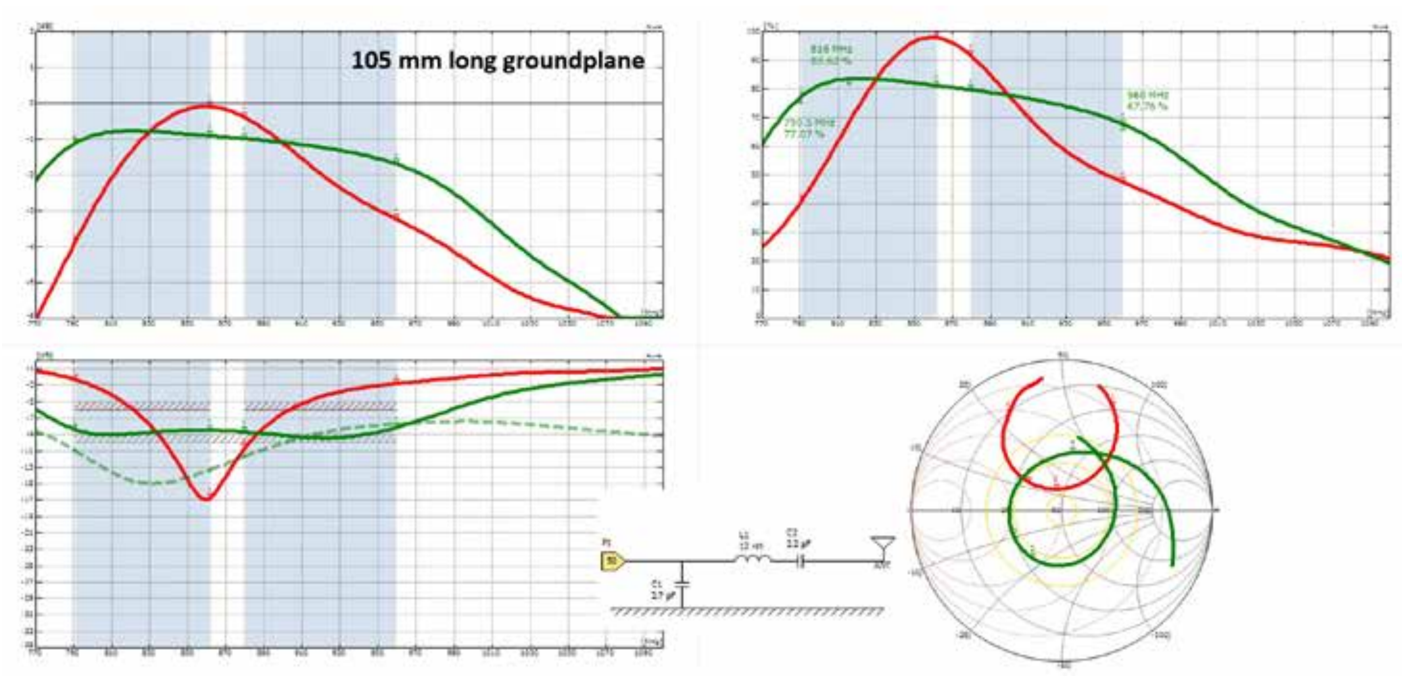
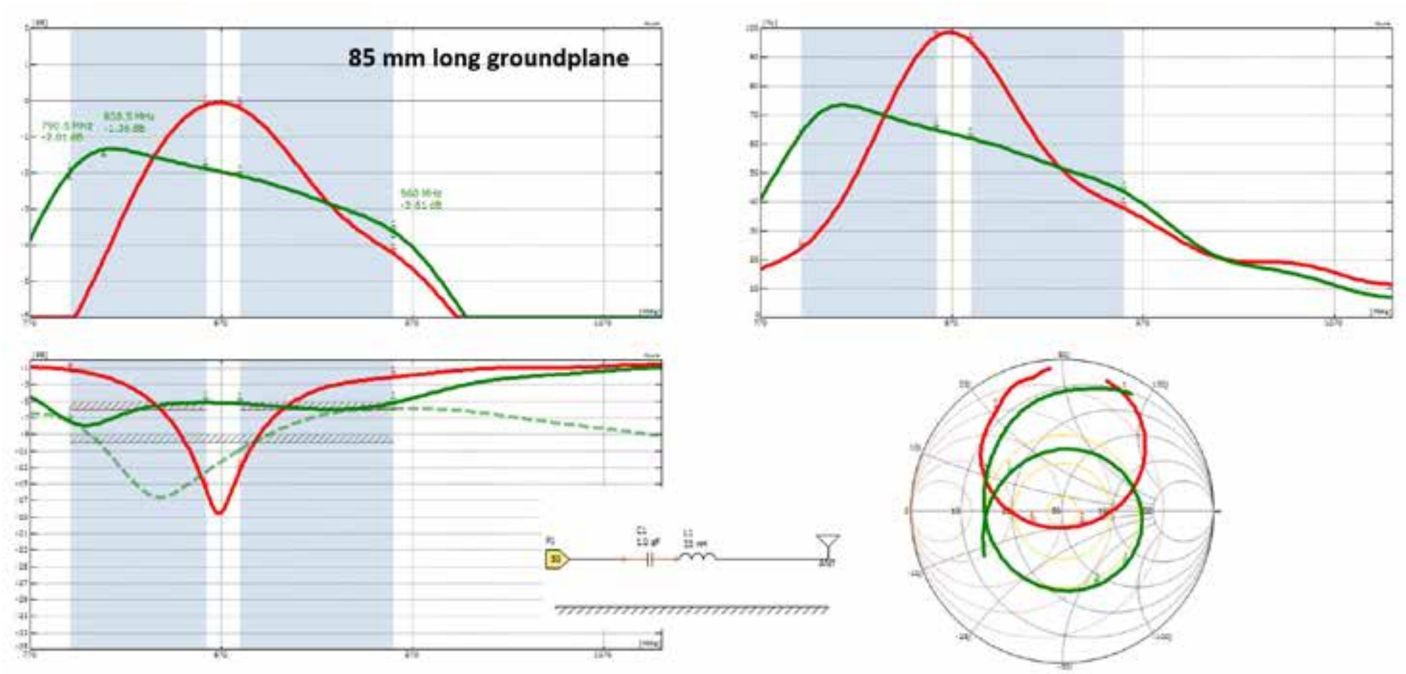
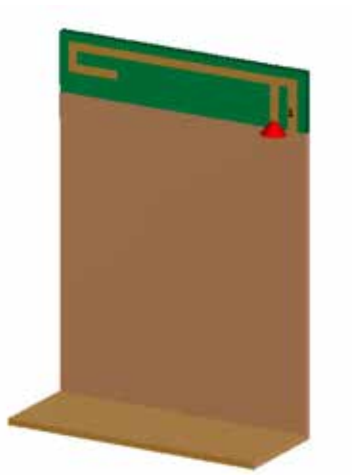


ILLUSTRATION 53: *Gain, efficiency, return loss and Smith Chart of F antenna a PCB length of 85 mm(A8)*



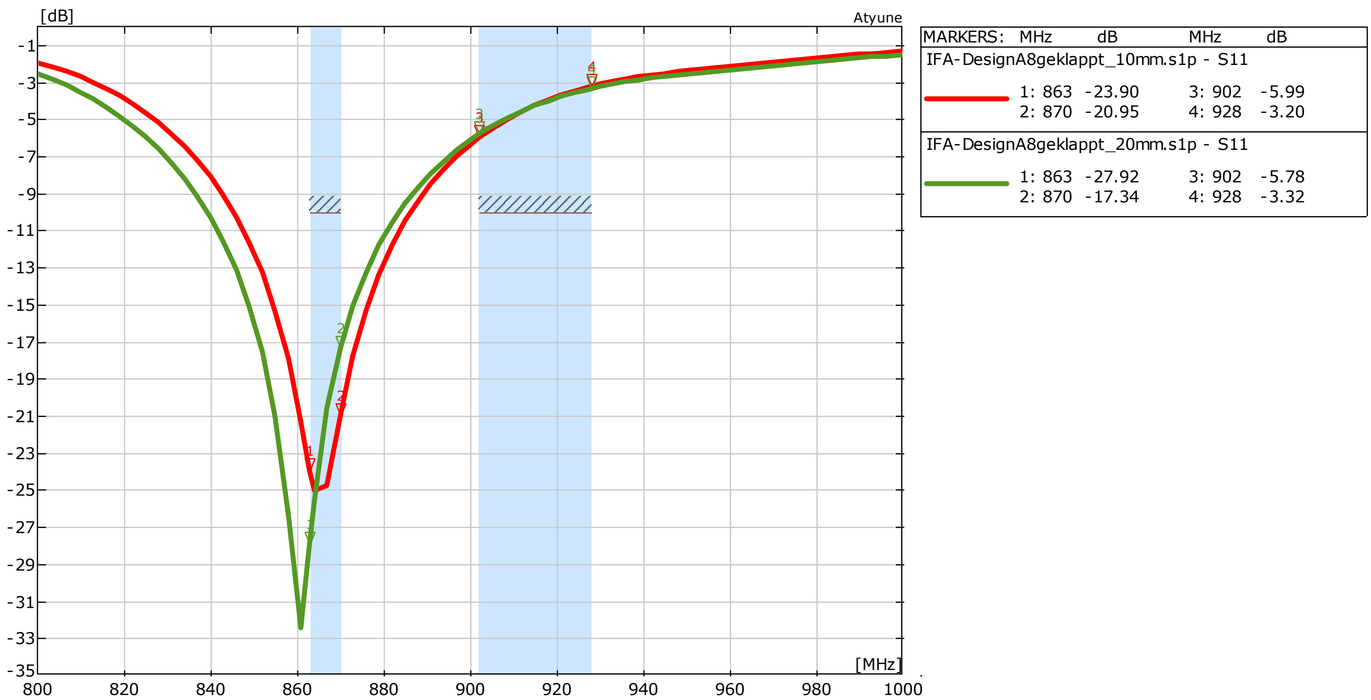
F ANTENNA AT 90 DEGREES WITH GROUND PLANE (A8 BENT)

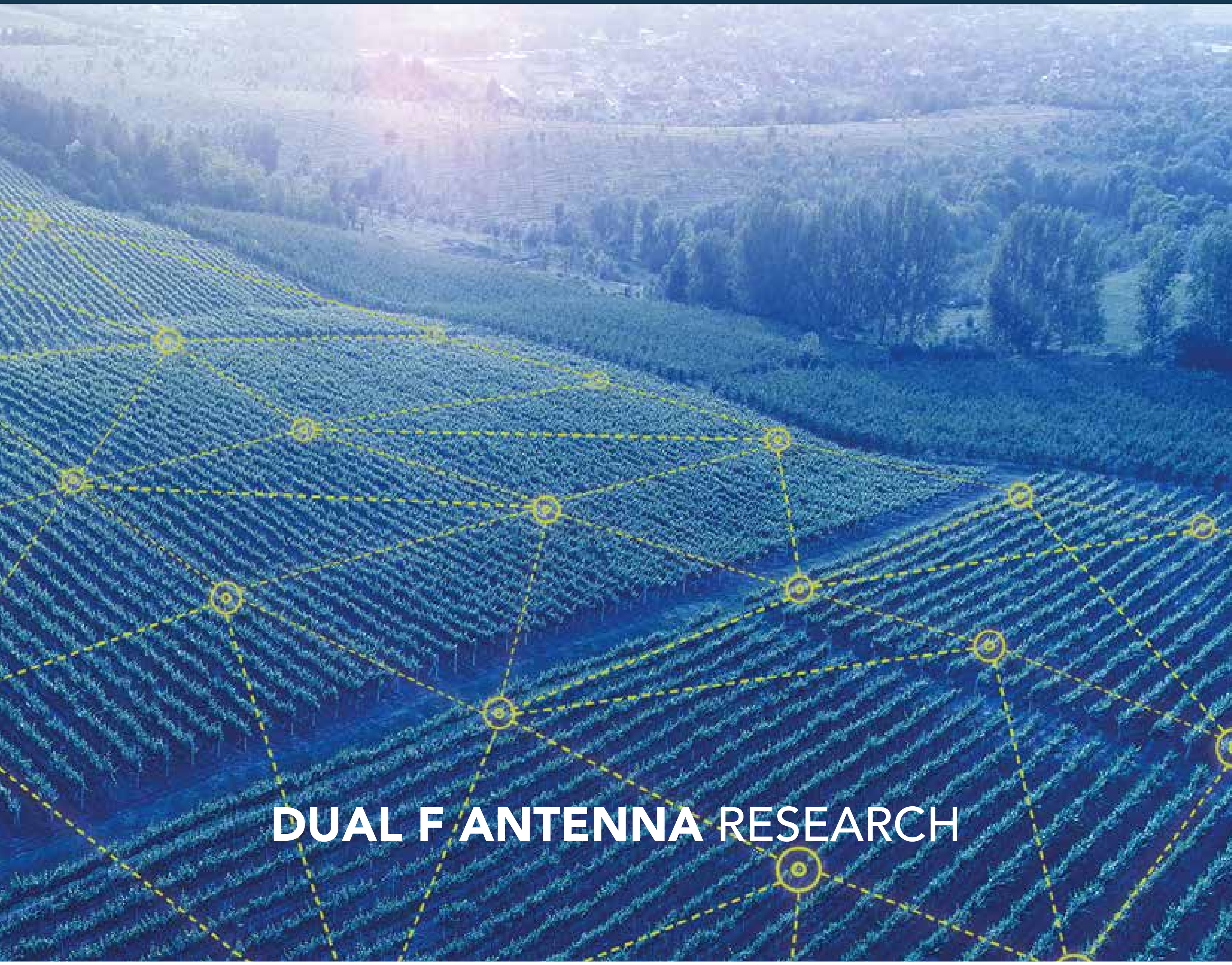
ILLUSTRATION 54: *F antenna at 90 degrees with ground plane (A8 bent)*



In this simulation the PCB was extended by 10 mm and 20 mm by folding the main PCB 90°. The conclusion is that it is possible to extend a PCB at an angle of 90° in order to increase the size of the ground plane. Standard PCBs made of FR4 can be attached and then bent. If the copper of the PCB is processed beforehand, then this bending is possible several times before the material breaks. Since such a PCB is only bent once during assembly, it is very unlikely that the PCB will break. The finding in this simulation is that a PCB can be extended by bending it 90° in order to increase the mass surface.

ILLUSTRATION 55: *F antenna at 90 degrees with ground plane (A8 bent)*

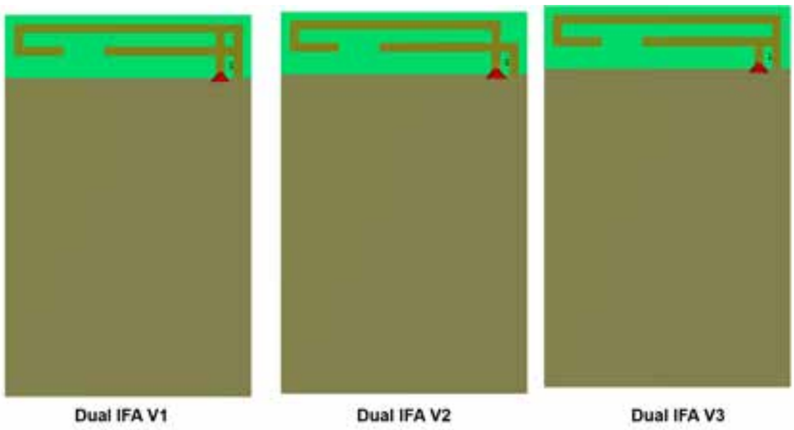




DUAL F ANTENNA RESEARCH

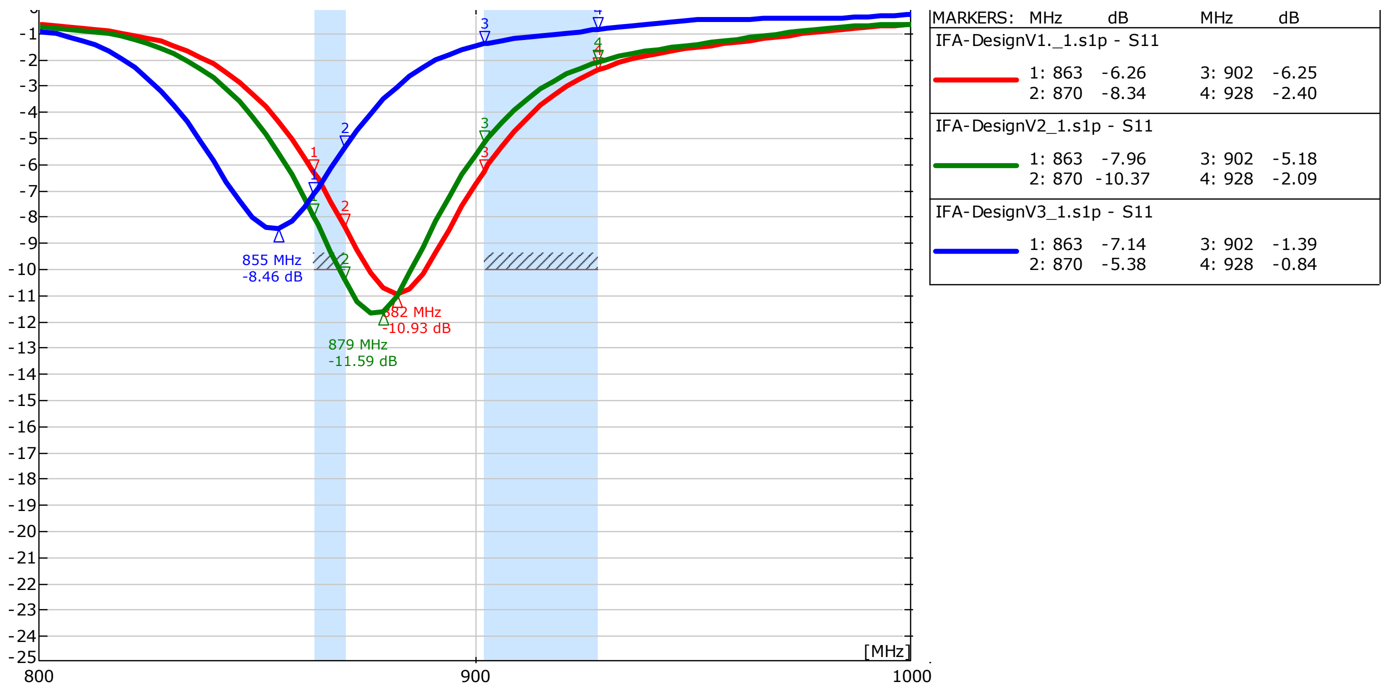
Author: Harald Naumann
https://www.linkedin.com/in/naumann/

ILLUSTRATION 56: *Dual F antenna research*



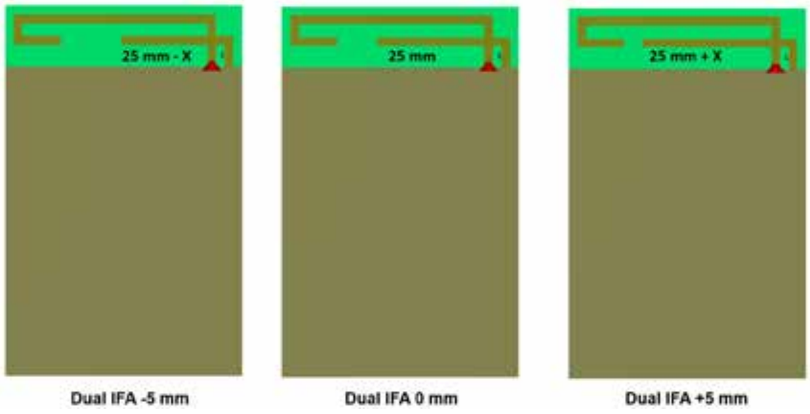
In this simulation, several possible structures for a dual inverted F antenna were investigated. Version 1 is the classic version, which can be found in several places. In version 3, the feed was placed at the second radiator. In version 2, the best result in return loss was achieved in the preliminary investigation. For this reason, the F antenna in version 2 is considered in more detail in the further simulation. When two F antennas are combined into a dual F antenna, a trade off must be made. With only one shorting bar, you can only better optimise the frequency range of one or the other antenna.

ILLUSTRATION 57: *Return loss of dual F antenna research*



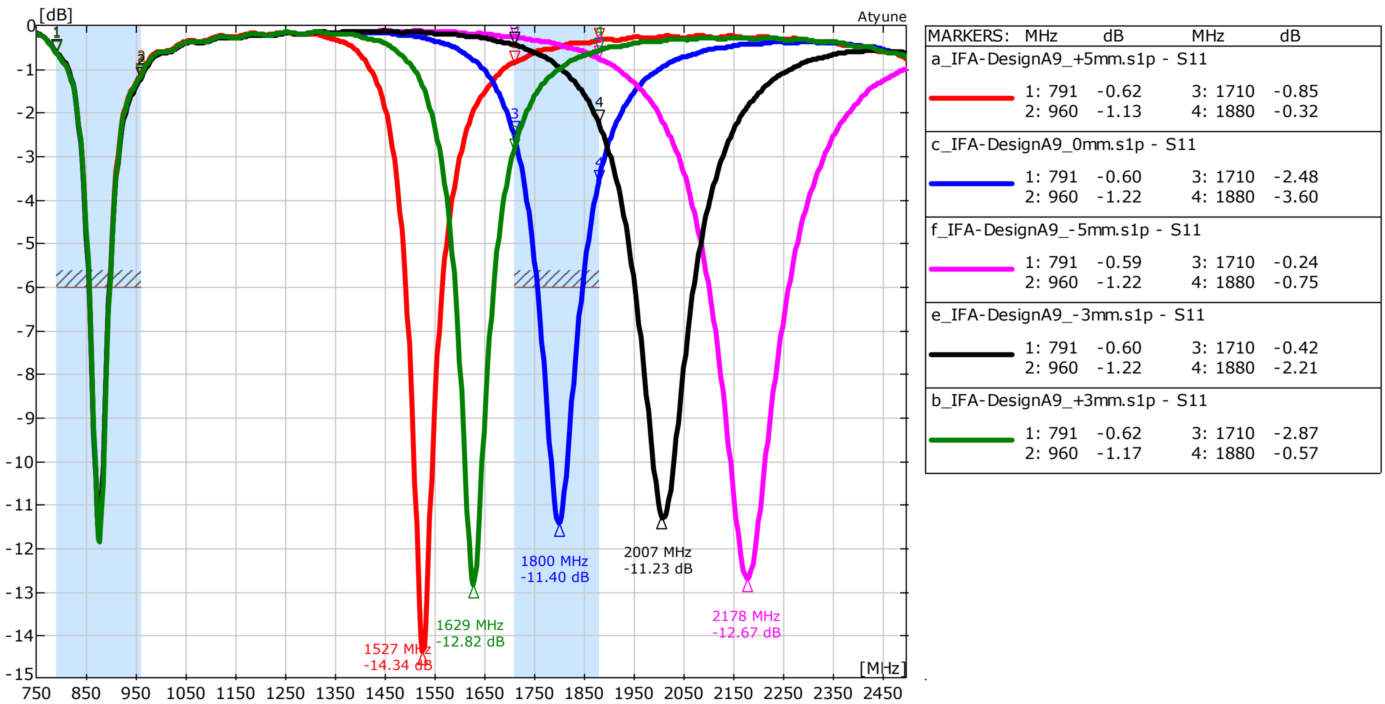
DUAL F ANTENNA WITH CHANGE IN LENGTH OF RADIATOR (A9)

ILLUSTRATION 58: *Dual F antenna with change in length of radiator (A9)*



In this simulation, the length of the second radiator was lengthened or shortened. The radiator with zero length had a length of 25 mm and is represented by the blue curve in the simulation. For the green and red curves, the radiator was extended by 3 mm and 5 mm respectively. For the black and pink curves, the radiator was shortened by 3 mm and 5 mm respectively. It is interesting to note that both lengthening and shortening improve the return loss. Each lengthening or also shortening of the second radiator with a resonance frequency of approximately 1800 MHz causes no change in the other radiator at approximately 900 MHz. The conclusion from this simulation is that the two radiators of the dual antenna can be changed independently of each other.

ILLUSTRATION 59: *Return loss Dual F antenna with change in length of radiator (A9)*



DUAL F ANTENNA OF THE WIDTH OF THE RADIATOR (A10)

In this simulation, the width of the second radiator was expanded in several steps from 0.5 mm to 3 mm. The widest radiator with 3 mm shows the best value in return loss. It is expected that widening to 4 mm would again improve the return loss.

The finding in this simulation is that the width of the radiator influences the peak value of the return loss. We have found the same effect in other simulations before. The wider the radiator, the better the return loss.

ILLUSTRATION 60: *Dual F antenna of the width of the radiator (A10)*

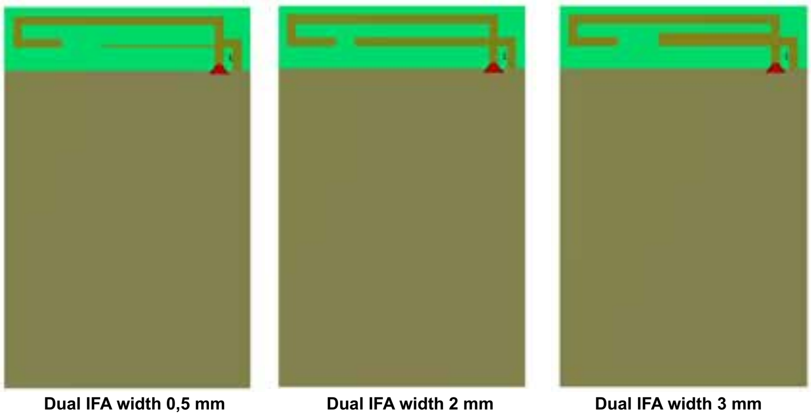
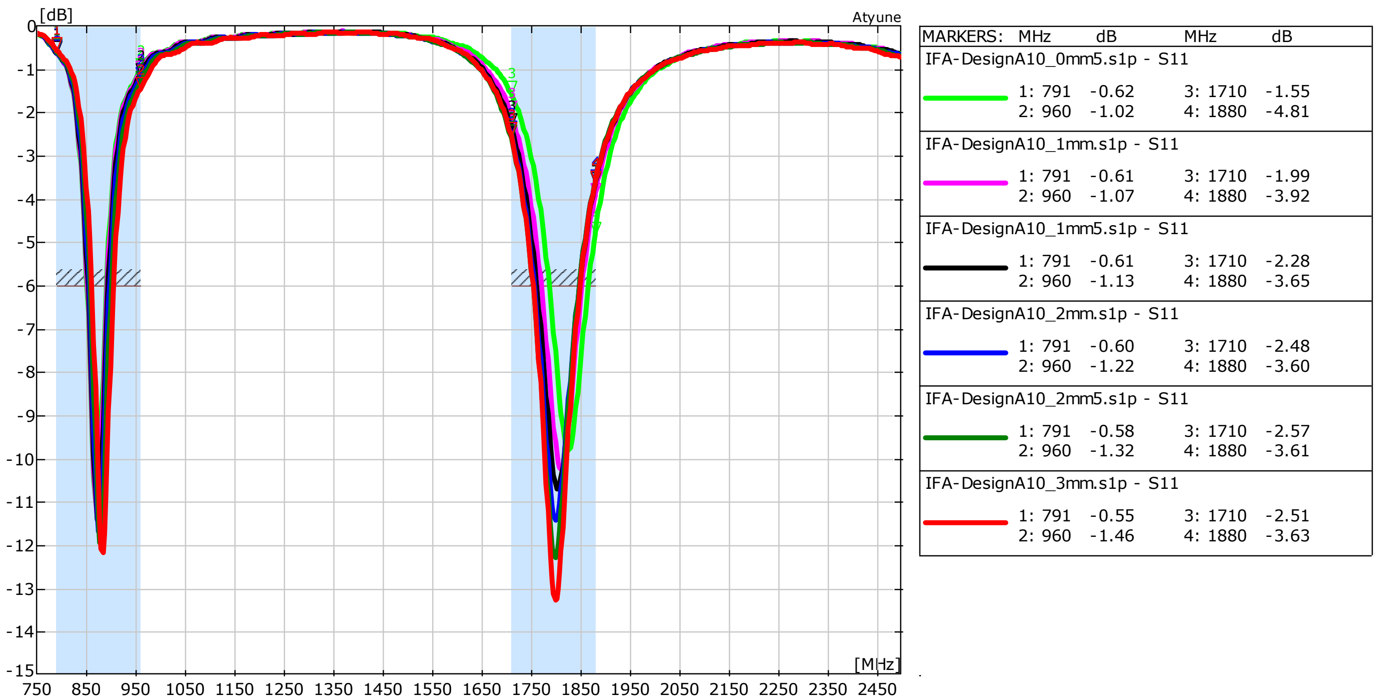
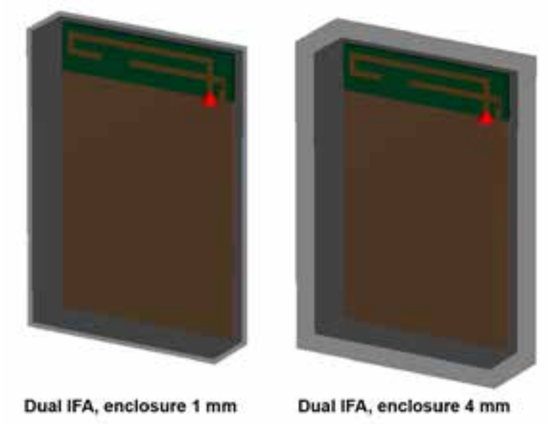


ILLUSTRATION 61: *Dual F antenna of the width of the radiator (A10)*



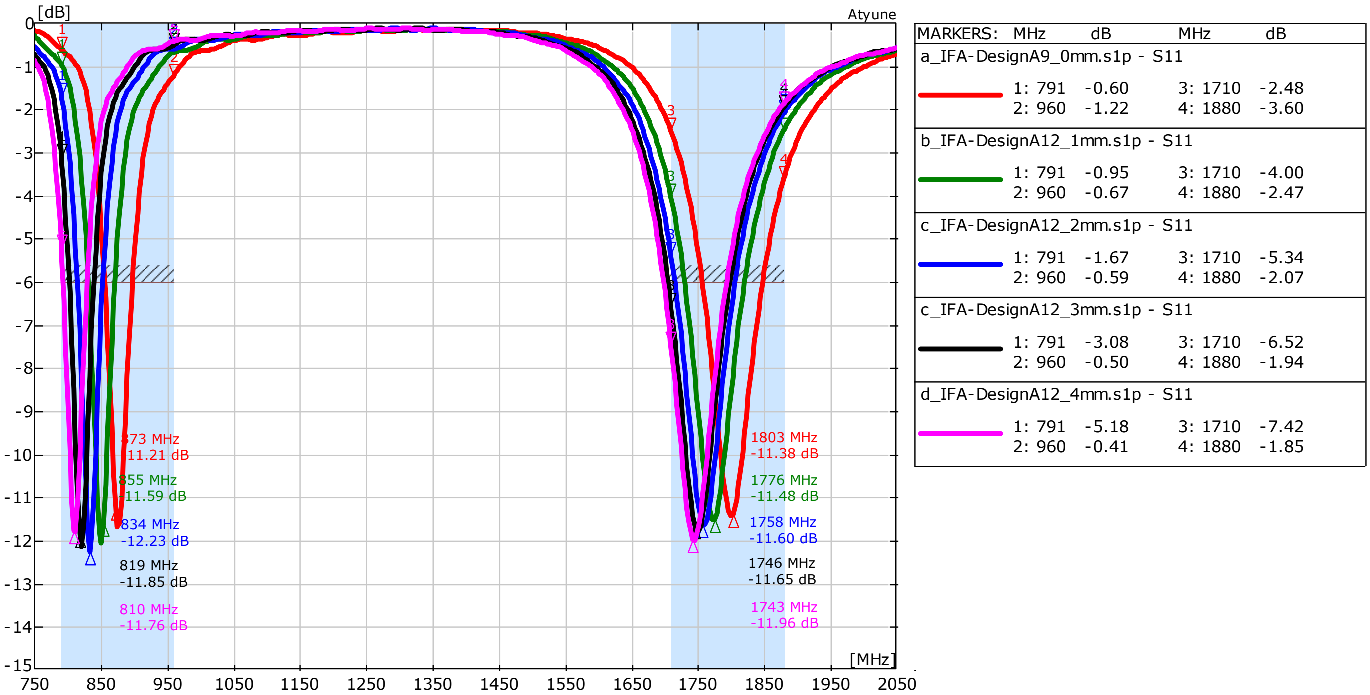
DUAL F ANTENNA AND THICKNESS OF **THE HOUSING (A12)**

ILLUSTRATION 62: *Dual F antenna and thickness of the housing (A12)*



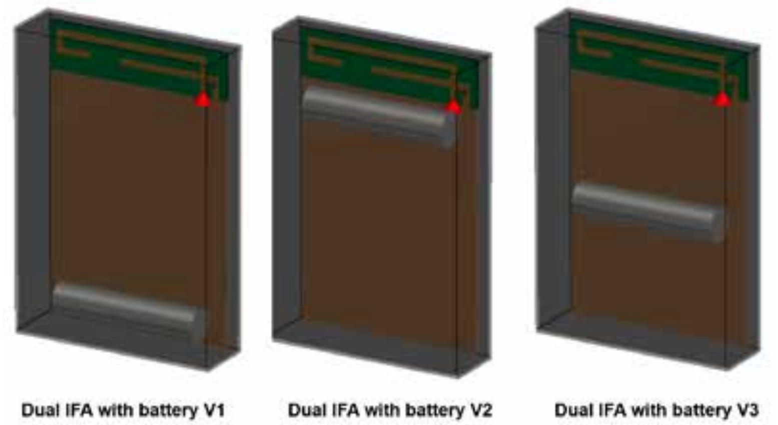
In this simulation, the influence of the plastic enclosure on the centre frequency and the return loss of the antenna is investigated. The thicker the material of the enclosure, the lower the centre frequency of the antenna. Furthermore, a higher epsilon R of the plastic also leads to a reduction of the centre frequency. The maximum value of the return loss hardly changes. The fact that the centre frequency changes to a lower frequency due to the plastic in the nearby vicinity can be easily compensated for by shortening the antenna radiator.

ILLUSTRATION 63: *Return loss dual F antenna and thickness of the housing (A12)*



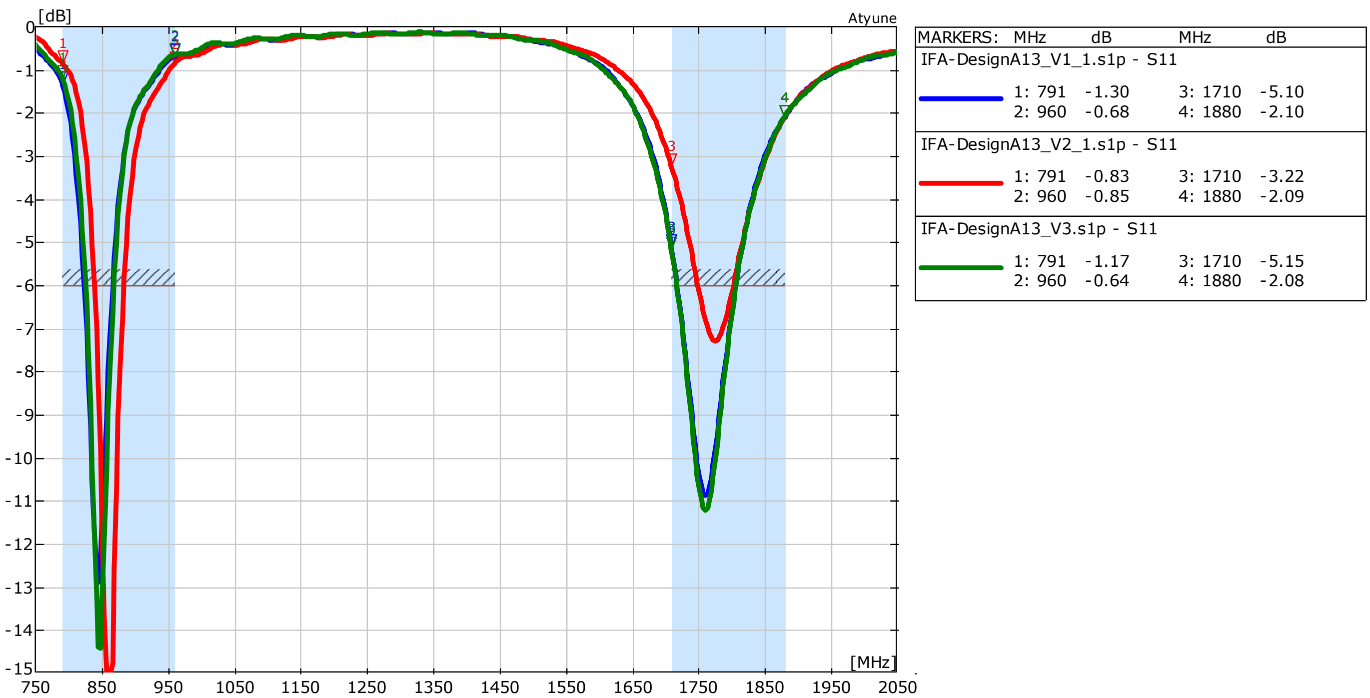
DUAL F ANTENNA WITH **BATTERY (A13)**

ILLUSTRATION 64: *Dual F antenna with battery (A13)*



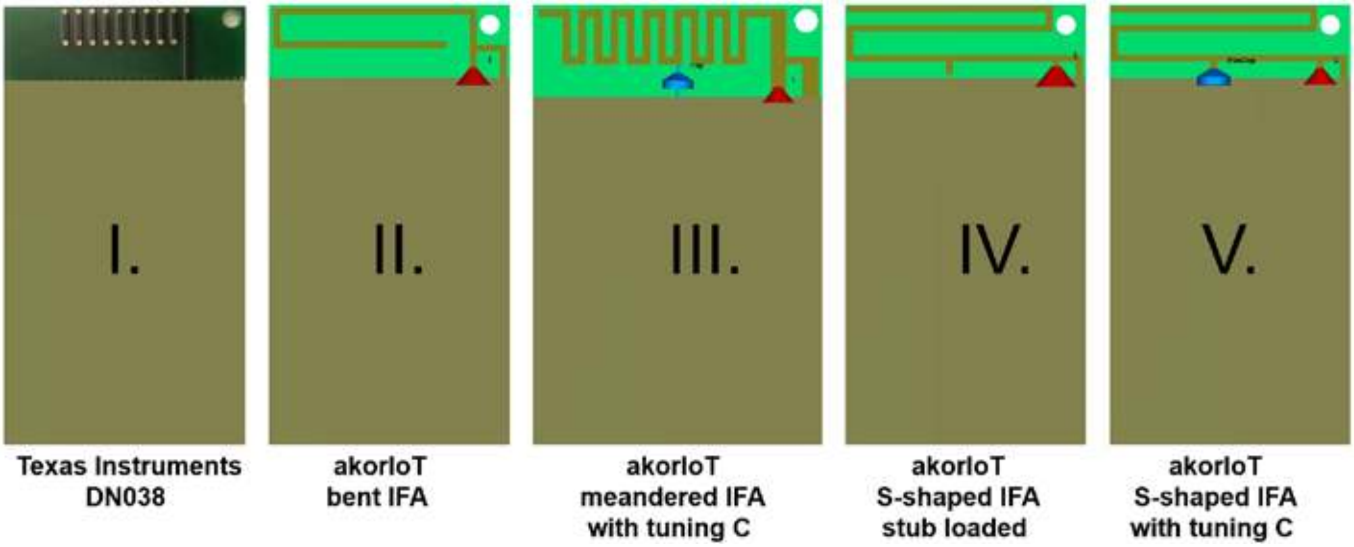
In this simulation, the influence of the battery on the antenna is visualised. The battery in this case is a metal cylinder connected to the ground. If the battery is at the bottom of the PCB, it has little influence on the antenna. In the middle of the PCB, the influence of the battery is not significant. However, if the battery is placed close to the antenna, the second radiator for 1800 MHz is very strongly influenced by the battery. As simulation shows us only the return loss, note that if the battery is placed at the top end near the antenna, then it will cause a shadow for the radio wave. The propagation of a radio wave is similar to light. The propagation is in the form of a beam in all directions. Objects that interrupt the light beam or even the radio wave will cause a shadow. If possible, you should therefore avoid placing a battery or similar metallic objects such as a display near the antenna.

ILLUSTRATION 65: *Return loss Dual F antenna with battery (A13)*



OPTIMISATION THROUGH IFA AND **CAPACITIVE TUNING**

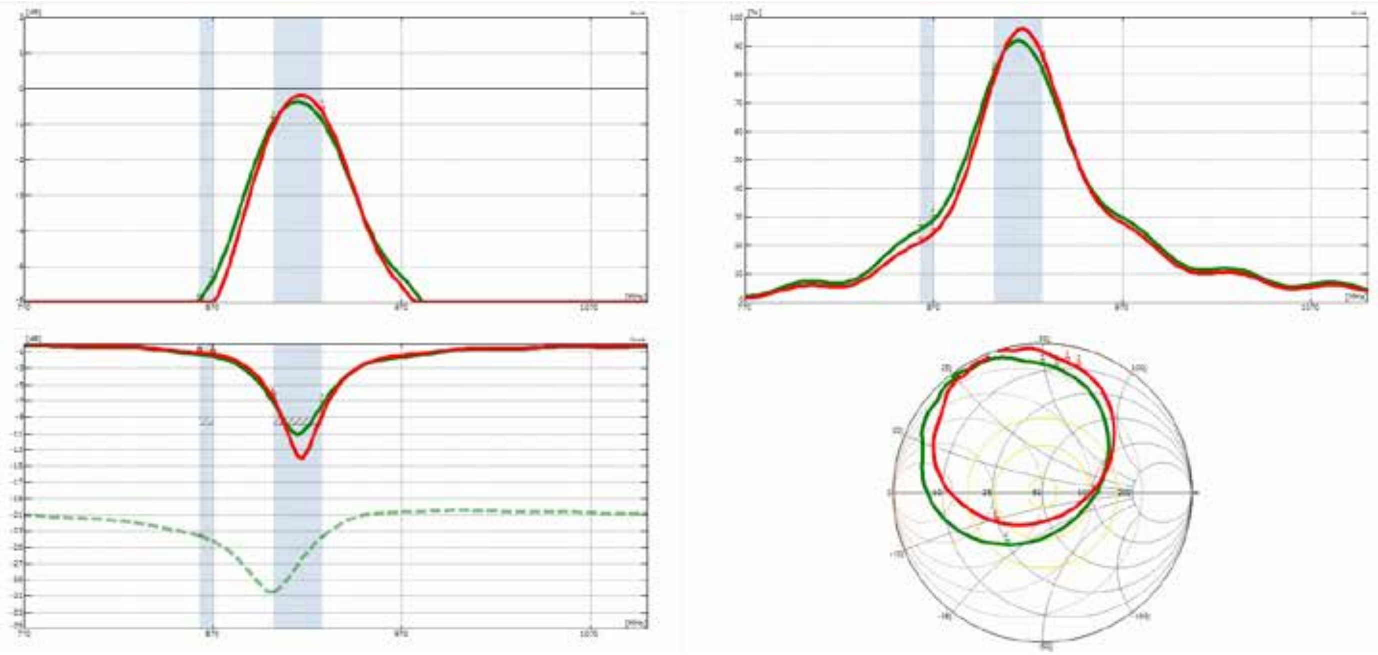
ILLUSTRATION 66: *Antenna I based on TI DN038. Antenna II to V on same PCB space but better performance*



The graphic above shows the original antenna from Texas Instruments from the design note DN038. We had already specified the technical parameters of this antenna at the beginning of the document. The aim of antenna II, III IV and V is to surpass antenna I technically. At the same time, the installation space for the antenna should not be larger than that of Texas Instruments. In order to be as comparable as possible, even the hole in the PCB at the top right has been adopted. The hole in the PCB means that no conductors can be routed there.

Optimisation using an inverted F antenna (II)
In the first approach, a folded F antenna was simply used. With an F antenna, the impedance was adjusted by changing the shorting arm. In this case, the length of the loop was optimised to give an antenna efficiency of 95% at the peak. This is represented in the graphs below by the red curves. The green curve represents the attempt to optimise the antenna with a matching network. However, since the antenna has already been optimised with the shorting arm, no further improvement is possible. The simulation software has chosen to use a capacitor as the default component, but has not been able to achieve any improvement. It is the other way round, the capacitor causes losses and the efficiency drops to about 90 % at the peak. The finding in this simulation is that even this simple F antenna outclasses in its impedance matching with the shorting arm all mentioned Texas Instruments antennas. The second finding is that with the shorting arm we can optimise an antenna to such an extent that further optimisation by components in the matching network is no longer necessary.

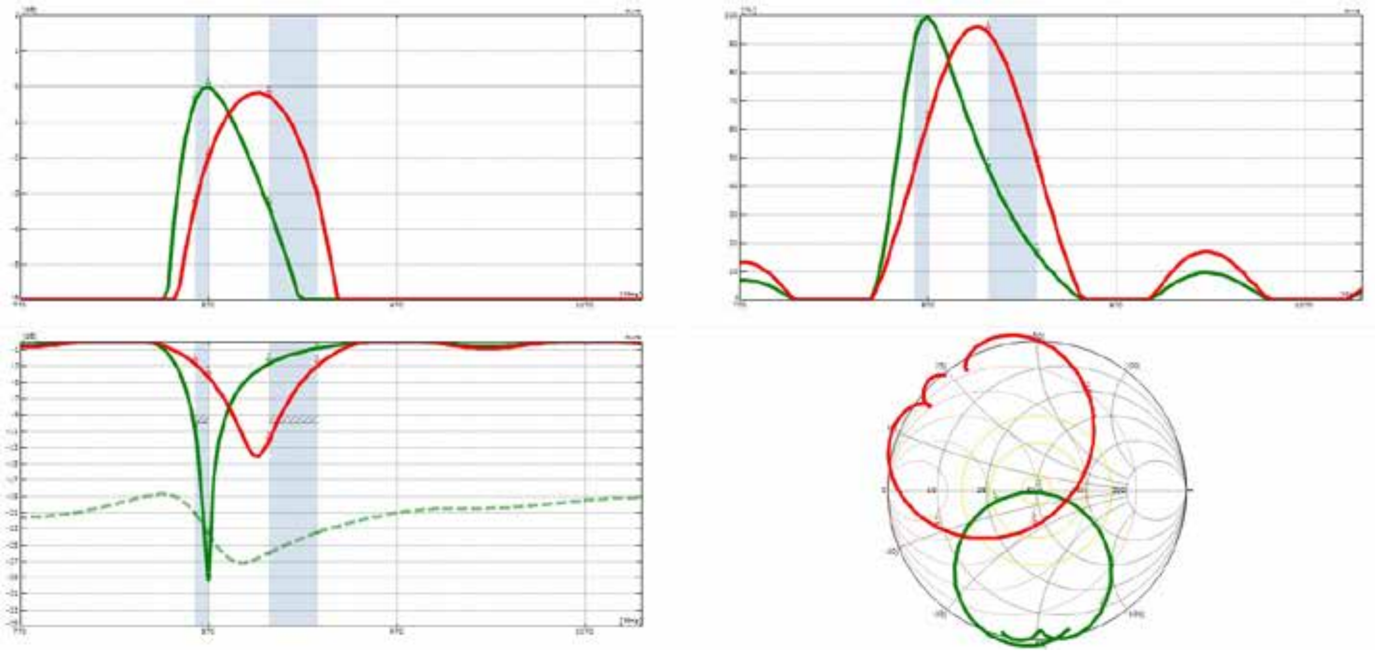
ILLUSTRATION 67: *Gain, efficiency, return loss and Smith Chart for antenna II*



Optimisation using a meandered inverted F antenna (III)

In this simulation, a meandered inverted F antenna was extended with a capacitor to tune the antenna. The antenna represented by the red curve has its centre frequency between the European frequency of 868 MHz and the American frequency of 915 MHz. By changing the capacitor, the antenna can work for either 868 MHz and 915 MHz. This requires only two capacitors and a switching transistor. In the Texas Instruments proposals, the possibility of switching is not mentioned at all. In all three versions of the documentation it is assumed that different antenna structures have to be built for different frequency bands. This leads to double inventory storage and double costs in purchasing and manufacture. The proposal we have shown requires only one PCB, does not take up more space and, on top of that, has a much better antenna efficiency. The green curve shows an optimisation with a passive component in the antenna's adaptive network. If requested, this antenna can be switched between the two frequencies for Europe and America with the addition of two simple components to the antenna's matching network. However, since the efficiency of the antenna is already extremely high without the matching network, these costs for components in the matching network can be saved. The insight in this simulation is that a fully optimised antenna cannot be further optimised by adding more components. The second insight is that this antenna is clearly better than the design from Texas Instruments.

ILLUSTRATION 68: *Gain, efficiency, return loss and Smith Chart for antenna III*

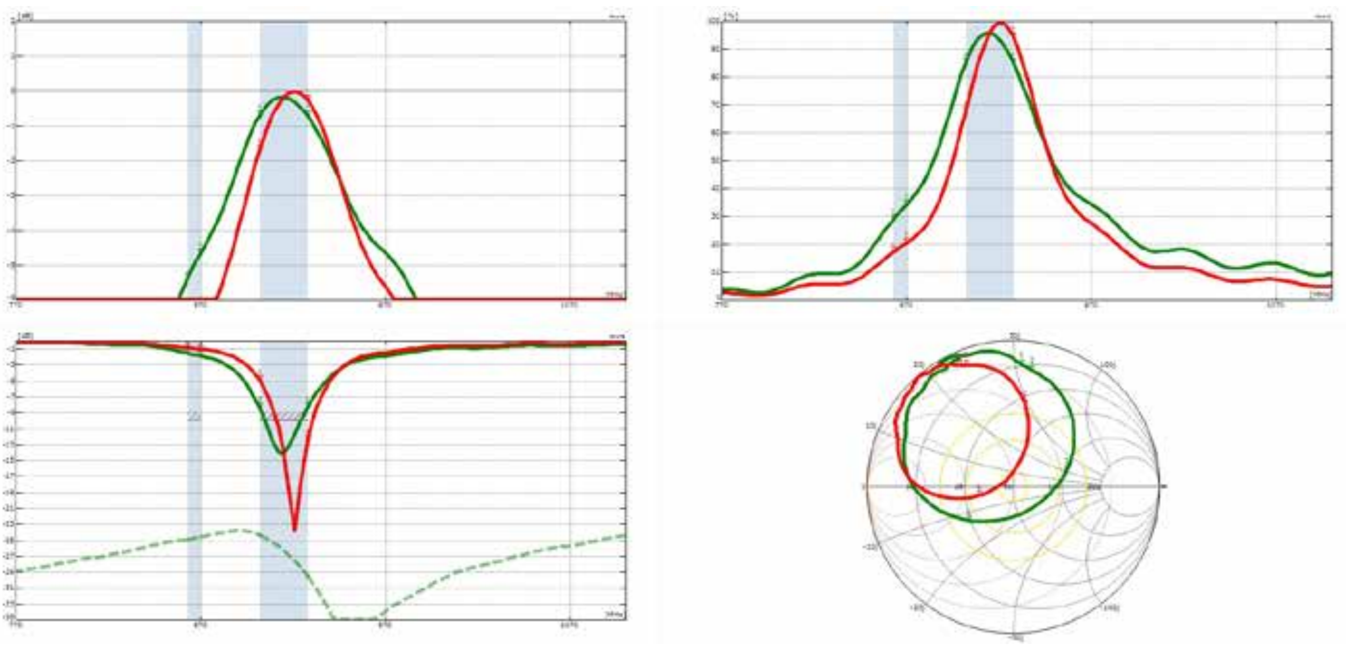


Author: Harald Naumann
https://www.linkedin.com/in/naumann/

Optimisation using an inverted F antenna with S-structure (IV)

This simulation shows an antenna with an S-structure . The red curve shows the antenna without the use of other passive components in the matching network. The small rectangular stub on the antenna near the ground plane represents a capacitor. The rectangular area facing the ground plane is the capacitor for matching. This means that there are no costs for equipping or procuring the antenna. The red curve shows a peak value of 100 % in antenna efficiency without the use of additional components. Since the antenna was optimised in impedance by the shorting arm and tuned by the small stub, no further optimisation is possible by adding components in the matching network. The software tries to improve the antenna and adds a capacitor in the matching network. This causes the green curve for the efficiency to shift a little to the left, but at the same time the efficiency drops to 95 %. Optimising the centre frequency by lengthening the radiator would do the same, but keep the efficiency at 100%. This shows that the mechanically optimised antenna cannot be optimised with additional components. This antenna is also far better than the Texas Instruments antenna.

ILLUSTRATION 69: *Gain, efficiency, return loss and Smith Chart for antenna IV*

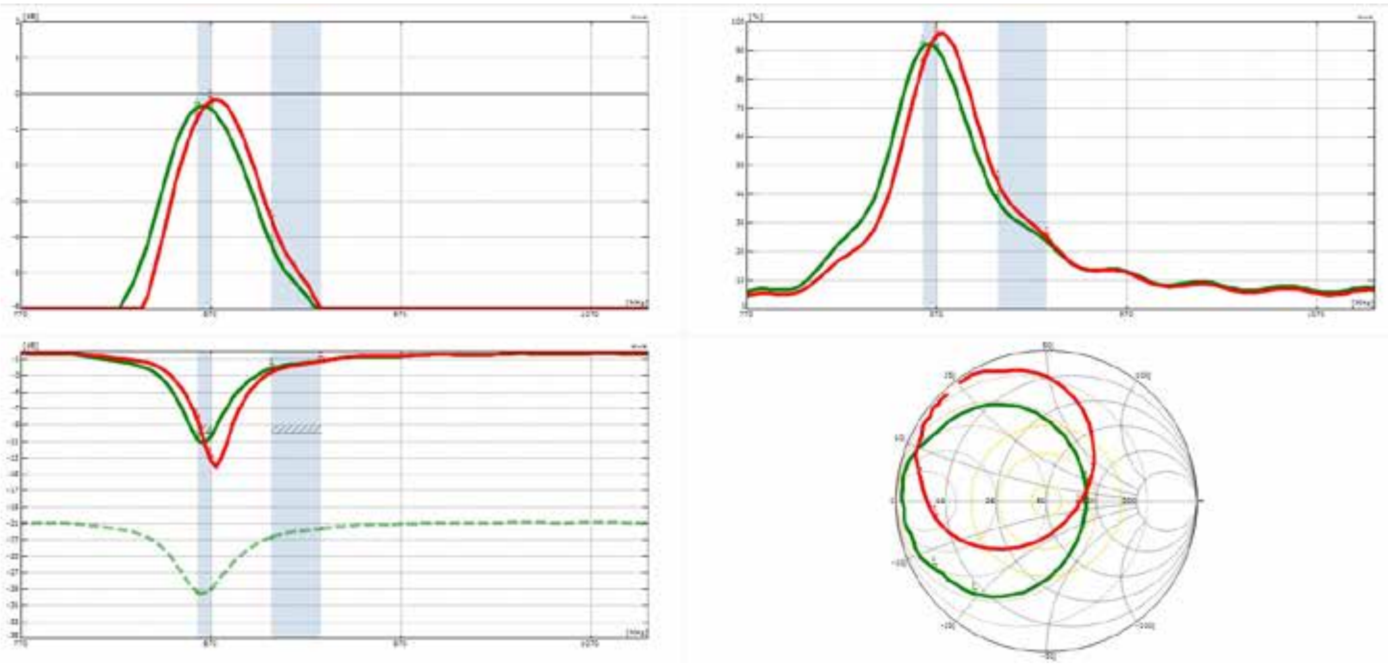


Author: Harald Naumann
https://www.linkedin.com/in/naumann/

Optimisation using inverted F antenna with S structure and tuning capacitor (V)

The antenna in this simulation is very similar to antenna number IV. Here, a chip capacitor was used to balance the antenna. If this capacitor is made switchable, the antenna can be switched between 868 MHz and 915 MHz. The capacitor in the simulation tunes a resonance frequency of approximately 868 MHz. If this capacitor is changed by switching, then the American band with 915 MHz can also be covered with the same PCB. Again, a component in the matching network was used to shift the antenna's centre frequency minimally downwards. To switch between the two frequencies, a capacitor can be used for tuning and thus for shifting the centre frequency. At the same time, other components in the matching network can be switched over. The possibility of switching the centre frequency was not considered in any of the three design notes from Texas Instruments. The finding in this simulation is that shifting the centre frequency again causes the efficiency of the antenna to drop a little. The second finding is that this antenna shows a better efficiency compared to the Texas Instruments antennas and can be switched between frequencies at the same time.

ILLUSTRATION 70: *Gain, efficiency, return loss and Smith Chart for antenna V*



Author: Harald Naumann
https://www.linkedin.com/in/naumann/

Inverted F antenna with S structure and tuning capacitor (V) optimised in a plastic enclosure
In this simulation, we summarise the points we have learned and test an inverted F antenna with an S-shaped structure and capacitive tuning in a plastic enclosure made of ABS. This means that the influence of the plastic is included in the simulation in the graphics shown.

ILLUSTRATION 71: *SFIA with tuning C and enclosure*

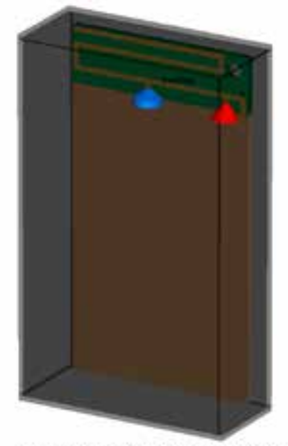

SIFA with tuning capacitor and enclosure

ILLUSTRATION 72: *Simulation of the radiated energy in 3D at 850 MHz*

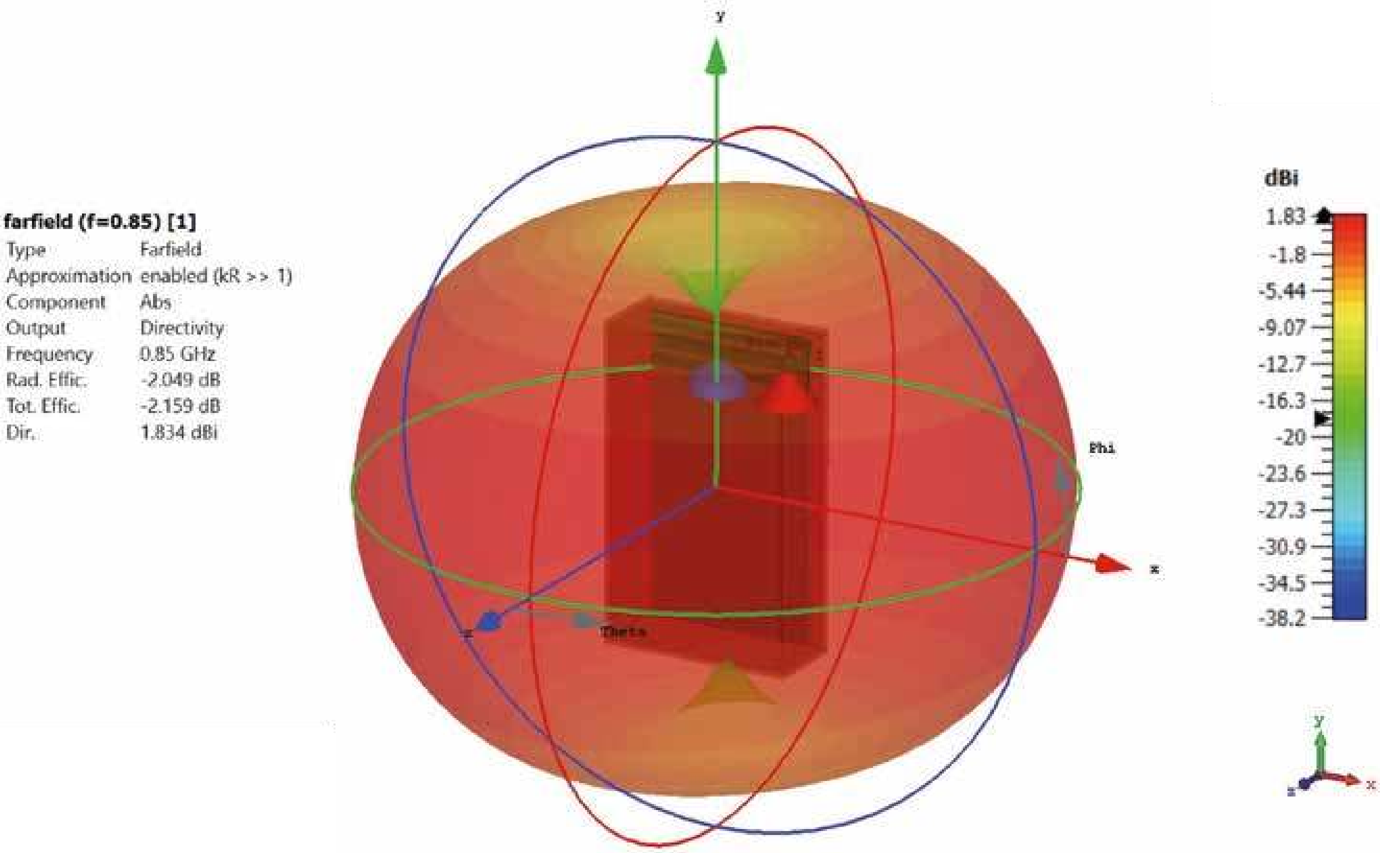
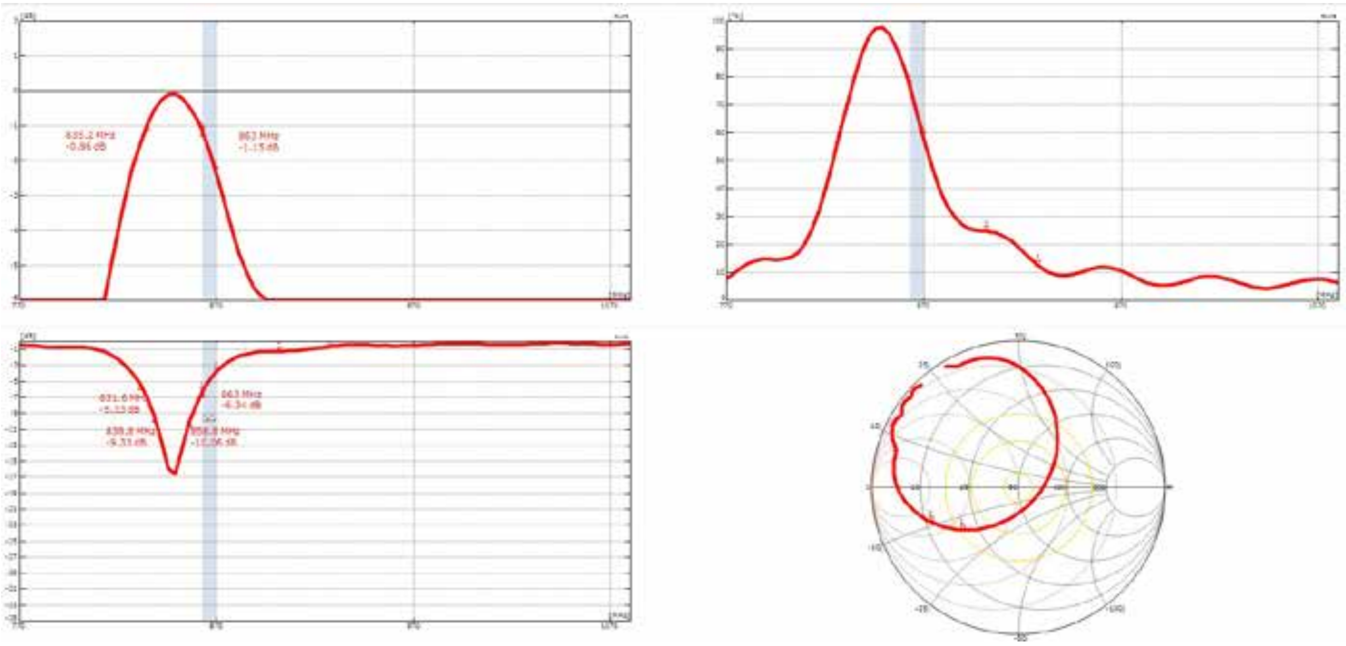


ILLUSTRATION 73: *Gain, efficiency, return loss and Smith Chart for antenna inside the plastic enclosure at 850 MHZ*



The four curves with gain, efficiency, return loss and Smith chart show the initial design of the antenna at 850 MHz without optimising the radiator to the centre frequency of 868 MHz. The bandwidth of the antenna was evaluated by the markers on the band corners at a dip of -1 dB. The delta between 835 MHz and 863 MHz is 28 MHz. The second observation was made using a return loss of -10 dB. Between 838 and 856 MHz a delta of 18 MHz was detected. With a return loss of -6 dB, the lowest value is 831 MHz and the highest value is 863 MHz. The delta is therefore 32 MHz. If you accept the -1 dB drop on the band corners, the antenna is well suited for the American frequency band at 915 MHz with 28 MHz bandwidth. Since only 7 MHz bandwidth is needed in the European band, the drop in efficiency at the band corners is hardly measurable. The next step is to adjust the length of the radiator to 868 MHz.

When looking at the S1P data, one must always be aware that the software Atyune considers the antenna as a dipole and only tells us how much energy cannot be taken over by the dipole. Atyune considers the matching network as a quadripole and told us how much energy is reflected and transferred into the antenna after the matching network at the end. Atyune cannot determine whether this energy is then actually radiated or absorbed in the enclosure, for example.

Author: Harald Naumann
https://www.linkedin.com/in/naumann/

Measurement of the radiated RF power of the final IoT device

ILLUSTRATION 74: *MegiQ RMS setup up to measure the radiated energy in 3 axes*

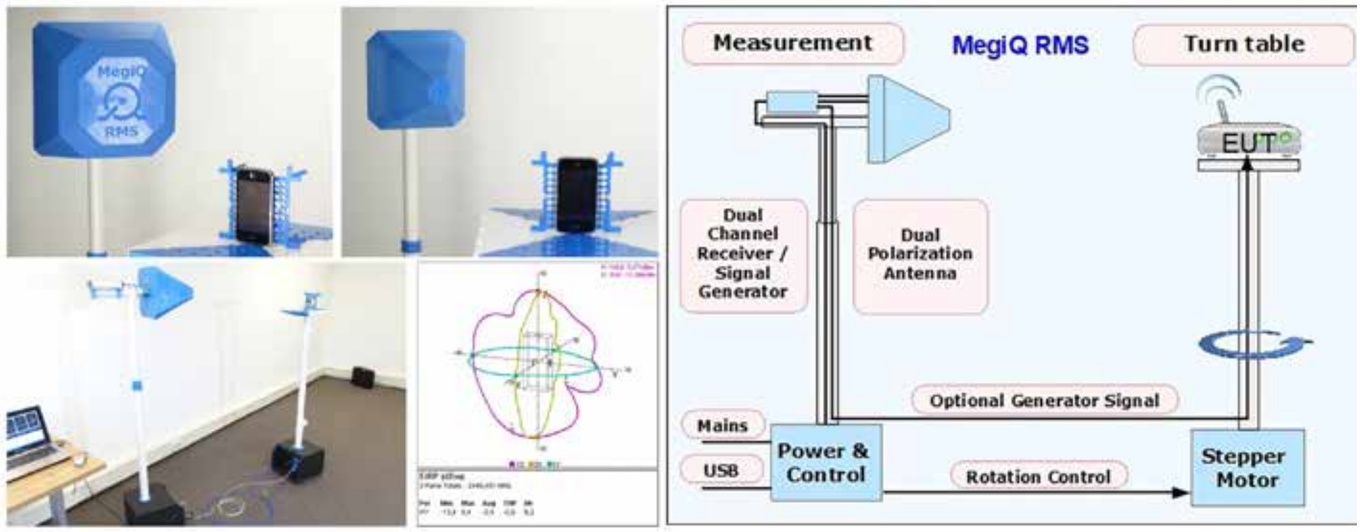
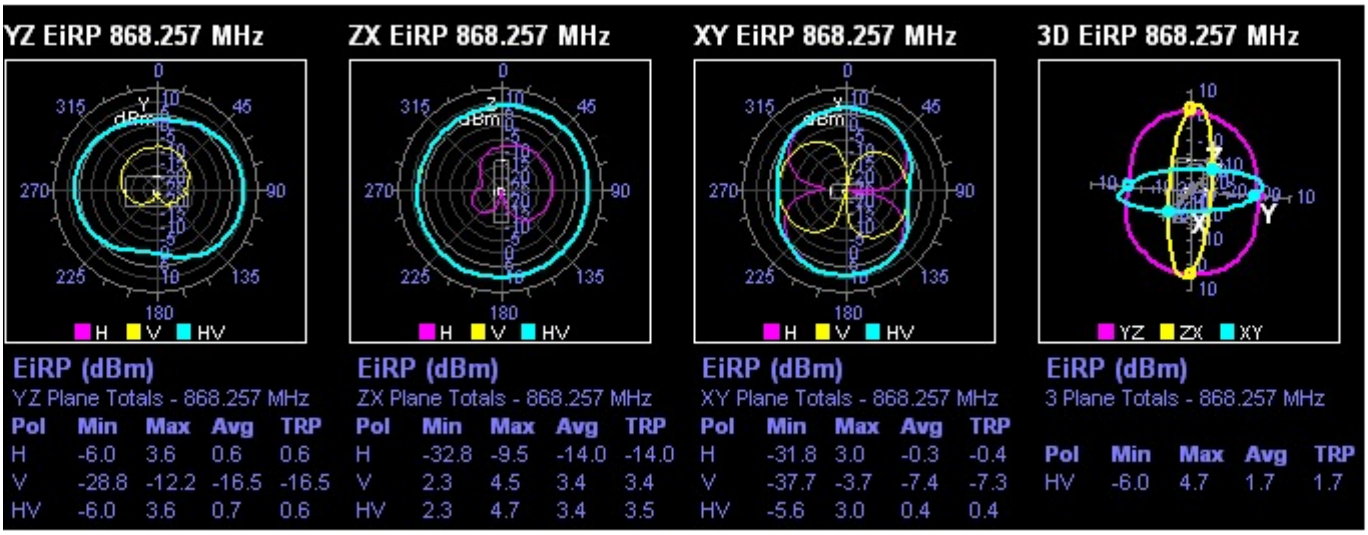


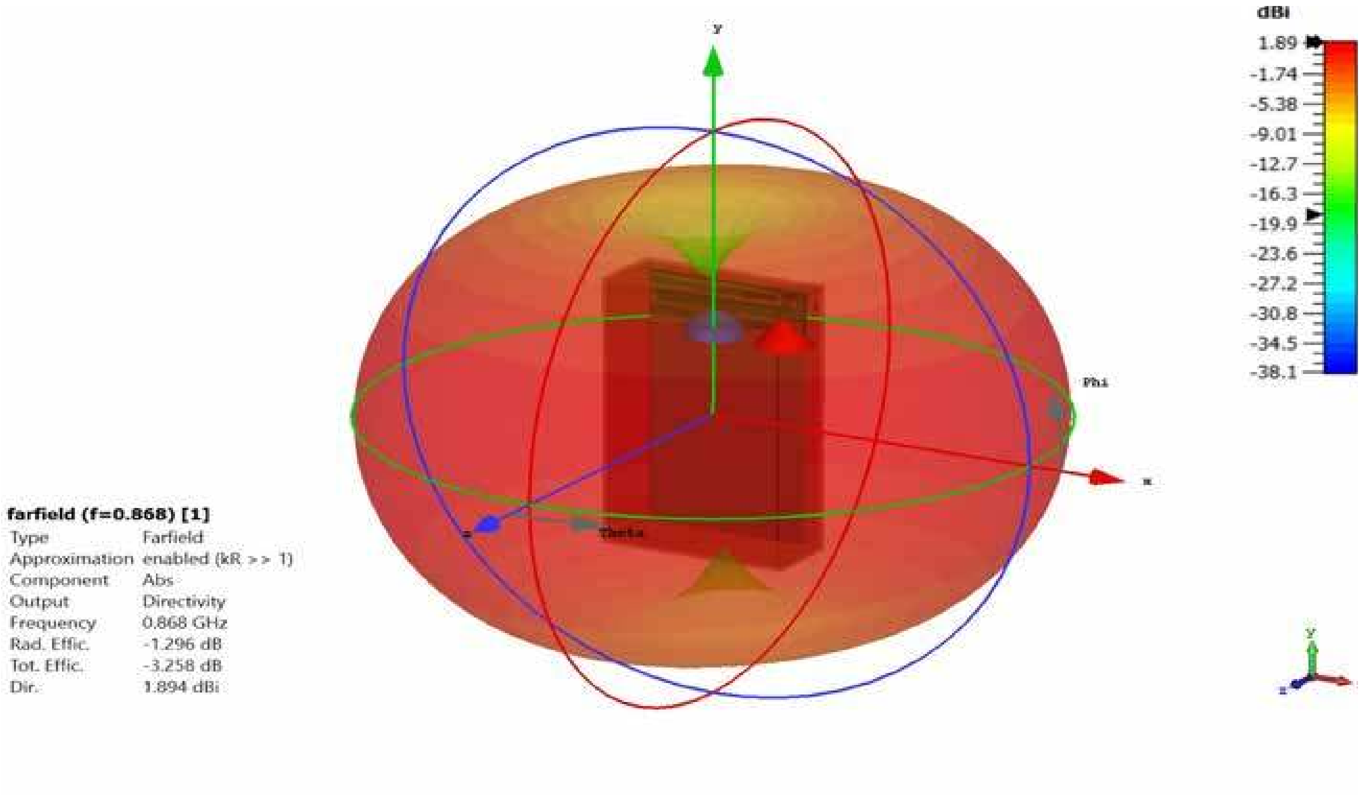
ILLUSTRATION 75: *Radiated energy in 3 axes measured with MegiQ RMS*



How much RF energy is really emitted can be determined in a measurement chamber costing around 100,000 Euros or with the inexpensive Radiation Measurement System (RMS) from MegiQ for 14,000 Euros. With the MegiQ RMS[13] , it is possible to measure directly in your own laboratory whether the test setup matches the simulation. The measurement chamber and the RMS provide the same measurement result. The measuring system has a turntable on which the test object is rotated 360 degrees in 3 axes and measured.

[13] Cf. akorIoT: MegiQ RMS at akorIoT, in: akorIoT, 14.02.2021, https://www.akoriot.com/radiation-measurement/ (retrieved on 19.01.2022).

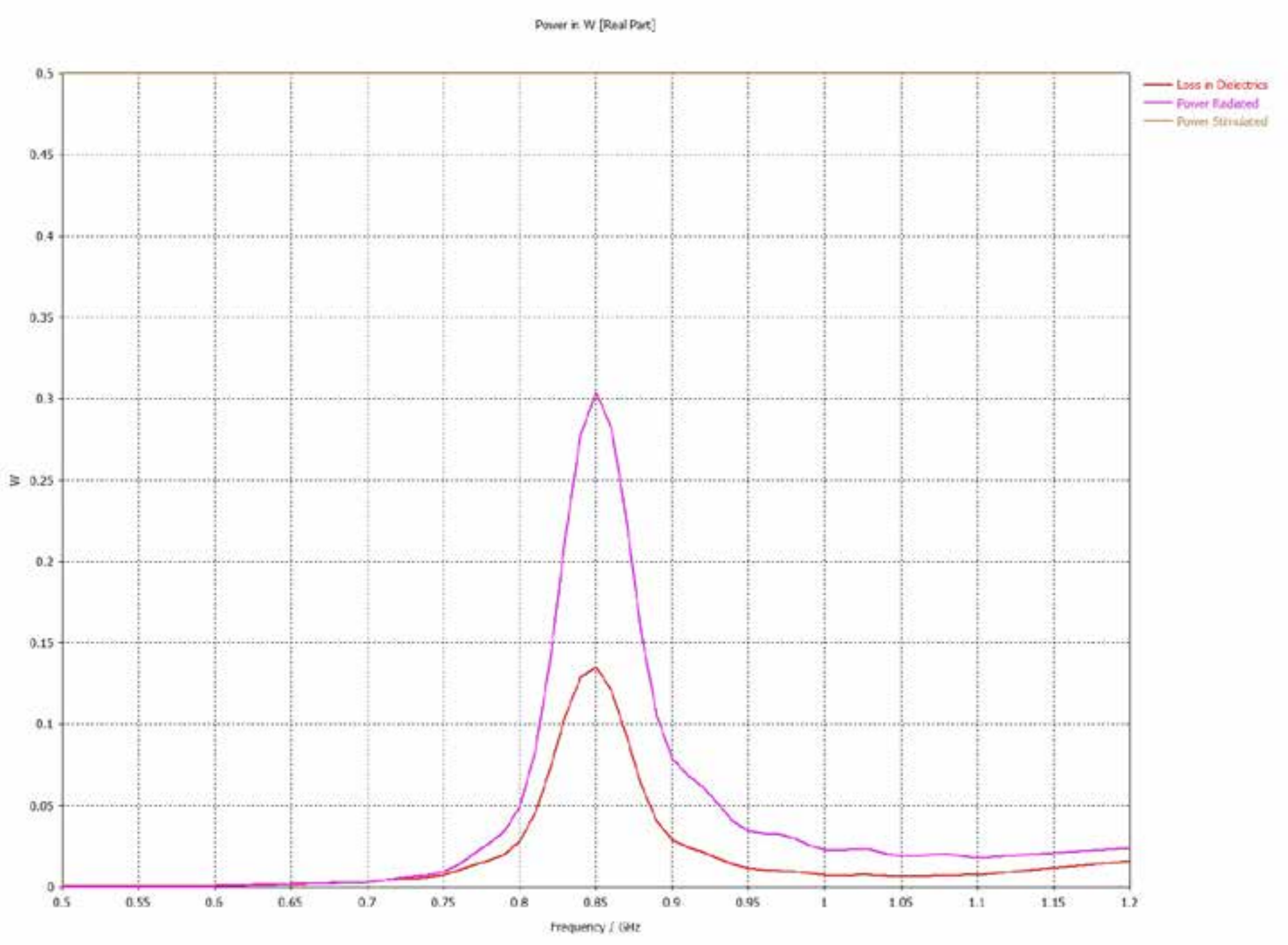
ILLUSTRATION 76: *Simulation of the radiated energy in 3D at 868 MHz*



With the CST Studio Suite simulation software for antennas, deeper study is possible than with Atyune. CST can also include a matching network in the simulation. How then the radiated power into space looks three-dimensionally can be shown with CST. The three-dimensional simulation of the radiated power shows us a structure that looks similar to an apple. We find zeros at the top and bottom with approximately -30 dB dips. The three-dimensional body is very uniform because the antenna system consisting of the inverted F antenna and the ground plane is only "disturbed" by the plastic enclosure. Since the plastic enclosure was constructed as a uniform cuboid around the antenna system, the end result is the typical shape of an apple. However, the simulation shows very clearly that not only the inverted F antenna is radiating, but also the complete antenna system consisting of both antenna and ground plane.

The antenna in the simulation is based on the first design with an 850 MHz resonance frequecny. By shortening the length of the radiator and adjusting the impedance (changing the shorting arm and capacitive tuning), the radiated efficiency was improved from -2.159 dB to -1.296 dB. The total efficiency is -3.258 dB and includes all losses of the overall construction including the losses in the FR4 PCB material and the enclosure.

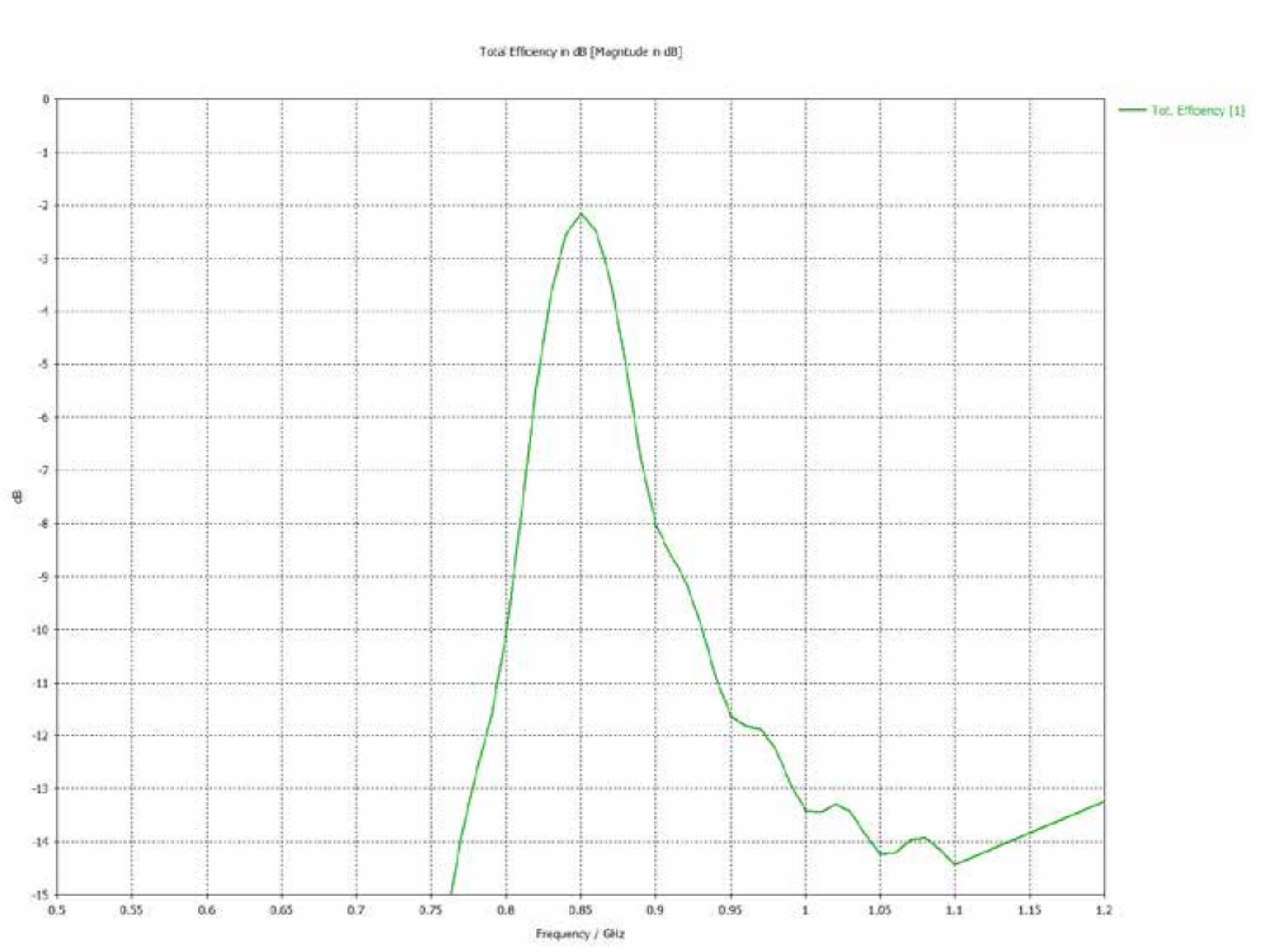
ILLUSTRATION 77: *Loss in dielectrics, power radiated, power stimulated at 850 MHz centre frequency*



Three curves can be seen in the illustration above. The brown curve shows the injected power of 0.5 W at 500 MHz to 1200 MHz. Since the same power is simulated over the entire frequency range, the result is a straight line. The pink curve shows the radiated power of approximately 0.3 W. If the ratio of 0.3 W to 0.5 W is converted into dB, the result is approximately -2.1 dB. This -2.1 dB becomes visible in the green curve below in the Total Efficiency. CST also shows us the dielectric losses in the FR4 PCB material, represented in the red curve. Of the 0.5 watts fed in, approximately 0.13 watts are lost in the FR4. These losses can be minimised by replacing the 1.55 mm FR4 with a 0.8 mm FR4. Another possible measure is to make cut-outs in the PCB to exchange some of the FR4 material for air. Cut-outs have been used in the Gillette order button, for example.

The finding of this simulation is that one can integrate a very good PCB antenna into the main PCB made of FR4, which in the end can be better optimised than classic chip antennas.

ILLUSTRATION 78: *Total efficiency of -2,1 dB at 850 MHz at 850 MHz centre frequency*



ANALYSIS OF SEVERAL WIRELESS **IOT DEVICES**

In the following sections we look at different wireless IoT devices with integrated PCB antennas. From the examples shown, it is easy to see that PCB antennas should not simply be adopted one-to-one. Other examples show which measures have been taken to optimise the antennas. Furthermore, errors in the production of the PCB antenna are explained in more detail.

MINIATURE HELICAL PCB ANTENNA FOR A **LORAWAN TAG**

The antenna design in this LoRaWAN tag is just one example out of thousands based on the application note for the Texas Instruments DN038. The customer's project objective was to match the antenna to the European 868 MHz band without changing the structure. With this example, we explain what the IoT developer could improve. Since there was no budget for optimising the antenna, an improvement was only sought by changing the matching network. However, since the impedance of the antenna in TI's Design Note DN038 is already far from the targeted 50 Ω (only approximately 10 Ω), a direct copy of the antenna will therefore not be better than the starting point in design note DN308.

Author: Harald Naumann
https://www.linkedin.com/in/naumann/

ILLUSTRATION 79: *LoRa tag without enclosure*

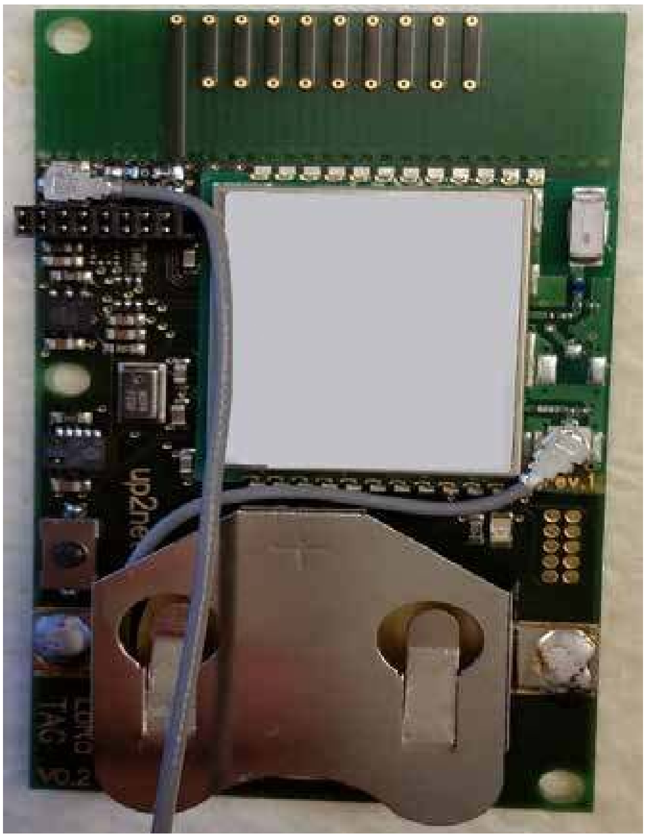


ILLUSTRATION 80: *LoRa tag with enclosure*

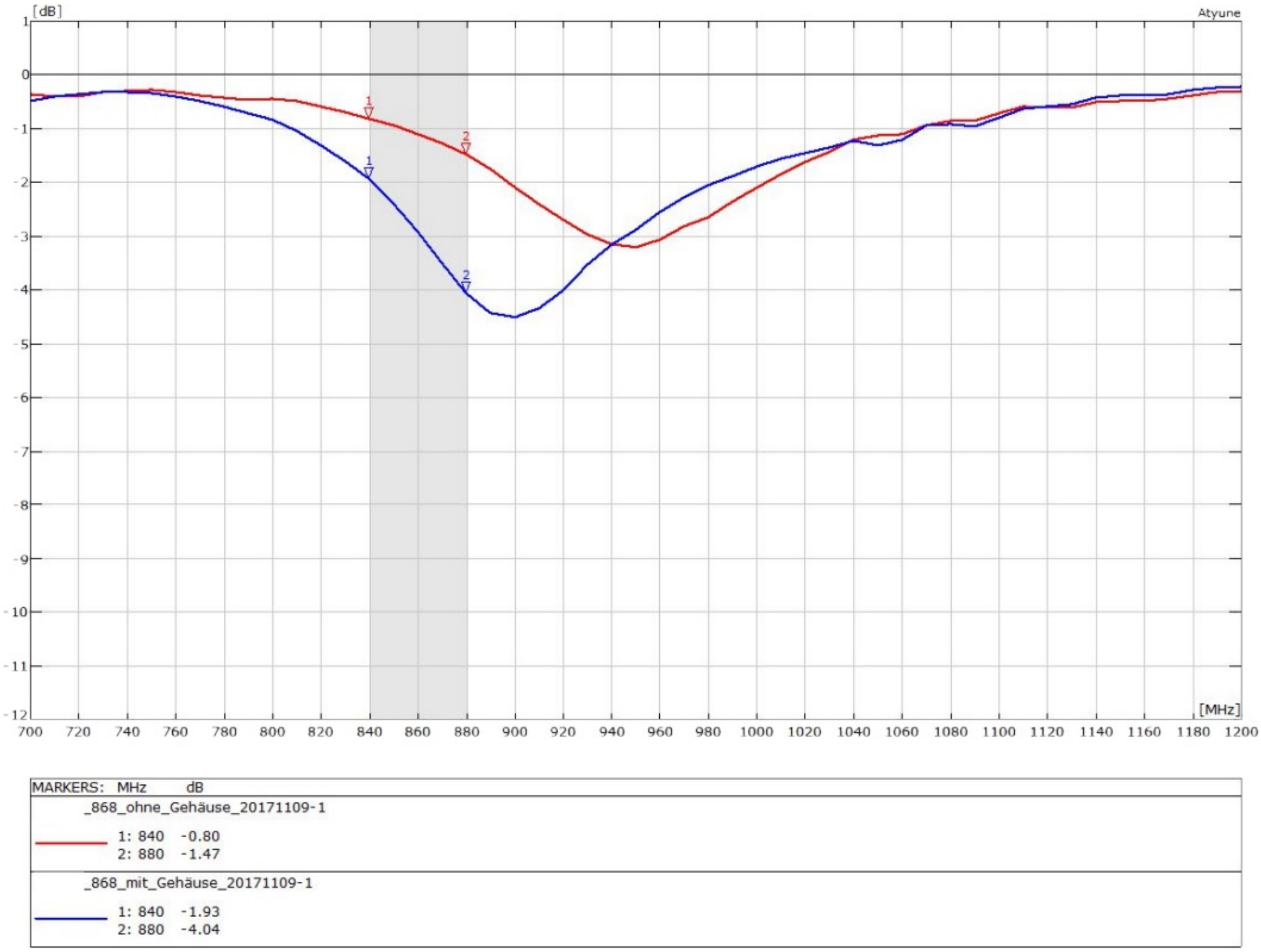
Text excerpt from the TI design note DN038

"There are several ways to tune an antenna to achieve better performance. For resonant antennas, the main factor is the length. Ideally, the frequency which gives least reflection should be in the middle of the frequency band of interest. Thus if the resonance frequency is too low, the antenna should be made shorter. If the resonance frequency is too high, the antenna length should be increased. Even if the antenna resonates at the correct frequency it might not be well matched to the correct impedance. Size of ground plane, distance from antenna to ground plane, dimensions of antenna elements, feed point and plastic casing are factors that can affect the impedance."

This text regarding the DN038 is valid for any antenna structure. Even an SMD mounted chip antenna will change its impedance on a change of the distance to the ground plane. SMD mounted chip antennas have a radiator of set length. If they support multi band for cellular, then most of the time you will have no opportunity to make the radiators longer.

HELICAL ANTENNA FOR LORAWAN TAG **NOT MATCHED**

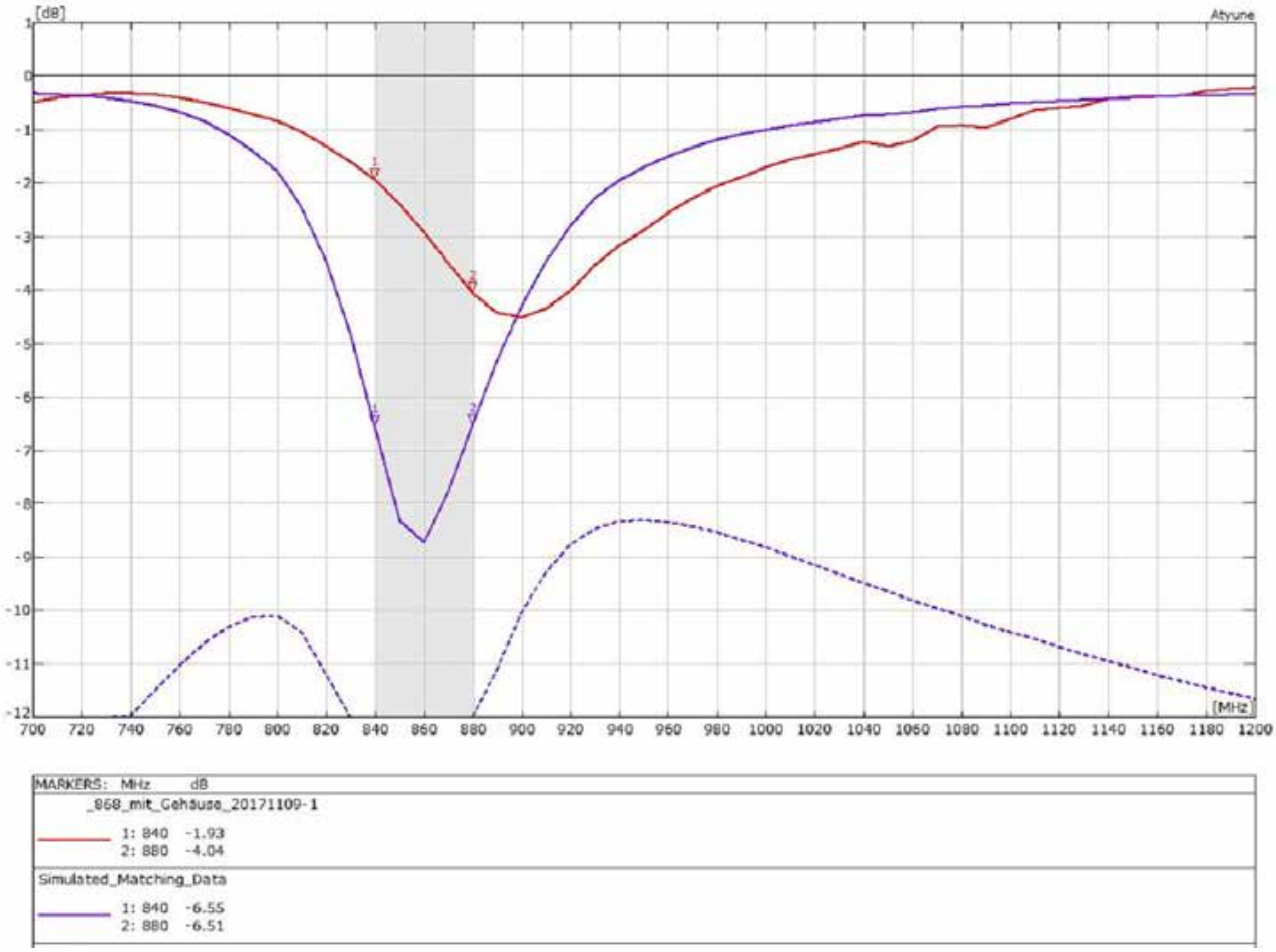
ILLUSTRATION 81: *LoRa antenna return loss – with and without enclosure*



In this LoRaWAN tag project, the length of the helical PCB antenna structure was not changed. As a first step, we always measure the resonance of the antenna with enclosure (blue return loss curve) and without enclosure (red return loss curve). Both resonance frequencies are in the region of 868 MHz. If we put the PCB in an enclosure then the centre resonant frequency drops from 950 MHz to 900 MHz. Such a drop is common. At 900 MHz the centre frequency is still too high. We can conclude that the helical PCB antenna track is too short. To minimise the design effort the PCB track of the antenna was not expanded and the antenna was tuned by using a matching circuit only.

HELICAL ANTENNA FOR LORAWAN TAG TUNED AND MATCHED

ILLUSTRATION 82: *LoRa helical antenna matched*



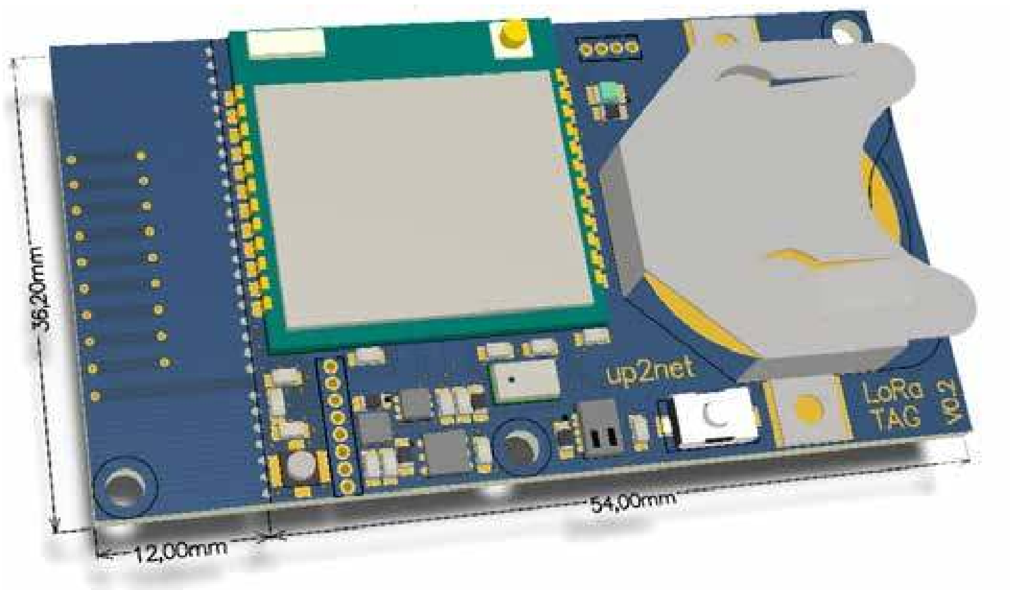
To make the antenna longer you just add an inductor in series with the antenna. The free of charge software Atyune does the calculation for matching and tuning automatically. We input the centre frequency and the bandwidth and pressed the button to start the calculation. For the LoRa-Tag we used a higher bandwidth than necessary because we cannot know where the tag will be mounted and this gives margin for error. If the end customer screws it on a plastic carrier box, then the centre frequency will jump down again.

Be aware that screwing an antenna onto metal will short the electric field and detune the antenna immediately. For attachment to a metal chassis, we will need another more complex antenna design.

Author: Harald Naumann
https://www.linkedin.com/in/naumann/

RECOMMENDATIONS FOR THE ANTENNA AT LORAWAN TAG

ILLUSTRATION 83: *LoRaWAN tag antenna 3D drawing*

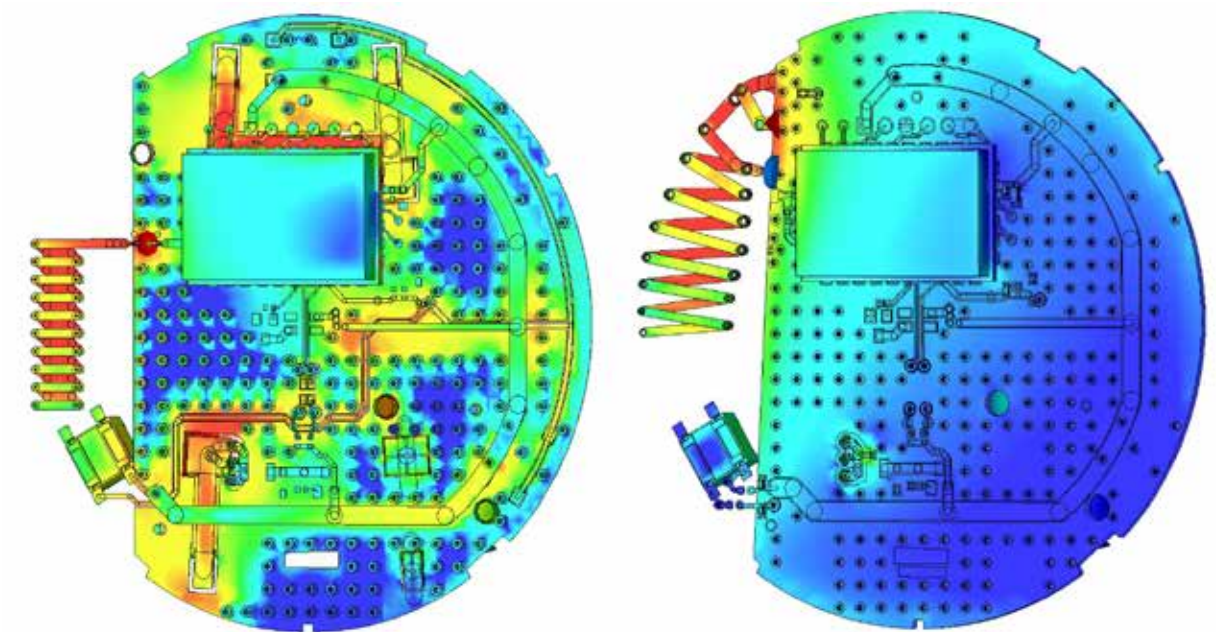


For a proof of concept, the selected helical PCB antenna is acceptable. If the LoRa-Tag moves to mass production, then it makes sense to lengthen the track of the helical PCB antenna. Moreover, it makes sense to stretch the antenna and to use the complete board space. Based on that change the distance to the ground plane of the PCB antennas will be bigger. With greater distance, the impedance of the antenna will increase. Because, as noted in the TI application note, the impedance is too low the changes will result in an impedance closer to 50 Ω and so the loss in the matching circuit will be lower. A lower loss means a better range or a lower power consumption.
The unused board space for the antenna of this LoRa-Tag is quite large. The spare real estate is sufficient that we could consider using an F-antenna. In this case, the antenna structure of the F antenna will be a meander or a helical PCB antenna similar to the basic TI design.
This real-life example shows that TI's instruction was followed exactly. Unfortunately, a change in the antenna structure and optimisation was out of the question due to lack of budget despite the fact that it could have yielded improved in-field performance and with the use of a PCB antenna, lower manufacturing costs.

SIMULATED ANALYSIS OF **AN 868 MHZ SENSOR**

The two illustrations below show the simulation of two identical PCBs of a LoRaWAN sensor. The PCBs were simulated with the ABS plastic housing.

ILLUSTRATION 84: *Before and after with a LoRaWAN sensor*



To make the current distribution on the PCB visible, the layer for the enclosure was made invisible. The red area, which changes from orange to yellow, shows the highest currents. On the left side you can see the original PCB of the IoT developer. The simple L-antenna of Design Note DN038 was chosen and copied one-to-one. In addition, the incorrect routing of the PCB drives the RF currents into the PCB. You can see a red area in the upper part of the PCB near the contacts of the radio module.

This energy is converted into RF energy on the PCB and is not radiated via the antenna. These currents could generate fields overlapping in wrong phase and reduce the radiated energy to the air. Furthermore, the undesired currents can create harmonics on the PCB by mixing with semiconductors.

Furthermore, you can see that the connector near the end of the L-antenna is also loaded with RF currents. The result of the sum of all errors was that the range of the LoRa sensor was quite shorter than expected.

On the right side we see the modified PCB with the same radio module in the same enclosure. In order to increase the radiated energy, various changes were made to the PCB. The result is clearly visible. On the modified PCB, it is primarily the antenna which radiates and on the PCB we no longer observe any red, orange or yellow areas. The original PCB which had only two layers was changed to a PCB with four layers. The result is that there is an almost continuous mass surface as a so-called ground plane. The mass surface on the different layers were connected with vias. The original L-antenna was changed to an inverted F-antenna. You can see that next to the feed point, represented by the red cone, there is a shorting arm to ground. The uniform helix structure of the antenna has been changed to a non-uniform structure. The turns near the feed point are further spread than at the end of the antenna. At the same time, the new antenna structure has been shifted so that the connector, which continues to face the antenna, is significantly further away from the end of the antenna. In such a small area it is impossible to achieve the frequency bandwidth for both the European 868 MHz band and the American 915 MHz band. For this reason, a switch with capacitive load was inserted before the shorting arm of the F antenna. The capacitor for switching is represented by the blue cone as in the other simulations.

A further modification on the PCB, at the connector near the antenna, decouples it from the high frequency. It clearly demonstrates that a mechanically greater distance of the metallic connector housing interferes less with the antenna. The further away the end ofthe antenna is from the connector, the less it can interfere with it. Since the

Author: Harald Naumann
https://www.linkedin.com/in/naumann/

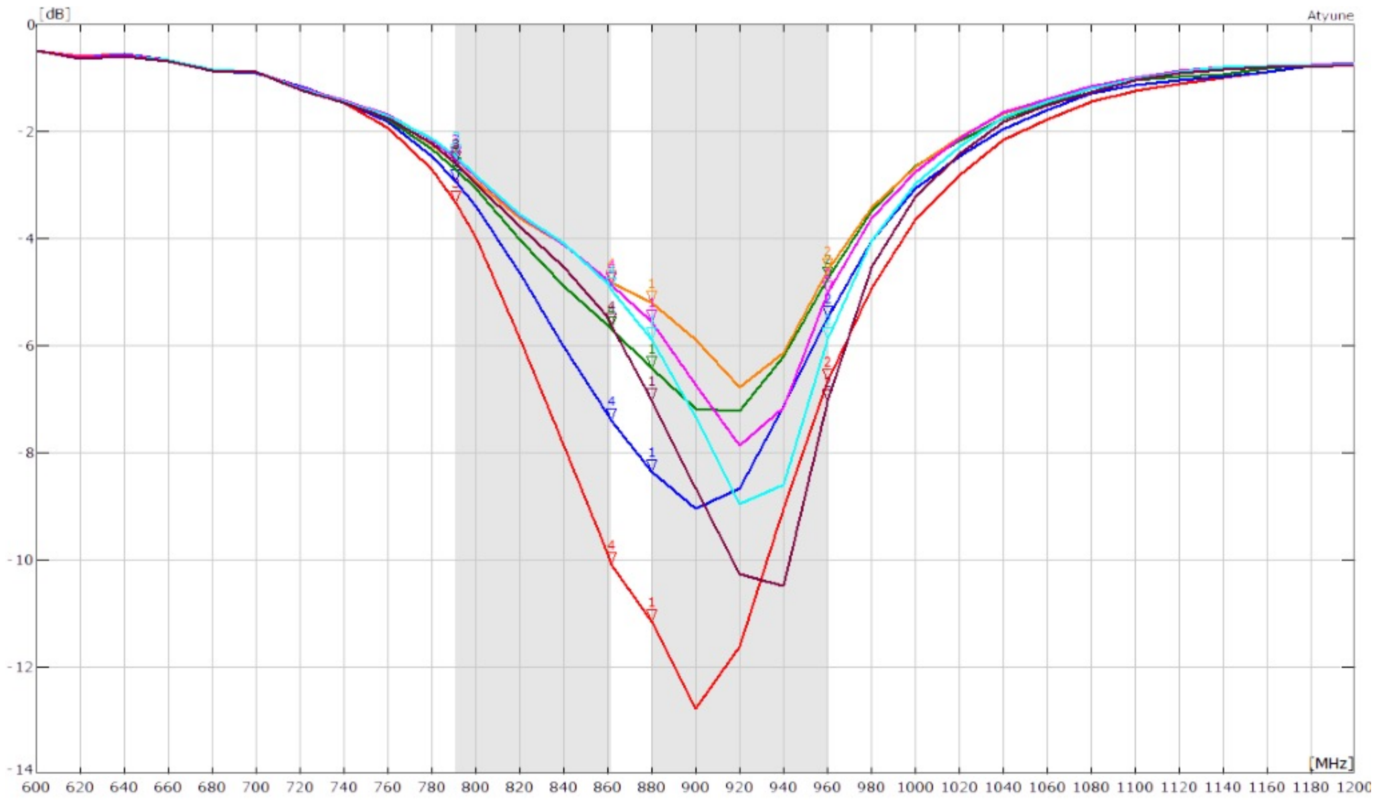
installation space is limited, the helix structure has to be pushed closer together. If the helix structure is pushed closer together, the performance of the antennas decreases. As is clear, in such situations, a simulation of the antenna is clearly advantageous over a mechanical construction with a real PCB. You can change the distance between the connector and the antenna and push the helix structure closer together and see immediately whether it is better or worse.

Somewhere through trial and error you will find a compromise between the optimal distance and the distance of the tracks in the helix structure. Such a multiple change and evaluation is impossible with a mechanically built test board. A simple test setup with a taped antenna structure is not necessary because the helix structure is distributed over the-upper and lower layers of the PCB. The result of all the changes was an increase in radiated power of 10 dB. 8 dB means a doubling of the range in the free field. 3 dB means doubling or halving the current. 10 dB is 3 dB + 3dB + 3 dB + 1 dB. With the same range,the transmission line could be reduced by 10 dB and the current by approximately 2 x 2 x 2= 8. A good antenna increases the range or reduces the energy consumption.

LPWAN ANTENNA FOR NB-IOT FOLLOWING **AN INCORRECT** DATA SHEET

Besides faulty reference designs, one also finds incorrect data sheets for antennas. The data sheet of the selected chip antenna states that it supposedly works from 792-960 MHz. Unfortunately, this statement is only partially correct. The specified frequency band of the antenna is only valid if you limit yourself to band 8 or band 20. The frequency bandwidth of the chip antenna does not cover the complete frequency range from 791 - 960 MHz. Even if you limit yourself to only one of the two frequency bands mentioned, you will find that the return loss of -6 dB at the band corners is not achievable. Furthermore, the maximum antenna gain is only 0.5 dBi. Other similar chip antenna data sheets claim 1.15 dBi. In addition, the mentioned frequency bandwidth is only valid on a 35 mm x 115 mm ground plane. We confirmed the performance of the chip antenna on an evaluation board with a MegiQ VNA. This control measurement showed a difference with worse performance than that claimed in the data sheet. As a further test, the antenna PCB was shortened in steps of 14 mm and the return loss was measured again. As we shortened the length of the PCB, the centre frequency of the antenna shifted upwards. At the same time, the frequency bandwidth of the antenna which was already too narrow decreased. If you compare the return loss of the purchased chip antenna with the antenna you made yourself, you will find that shortening the ground plane also leads to a reduction in the return loss.

ILLUSTRATION 85: *Return loss of an NB-IoT chip antenna on different PCB length*



MARKERS:	MHz	dB	MHz	dB
_Eval_PCB_full-S11-VF.s1p - S11	1: 880	-11.16	3: 791	-3.33
	2: 960	-6.65	4: 862	-10.07
_Eval_PCB_14mm_weniger-S11-VF.s1p - S11	1: 880	-8.33	3: 791	-2.92
	2: 960	-5.47	4: 862	-7.39
_Eval_PCB_28mm_weniger-S11-VF.s1p - S11	1: 880	-6.42	3: 791	-2.71
	2: 960	-4.73	4: 862	-5.69
_Eval_PCB_42mm_weniger-S11-VF.s1p - S11	1: 880	-5.20	3: 791	-2.58
	2: 960	-4.58	4: 862	-4.82
_Eval_PCB_56mm_weniger-S11-VF.s1p - S11	1: 880	-5.54	3: 791	-2.49
	2: 960	-5.01	4: 862	-4.86
_Eval_PCB_70mm_weniger-S11-VF.s1p - S11	1: 880	-5.88	3: 791	-2.47
	2: 960	-5.89	4: 862	-4.93
_Eval_PCB_84mm_weniger-S11-VF.s1p - S11	1: 880	-7.00	3: 791	-2.59
	2: 960	-7.03	4: 862	-5.60

ANTENNA DESIGN **BASICS**

In order for a PCB antenna in a custom enclosure to work properly in the final design, the layout must be tweaked in many places. The possible changes are explained in the following steps using antenna simulations and test boards. The use of simulation is much more time-saving than the construction of test boards. In the simulations, only one parameter of the PCB antenna layout is changed and explained at a time. Each IoT developer must decide for himself which changes need to be made to the three reference designs mentioned or, if necessary, call in an external consultant.

If sufficient installation space is granted for the PCB antenna in the first step, then external consulting can adapt the template at the end. However, it is even better to bring in the external consultant at the beginning, if there is a lack of expertise, so that the consultant has the opportunity to make a different and better proposal for a PCB antenna before any costs are incurred.

Influence of FR4 from different manufacturers (series of measurements)

This series of measurements shows the return loss of four PCBs with an F-antenna. As this is a PCB from a customer project, pictures of the PCB cannot be shown. The PCB had dimensions of 65 mm x 86 mm and is therefore similar in size to the PCBs in the simulations discussed earlier. The PCB layouts of the four measurement boards are exactly the same. The difference is that the PCBs were ordered from four different suppliers. The peak value in the return loss shows a delta of 3 dB. The return loss curves show a deviation of 12 MHz from the lowest to the highest centre frequency. The grey marked area shows the frequency range from 868 MHz to 870 MHz in Europe. The red curve covers the frequency range well. All four board antennas would work. A matching network was not used. Use of a matching network could obviously correct the deviation a little. The graph shows that a change of supplier for the FR4 leads to changes in the antenna.

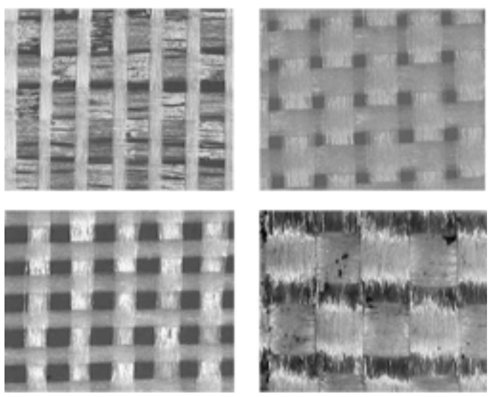
What is going on? A printed circuit board made of FR4 is assembled from different materials. The copper traces are glued to the core of the PCB with resin. The resin is applied to woven glass and pre-dried. This material is called pre-impregnated. The resin is not completely hardened. When heated, it flows and sticks the copper, glass fabric and core together. These various elements from different suppliers vary in thickness. The thickness, resin content and type of resin affect Epsilon-R and Tangent Delta. It is therefore not surprising that an order for a PCB from four suppliers will produce different results. The supplier for the PCB material should therefore not be changed. The same applies to the manufacturer for components in the matching network. The manufacturer should not be changed. In addition, where possible the supplier should be required to communicate any production process changes and to supply samples to make sure that no significant changes to performance will result from the changes.

[14] Cf. Würth Elektronik: Printed Circuit Boards > Signal Integrity: in: Würth Elektronik, 15.02.2021, https://www.we-online.com/web/en/leiterplatten/webinare/archiv/signalintegritaet_webinar/webinar_archiv_8.php (retrieved 10.01.2022).

ILLUSTRATION 86: *Improved signal integrity through impedance-matched PCBs Würth Elektronik Circuit Board Technology* [14]

FR4 Prepreg Typ 106
Thickness 50 um
εr = 2.8 - 3.7
Resin content ~50 %

FR4 Prepreg Typ 1080
Thickness 60 - 70 um
εr = 3.2 - 3.7 um
Resin content ~60 %

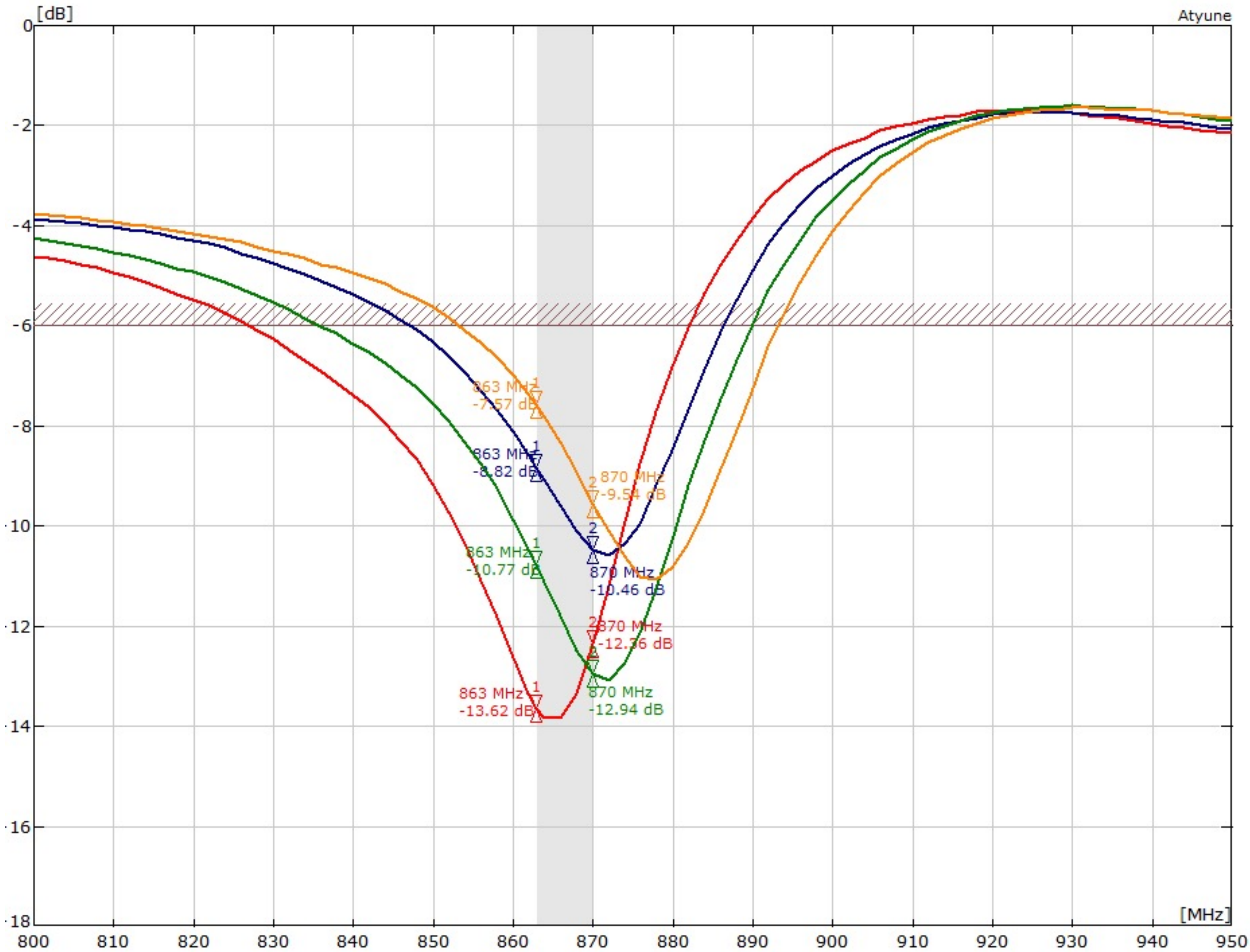


All Prepreg, glas εr ~ 6.1 resin εr ~ 3.2

FR4 Prepreg Typ 2116
Thickness 90 - 110 um
εr = 3.6 - 3.8
Resin content ~50 %

FR4 Prepreg Typ 7628
Thickness 170 - 190 um
εr = 4.1 - 4.6
Resin content ~45 %

ILLUSTRATION 87 *Return loss of F antenna in same shape on same PCB size with four different manufacturers*



MARKERS: MHz	dB
868MHz_C	
1: 863	-13.62
2: 870	-12.36
868MHz_E	
1: 863	-8.82
2: 870	-10.46
868MHz_L	
1: 863	-10.77
2: 870	-12.94
868MHz_M	
1: 863	-7.57
2: 870	-9.54

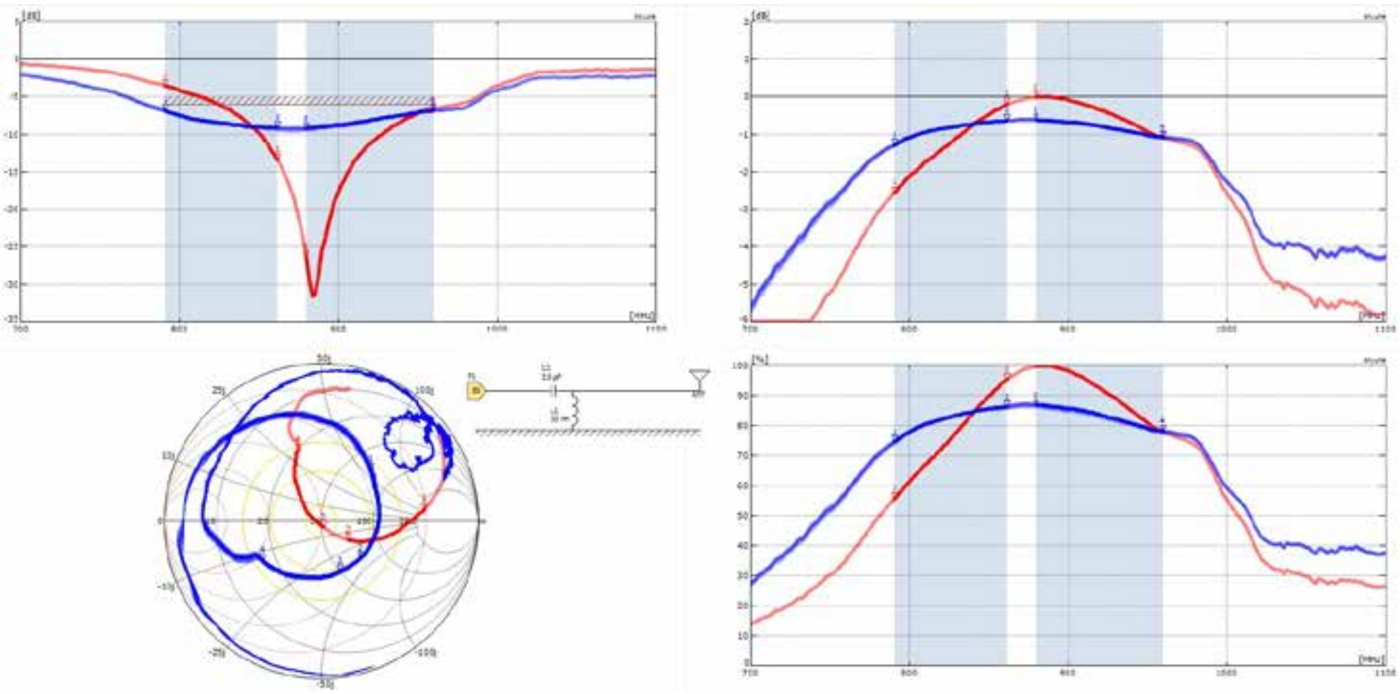
INVERTED F ANTENNA **FOR 868 MHZ** OPTIMISED FOR 791 - 960 MHZ

The following diagrams were not simulated but measured. The red curve shows an inverted F antenna which has not yet been matched by additional components to the licence-free band 868 MHz in Europe. The left blue area marks band 20 and the right blue area marks band 8. NB-IoT and LTE-M are used in Europe in these two bands.

Exactly between these two bands that the licence requires is the licence-free band. Since the return loss of the antenna without further components is already at -32 dB, it can very easily be matched to the centre of the licence-free band.

Since the return loss of this antenna without components in the matching network is already very high and, on top of that, it shows a very high bandwidth, this antenna was matched to the cellular band 8 and band 20 with only two components. The efficiency of the antenna is still 75 % and 78 % at the band corners and even about 88 % at the peak.

ILLUSTRATION 88: *Gain, efficiency, return loss and Smith Chart of inverted F antenna for 868 MHz optimised for 791 - 960 MHz*



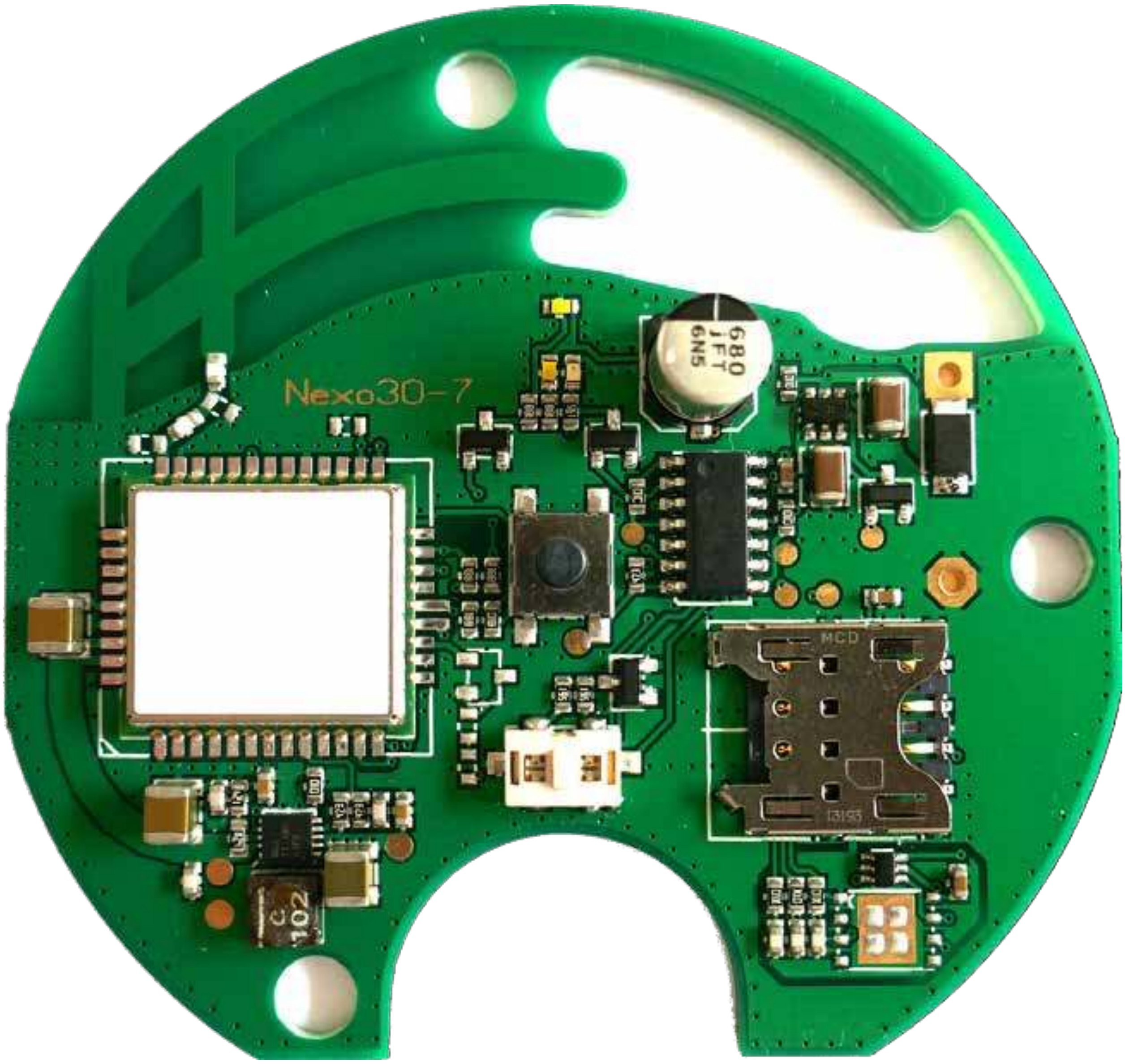
DUAL INVERTED F-ANTENNA USED IN THE GILLETTE ORDER BUTTON

The multi band F antenna on the button's round PCB was taken from the IoT / M2M Cookbook[15] . The original shape of the F antenna in the Cookbook was rectangular on a PCB measuring 50 mm x 100 mm. After the development on the rectangular PCB was successfully completed, the customer wanted the order button on a PCB in a round housing for a design that was more aesthetically pleasing. To reduce the cost, the PCB was designed with only 2 layers. The frequency range was set for GSM 900 (band 8, 880 MHz - 960 MHz) and GSM 1800 MHz (band 3, 1710 MHz - 1950 MHz). The structure of the antenna was tailored to a diameter of 70 mm. The end of the F antenna turns away from the edge of the PCB by approximately 2 mm, distancing itself from the wall of the enclosure by 2 mm. This 2 mm gap increases the bandwidth of the antenna. Another measure to increase the frequency bandwidth is the cut-out in the PCB below the antenna and the main PCB. The top view of the PCB clearly shows the vias at the edge of the PCB and also around the cellular radio module. Since the PCB only has two layers, the ground islands on the top and bottom must be well connected. You can see a lot of vias near the shorting arm. Each via must be thought of as an inductor. With an ohm-meter you would measure a resistance of 0 Ω between the two layers. For the high frequency signal, the vias are inductors connected in series with the ground surface on the top and the bottom. By connecting many inductors in parallel, the total inductance is reduced. This means that the high current short-circuit point of the antenna can be well distributed over both ground surfaces in the PCB. A good ground plane is necessary to radiate the power perfectly with a monopole antenna.

[15] Naumann, Harald: IoT / M2M Cookbook, in: akorIoT, 10.01.2014, https://www.akoriot.com/iot_books/ (retrieved am 12.12.2021).

ILLUSTRATION 89: *Inside of the Gillette order button*

ILLUSTRATION 90: *Dual F antenna for NB-IoT, LTE-M and GSM at the PCB of the Gillette order button*



THE SUB-GHZ IOT DEVICE IN A MATCHBOX

The box of matches is a symbolic size of the tracking device for pets or the bracelet for seniors. It could just as easily be a sensor with NeoMesh. Or an order button with NB-IoT. Technically, there is no difference. They are radio modules with antenna and battery in a very small enclosure.

A matchbox has the dimensions of 5 cm × 3.5 cm × 1.5 cm. If we assume a wall thickness of 1 mm, this leaves 4.9 cm x 3.4 cm for the PCB with the antenna. The other three PCBs mentioned below are real project requests we received in 2021.

IoT devices with length (L) x width (W) x height (H)

- PCB in matchbox device S: 49 mm x 34 mm = 1666 mm2. Height 14 mm
- PCB in IoT device A: 20 mm x 35 mm = 700 mm2 Height unknown
- PCB in IoT device B: 20 mm x 40 mm = 800 mm2. Height unknown
- PCB in IoT device C: 10 mm x 70 mm = 700 mm2. Height approximately 3 cm

The selected small chip antenna has dimensions of only 26.0 mm x 6.0 mm x 1.7 mm. It therefore fits mechanically into the matchbox with a width of 34 mm, but not into the IoT devices A, B and C. Cellular chip antennas are generally designed for the narrow side of the PCB. On the long side of the PCB, these would fit mechanically but not result in good performance.

To make it fit better, we extend the mass of the IoT devices A to C

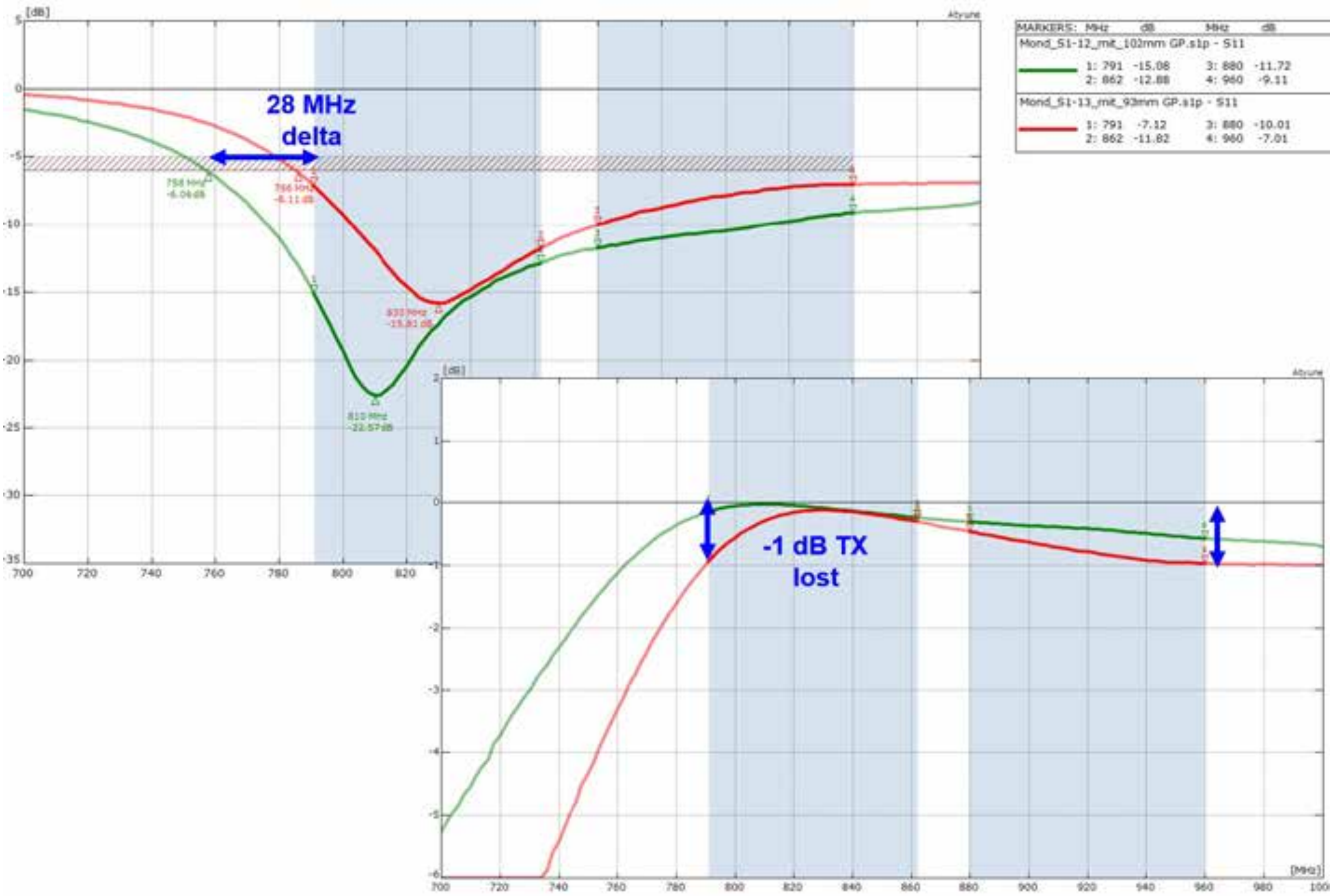
- PCB in IoT device A: 26 mm x 30 mm
- PCB in IoT device B: 26 mm x 40 mm
- PCB in IoT device C: 26 mm x 70 mm

The developers wanted 10 years of battery life and an additional important factor was good radiated power. Antennas work in both directions. Good return loss also leads to good data receipt performance. The better the device is at receiving, the faster the data is transmitted in NB-IoT, LTE-M and LoRaWAN. LPWAN technologies are able to readjust the modulation or retransmission. If the time to transmit is reduced, then the energy needed to receive is also reduced. When transmitting, we have the same effect. The faster the data is transmitted, the lower the energy consumption. With NeoMesh from NeoCortec, nothing is readjusted. However, the range is increased.

At -6 dB return loss, only approximately 21.5 dB of 23 dB at the cellular radio module is coupled into the antenna. 1.5 dB transmission power is lost. A -4 dB return loss becomes critical and the returning energy possibly leads to harmonics at the power amplifier of the cellular radio module. It is better not to test where the limit of the maximum return loss is. It is expensive to repeat the measurements for RED/CE/FCC certification.
In the data sheets of many chip antennas, the frequency bandwidth is listed for different lengths of ground plane. The series of measurements in the graph below with a chip antenna shows again that there is a relationship between the length of the ground plane and the bandwidth of the antenna. With a monopole antenna, the ground plane is part of the antenna. The antenna radiator and the mass surface of the PCB form the antenna system. Even the battery with its cable and the rolled-up mass surface in the battery becomes part of the antenna.

Author: Harald Naumann
https://www.linkedin.com/in/naumann/

ILLUSTRATION 91: *Return loss of NB-IoT chip antenna on 93 mm and 102 mm long ground plane*



As we have previously stated, a monopole antenna consists of 2 parts: the radiator and the mass surface (ground plane) below the antenna. In this example, the length of the PCB was shortened from 103 mm to 92 mm. The bandwidth of an integrated cellular antenna is rated at - 6 dB return loss. Shortening by 9 mm leads to a change of the lowest corner frequency of the antenna of 28 MHz. Furthermore, the possible radiated power at 798 MHz in band 20 is reduced by 1 dB. But also at 960 MHz in band 8 there is a change of 0.5 dB. If one were to shorten by a further 9 mm, the bandwidth would again be reduced. All the findings recognised above and in the sections before are not new. The minimum size of a dipole antenna was already determined and documented by Chu in 1947 and later extended. Chu, Wheeler, Harrington spent a lot of time between 1940 and 1960 thinking about small antennas. For a small antenna, the qualify factor, Q, is proportional to the reciprocal of the volume of a sphere into which the antenna fits.

ILLUSTRATION 92 *Chu's Antenna Theorem*

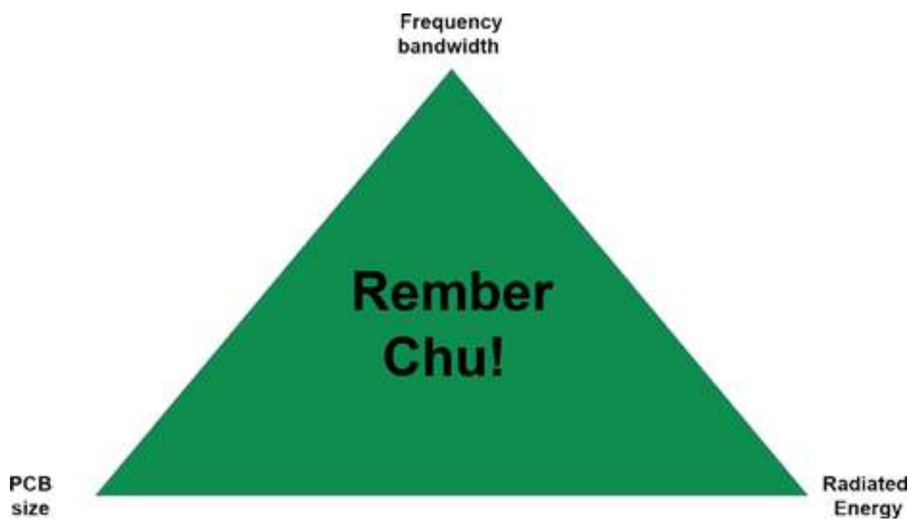
$$Q = \frac{1}{ka} + \frac{1}{(ka)^3} \quad BW_{max} = \frac{f}{Q} \Leftrightarrow Q \gg 1$$

TABLE 9: *Calculation of the antenna bandwidth with based on Chu's Antenna Theorem*

	in MHz				in cm		dBi
	Min frequency	Max. frequency	Bandwidth	Centre frequency	Radius by Chu	Diameter	Peak gain
LoRaWAN EU	863	870	7	866,5	1.11	2.22	-3.49
LoRaWAN US	902	928	26	915	1.16	2.32	-1.37
NB-IoT EU band 8	880	960	80	920	2.46	4.92	0.69
NB-IoT EU band 20	791	862	71	826.5	2.72	5.44	0.67
NB-IoT EU band 8 and 20	791	960	169	875.5	3.53	7.06	2.36
NB-IoT EU TX band 8	880	915	35	897.5	1.88	3.76	-0.81
NB-IoT EU RX band 8	925	960	35	942.5	1.76	3.52	-0.9
NB-IoT EU TX band 20	832	862	30	847	1.92	3.84	-1
NB-IoT EU RX band 20	791	821	30	806	2.1	4.2	-0.9

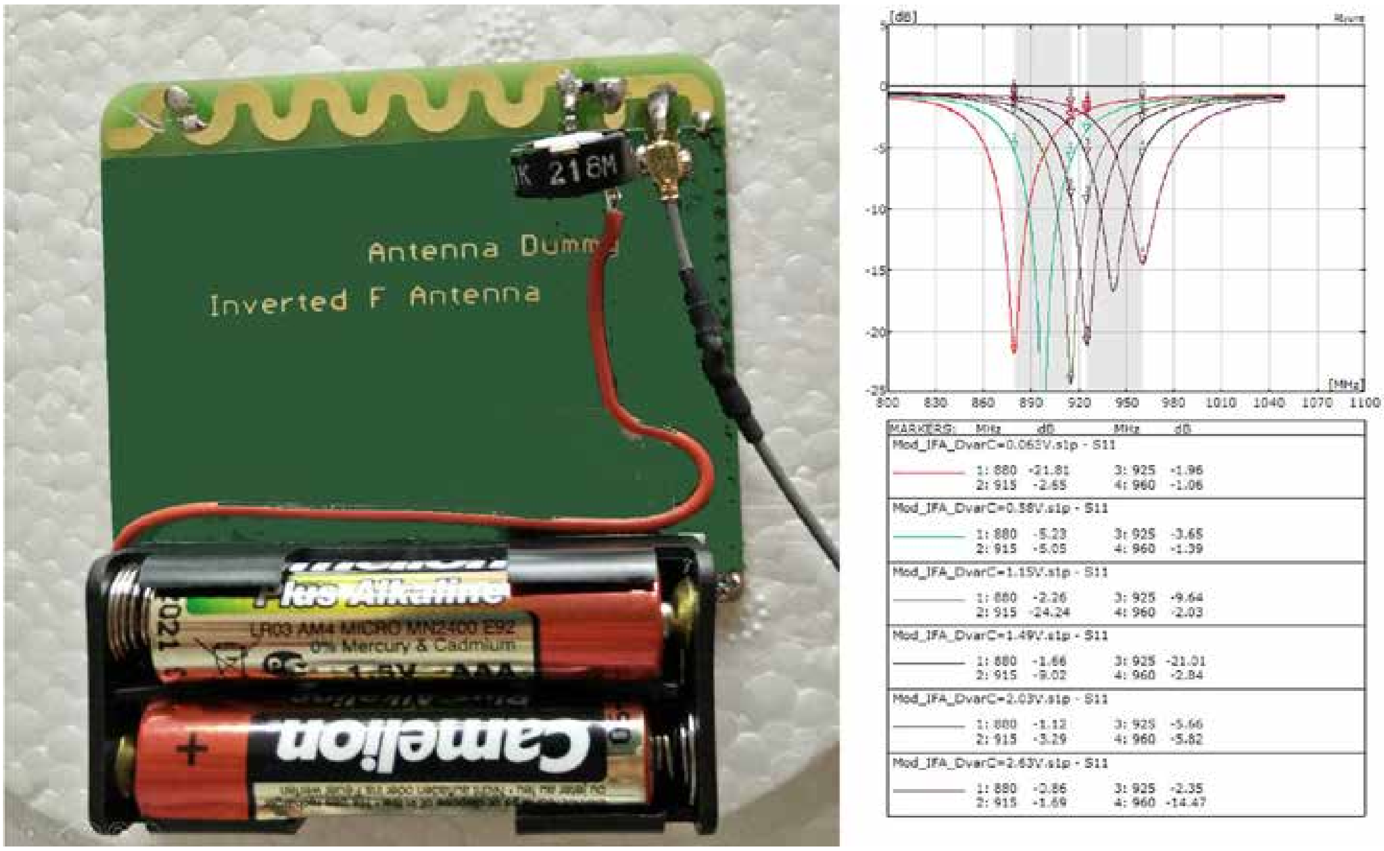
Anyone can play through the Chu limit. In the table, the Chu antenna theorem was used and the values for NB-IoT in the EU were calculated on band 8 and 20 plus the licence-free band at 868 MHz. The 868 MHz band lies exactly between band 8 and 20. The result is that with approximately -3 dB loss in antenna gain, IoT devices with NeoMesh, LoRaWAN and Mioty can be built 50 % smaller than NB-IoT in band 8 or 20. If one aims for both NB-IoT bands, then another 3 dB loss is added. Conversely, it can be said that limiting the antenna to one band and thus halving the frequency bandwidth halves the necessary size (radius) of the antenna.

ILLUSTRATION 93: *The Chu Theorem in the form of a triangle.*



The Chu Theorem tells us that we cannot reduce the dimensions of an antenna as we wish. Chu's theorem is valid for all antennas and therefore also for an antenna system consisting of a PCB antenna/chip antenna and its ground plane. If you reduce the ground plane too much, you ignore Chu and automatically reduce the frequency bandwidth and the radiated energy. If the bandwidth is too small, too much energy is reflected at the band corners. Radio certification then becomes impossible.

ILLUSTRATION 94: *Active antenna control to outsmart Chu*



To set up small devices such as a key fob with NeoMesh, LoRaWAN or NB-IoT, you have to actively control the antennas and change the centre frequency. The graphic shows an antenna that is shifted from a centre frequency of 880 MHz to 960 MHz with capacitive control. The Chu limit defines the possible bandwidth of the antenna, but active control of the antenna overcomes the problem.

The antenna could not be much smaller than calculated by Chu in 1947 with the findings of Wheeler and Harrington. Chu's formula shows the relationship of the radius of a dipole antenna to the frequency bandwidth and the antenna gain. Like the dipole antenna, a monopole antenna consists of two elements. With the dipole antenna, the two elements are directly visible.

Whoever tries to achieve the size of the matchbox or similar will make the acquaintance of Chu, Wheeler and Harrington. The antenna theorem is based on physics and physics cannot be outsmarted, as is well known.

CONCLUSION AND SUMMARY

The individual simulations and the example projects clearly show that one cannot simply adopt a PCB antenna layout 1:1 from a data sheet. Even the smallest change, such as a different plastic or a different FR4 from an alternative supplier, immediately leads to a change in the centre frequency and impedance. Just changing the dimensions of the PCB will change the antenna parameters. A layout for an antenna is only a rough initial value, which is then adjusted step by step to the target result by changing the layout. The statement that it is possible to adopt a layout from a reference design without any changes is therefore not correct. The layouts primarily serve as place holders for the chosen antenna structure. However, not every structure is equally suitable for every application. For example, the L-antenna with an impedance much lower than 50 Ω and with its extreme hand effect should be avoided for any portable device. If you do not have the basic knowledge about antennas, it is recommended to consult an external consultant. This person can also decide whether a PCB track antenna is possible at all, even in a limited installation space, or whether you have to go into the third dimension. Chip antennas use the third dimension and stack the tracks on different layers. Buying a chip antenna, on the other hand, does not mean that it will really work in the chosen environment. For purchased chip antennas and any form of Do It Yourself antenna, a test setup is recommended to check that you can achieve the target result. A simulation is an inexpensive way to determine in advance whether a PCB track antenna with limited installation space can function at all.

To minimise the costs of such a simulation, the idea of an antenna generator was born in the course of this study.

SEMI-AUTOMATIC ANTENNA GENERATOR

As you can appreciate, hundreds of simulations were necessary in the course of this study. To minimise the effort, standard models were created for the antennas shown. To start a simulation for an antenna in an enclosure, only a few mechanical and also electrical parameters are necessary. These parameters are manually transferred to the simulation software. The implementation of the antenna is not done by some kind of automated layout software, but by an experienced antenna designer. The standard model only provides a standard antenna. However, this extensive study has shown that in many places minimal changes can be made to optimise the antenna parameters. Some of the changes are interdependent. This means that a change in parameter A leads to a change in parameter B. Some adjustments to the antenna must therefore be made alternately several times to achieve the best result. Sometimes a compromise is necessary. A good example of a compromise is to reduce the antenna efficiency to 90-95 % and at the same time achieve the target bandwidth. The result of the semi-automatic antenna generator is to deliver a design for a customised antenna derived from a standard model.

ACKNOWLEDGEMENTS AND OUTLOOK

This study "Do it yourself PCB Antennas" was funded by NeoCortec[16] in Denmark.
Many thanks again from the author Harald Naumann[17] to the managing director Thomas Steen Halkier[18] for the trust and the investment in the study.

If another sponsor can be found, this study can be supplemented or a new study in the field of wireless IoT can be created.

16 NeoMesh technology overview: in: NeoCortec, 24.04.2019, https://neocortec.com/technology/ (retrieved 10.01.2022).

17 Cf. Contact profile Harald Naumann: in: Linkedin, n.d., https://www.linkedin.com/in/naumann/ (retrieved 10.01.2021).

18 Contact profile Thomas Steen Halkier: in: Linkedin, n.d., https://www.linkedin.com/ (retrieved 10.01.2022).

ABOUT **NEOCORTEC**

NeoCortec is a manufacturer of the NeoMesh wireless sensor network protocol stack, as well as ultra-low-power bi-directional wireless FCC & CE pre-certified communication modules with the stack integrated.

The NeoMesh protocol stack is a 2nd generation wireless communication protocol stack enabling nodes (sensors, actuators etc) to communicate with each other wirelessly and without setting up a separate, external wireless network. Instead will all nodes themselves establish the NeoMesh wireless network, forming a mesh network and where all nodes acts as routers for passing messages between nodes.

All stack layers are optimized for reliability, scalability and low power operation. The reliability comes from the dynamic routing where each node continuously calculates what the best next-hop in the mesh is. Any dead, missing or moved nodes are therefor immediately compensated for by creating a new route. Cable like reliability is achieved through frequency hopping between up to 15 channels and through a CRC32 equivalent check. Scalability is ensured through making the mesh topology flat without any hierarchical structure. There are no central coordinator to organize the network as this task is delegated to all of the nodes. This also makes it very easy to add new nodes to the mesh. Up to 65,000 nodes can be added to the same network. The low power consumption for all nodes makes it possible for all nodes to be battery powered, unlike earlier sensor network approaches with hierarchical structure where the router nodes had to be mains powered. The network modules operate either on sub-GHz frequencies or at 2.4 GHz in the license free ISM bands, and can easily be integrated with sensors or actuators into becoming nodes, or added to gateways to ensure cloud connectivity.

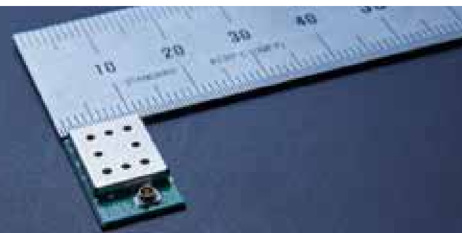
NeoMesh complements 5G LPWAN technologies like LTE-M and NB-IOT cloud connected sensors by extending the range of these LPWA networks into hard to reach places such as deep indoor or underground. As an example, nodes in the basement or at places without coverage can easily be reached through forming a mesh-net to a node with 5G connectivity. As an added bonus, there are no additional subscription cost for these mesh connected nodes.

Typical applications of NeoMesh include wireless sensor networks for installations used in home and building automation (HBA), industrial automation, alarm and security systems, indoor asset tracking and agricultural and forest monitoring, to mention a few.

In 2021 NeoCortec announced a collaboration with Honeywell Building Technologies for integrating NeoMesh in a Honeywell's new generation of wireless fire detectors.

NeoCortec is based in Copenhagen, Denmark, and is owned by the Danish Private Capital Fund HP Holding A/S.

- Communication modules
- Variants for 868 MHz, 915 MHz or 2.4 GHz ISM/SRD bands
- CE and FCC IC approved
- Ultra compact 11 x 18 mm



- MiniPCIexpress modules for GW
- Breakout boards
- Evaluation boards
- Evaluation kits
- NeoMesh software stack licenses
- Linux Gateway Software package

Contact
NeoCortec A/S Tonsbakken 16-18, 2740 Skovlunde, Denmark

Author: Harald Naumann
https://www.linkedin.com/in/naumann/