

Designing a GSM dipole antenna

TNE062 – RF System Design

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Abstract

This project report was written in the course TNE062 RF System Design and describes the design process of a dipole antenna intended for the GSM network. This project was carried out cooperating with Field Embedded Communications, a small company in Norrköping. Our aim was set to design a high quality GSM dipole antenna, working in both Europe and in the US. The antenna was first designed and simulated in ADS and later physically implemented. Finally, performance measurements were made. Since our final antenna isn't exactly what we anticipated, some changes ought to be made to tune the antenna into the correct center frequencies.

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1 Introduction

This project report was written in the course TNE062 RF System Design and describes the design process of a dipole antenna intended for the GSM network.

1.1 Background

This project was carried out cooperating with Field Embedded Communications, a small company in Norrköping. There are several types of antennas and one popular design is the dipole antenna, and they were in need of a new microstrip GSM antenna design. The antenna will later be used in one or more of their projects (see fig 1). For us, we enjoyed the opportunity to work with a company that would use our design in “real life” applications.

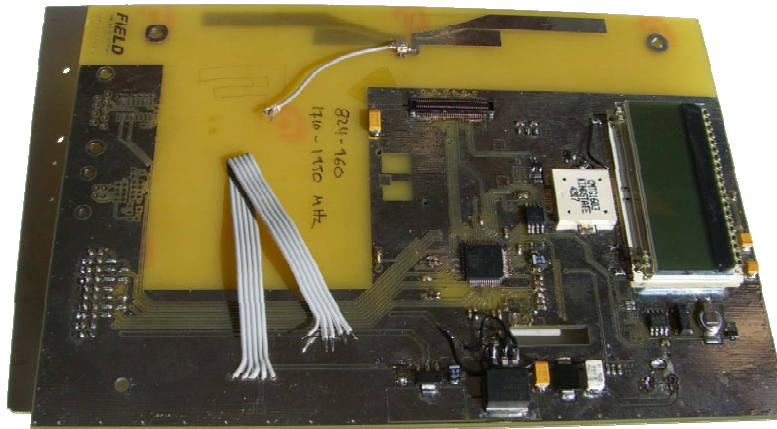


Fig 1. Field PCB prototype that will use our antenna.

1.2 Purpose

Our aim was set to design a high quality GSM dipole antenna, working in both Europe and in the US.

1.3 Method

We first started off by designing a simple dipole antenna in Agilent's ADS (Advanced Design System) where it also was simulated. We then conducted a small market research to see how commercial GSM antennas were designed and found two antennas to examine closer. One of them was the “SmartWing” dipole GSM antenna which gave us a hint of how such antenna could look like. Using the SmartWing as a starting point, a better GSM antenna was first designed in ADS and later physically implemented. Finally, performance measurements were made and our design was compared with the SmartWing.

2 Theory

In this chapter, we briefly highlight the relevant theory of dipole antennas and the GSM network.

2.1 Dipole antenna theory

The dipole antenna was originally designed by Heinrich Rudolph Hertz in the end of the 19th century and is used today in a wide range of applications. This section shortly describes some dipole theory and basic design rules.

2.1.1 General theory

A basic dipole consists out of two equal straight lines of the same length, lying on the same axis, separated by a small gap. The antenna is then fed from the center point, or the feeding point in order to transmit or receive electromagnetic radiation.

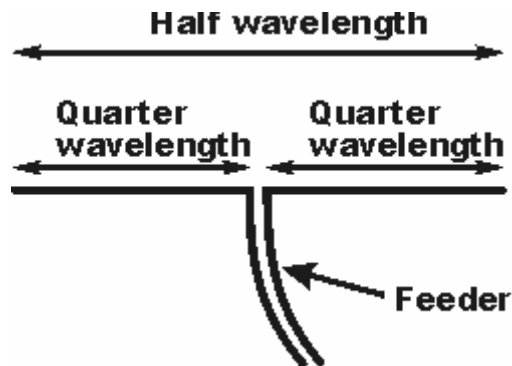


Fig 2. Simple half wave dipole antenna

The current distribution will have a sinusoidal shape (see figure below) with a constant minimum at the ends, and a maximum at the feeding point (the opposite for the voltage distribution).

$$I = I_0 e^{j\omega t} \cos kl$$

This yields that different lengths of the antenna can be used to transmit the same frequency. Note that one wing will be the other wings reflection. Since the current distribution is at maximum at the feed point, the input impedance will be low.

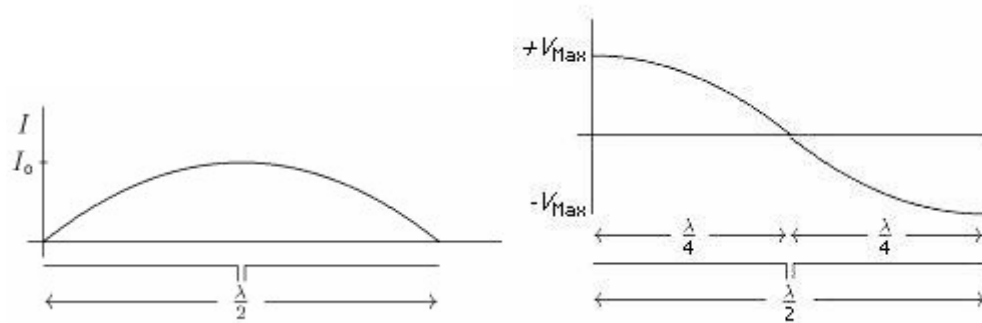


Fig 3. Current distribution and voltage distribution

2.1.2 Antenna length

The main factor for determining the frequency is the length of the antenna. Any number of half wave lengths will do the trick, one only has to consider the fact that propagation of an electromagnetic wave differs between free space and an electric conductor.

In order to compensate for this, the wave length in free space is multiplied with a factor, A, to get the electrical wave length. Since a micro strip dipole antenna is thin compared to the wave length, λ to thickness ratio is high yielding an A value of 0.98 according to the graph below.

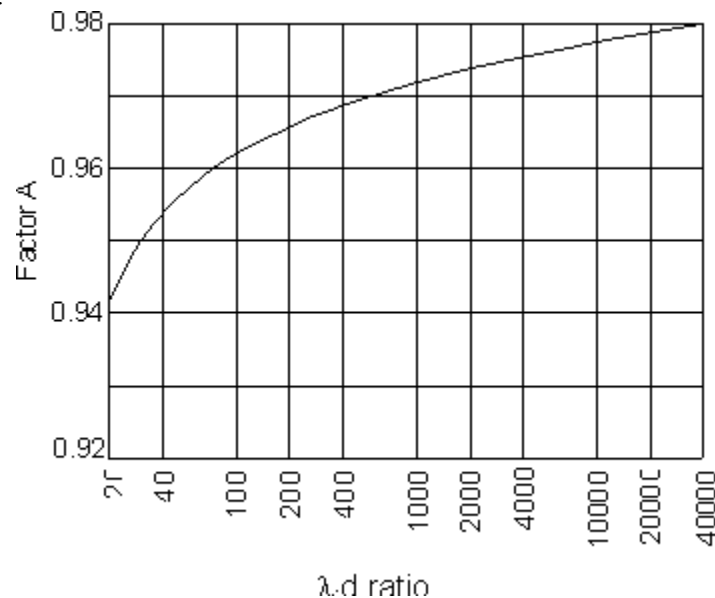


Fig 4. Graph for determine factor A

The length for a half wave dipole can then be calculated according to the formula below, where c is the speed of light.

$$l = \frac{c}{2f} \cdot A \Rightarrow l = 0.44 \cdot \frac{c}{f}$$

2.1.3 Radiation pattern

According to Pozar [6], the far-field pattern of a half-wave dipole antenna is:

$$E_{\theta} = V_0 \frac{\cos\left(\frac{\pi}{2} \cos \theta\right)}{\sin \theta} \frac{e^{-jk_0 r}}{r}, E_{\phi=0}$$

In order to be able to calculate the radiation intensity of the far-field pattern, the equations is simplified.

$$E_{\theta} = V_0 \frac{\cos\left(\frac{\pi}{2} \cos \theta\right)}{\sin \theta} \frac{e^{-jk_0 r}}{r} \approx V_0 \cdot \sin \theta \cdot \frac{e^{-jk_0 r}}{r}$$

The radiation pattern can be plotted by using the expression for the radiation intensity. This plot shows that the half wave dipole is a very omni-directional and there fore well suited for mobile applications.

$$U(\theta, \phi) = \frac{r^2}{2\eta_0} \left[|E_{\theta}|^2 + |E_{\phi}|^2 \right] = \frac{r^2}{2\eta_0} \cdot V_0^2 \sin^2 \theta \cdot \frac{1}{r^2} = C \cdot \sin^2 \theta$$

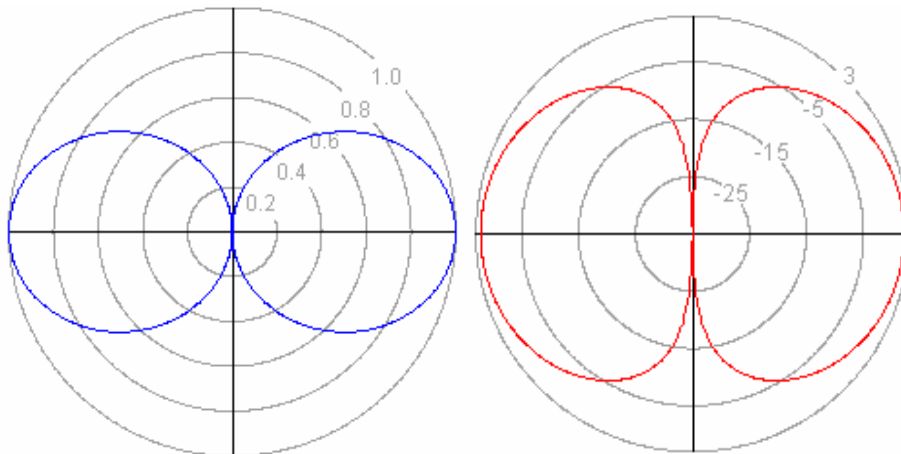


Fig 5. Normalized radiation pattern in linear scale and in logarithmic scale

2.1.4 Voltage standing wave ratio

To be able to make a suitable measurement of the antenna, one can look at the reflection. If the reflection is low, the amount of energy delivered to the system is high. When the system is an antenna, it could mean that the signal is emitted. But the energy doesn't have to be emitted, the possibility of energy loss has to be considered. For instance, if the antenna is attached with a long non ideal cable, the energy can be absorbed in the cable.

Using S parameters, the S11 parameter is the reflection at the input port. Since S11 is a complex number, it's not convenient to use as an indicator for the reflection. Voltage standing wave ratio is on the other hand a real number that is only depending of the magnitude of S11.

$$VSWR = \frac{V_{\max}}{V_{\min}} = \frac{1 + |\Gamma|}{1 - |\Gamma|} = \frac{1 + |S11|}{1 - |S11|}$$

A VSWR value of 1 means that the entire signal is absorbed by the system, i.e. there is no reflection (the system is matched). In addition, a high VSWR means that the signal is reflected back to the source. Plotting VSWR over frequency gives a good idea of the performance of the antenna.

On a smith-chart, the reflection is represented as the distance to the center (normalized value 1, i.e. 50Ω). So a smith-chart plot of S11 close to the center means that the reflection is low.

2.2 GSM Network

GSM is a digital cellular technology and stands for Global System for Mobile Communications. Today there are over 3 billion subscriber connections which make GSM the most popular standard for mobile phones in the world.

The GSM network is considered to be a very secure network and both speech and data are encrypted to prevent eavesdropping. A Subscriber Identity Module (SIM) card holds their identity number and authentication key and algorithm. GSM uses digital technology for time division multiple access (TDMA) transmission methods. With TDMA, the signal is divided into different timeslots which allows several users to share the same frequency channel. The system divides each 200 kHz channel into eight 25kHz time-slots. This supports data transfer speeds of up to 9.6 kbit/s. The longest distance the GSM specification supports in practical use is 35 kilometers.

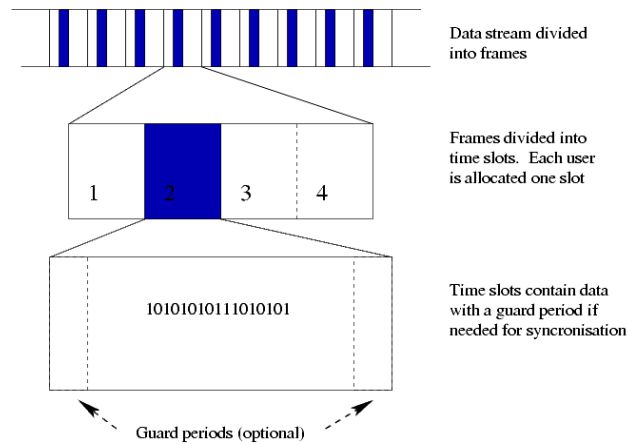


Fig 6. TDMA frame structure

Unfortunately, frequencies for GSM communications are not the same all over the world (see Appendix IV). In this project, we focus on the European (GSM-900 and GSM-1800) and US (GSM-850 and GSM-1900) standards frequency bands.

3 Designing a simple dipole antenna

To get to know ADS and get a feeling of what antenna design is all about, we started of by designing a simple dipole antenna. We picked 2.1 GHz, just a random frequency, to test the theoretical content. We are here using the RO4350B substrate (see Appendix II for substrate parameters).

$$l = 0.44 \cdot \frac{c}{f} = 0.44 \cdot \frac{c}{2.1 \cdot 10^9} = 63 \text{ mm}$$

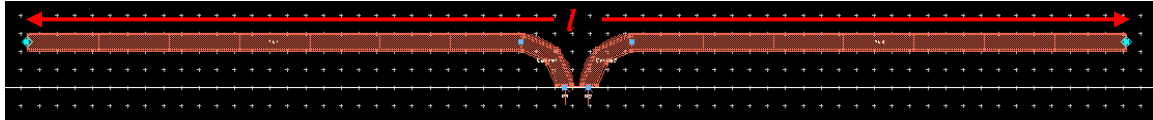


Fig 7. The design in ADS.

3.1 ADS Simulations

The following simulation results were retrieved from ADS.

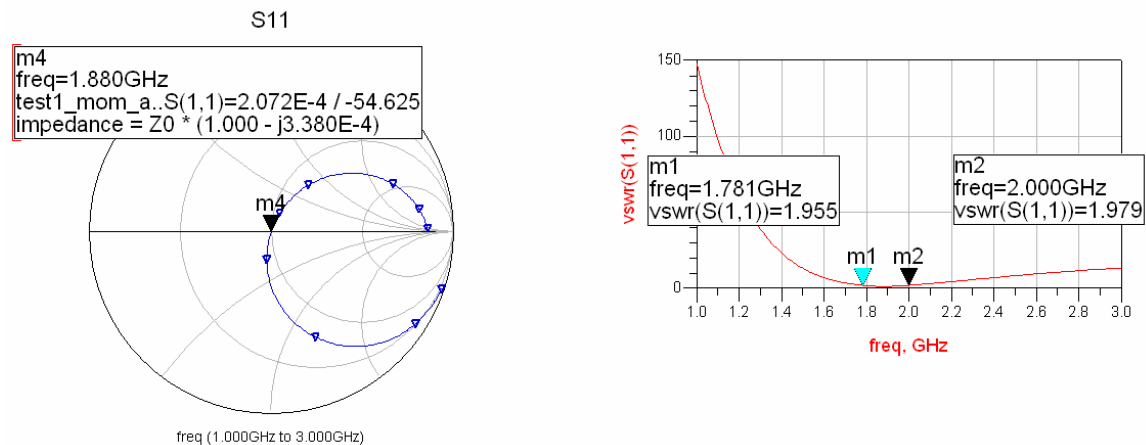


Fig 8. Simple dipole antenna simulation outputs.

As can be seen in the simulation, the antenna seems to be matched perfectly and the minimum SWR which occurs at frequency $f = 1.88 \text{ GHz}$. This is only because we are using a matched port ($R = 58.25$, $I = 1.85$), i.e. it is not matched to 50Ω as usual. The markers m1 and m2 are placed on the $VSWR < 2$ limits, so we can easily calculate the bandwidth to be:

$$B = 2.0 - 1.78 = 0.22 \text{ GHz}$$

The results are not equal to our calculations, the simulated center frequency is 10 % less than the theoretical. But, we have more trust in the ADS simulations than in our calculations since it uses a more complex model.

4 Designing the GSM dipole antenna

This chapter shows the development of a GSM dual band dipole antenna. To begin with, we examine a commercial product, the “SmartWing”.

4.1 The SmartWing – a commercial product

The “SmartWing” is a GPS and GSM antenna and is used in cars, mounted on the front window. In this project, we are ignoring the GPS antenna. The SmartWing are specified for the GSM frequencies: 824-960 MHz / 1710-1990 MHz (for more specifications in Swedish, see Appendix III).



Fig 9. The SmartWing antenna.

The antenna wings are placed on separate substrate layers (top and bottom), and this is visualized in ADS with different colors. The SmartWing was simulated with FR370HR parameters (see Appendix II). To examine the effects of the GPS antenna and the effect of placing the wings in different layers three simulations has been carried out.

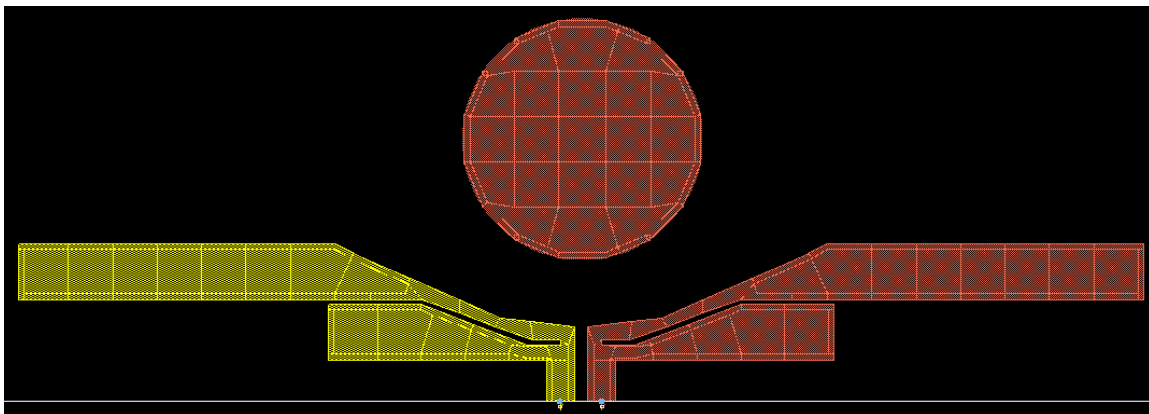


Fig 10. SmartWing, dual layer, with GPS patch, in ADS.

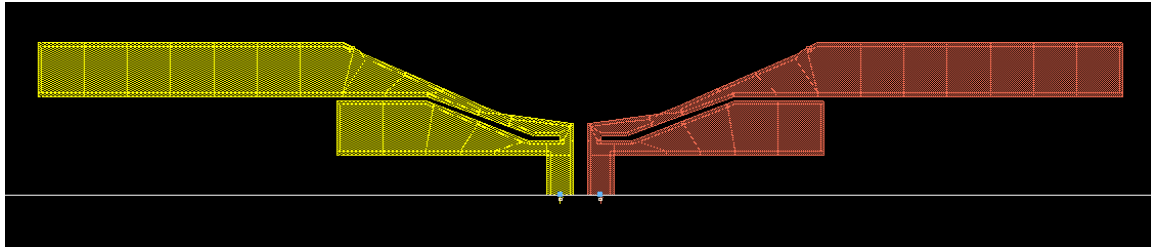


Fig 11. SmartWing, dual layer, without GPS patch, in ADS.

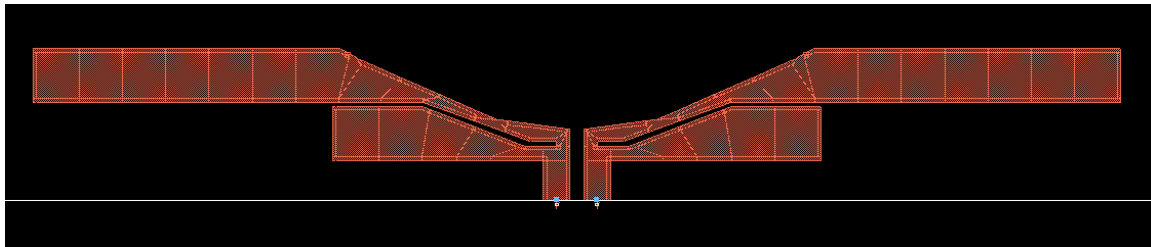


Fig 12. SmartWing, single layer, without GPS patch, in ADS.

The differences in the simulations between the different SmartWing variations can be considered as negligible. Therefore, we have only shown the simulation of the dual layer SmartWing with GPS patch (for the other simulations, see Appendix V).

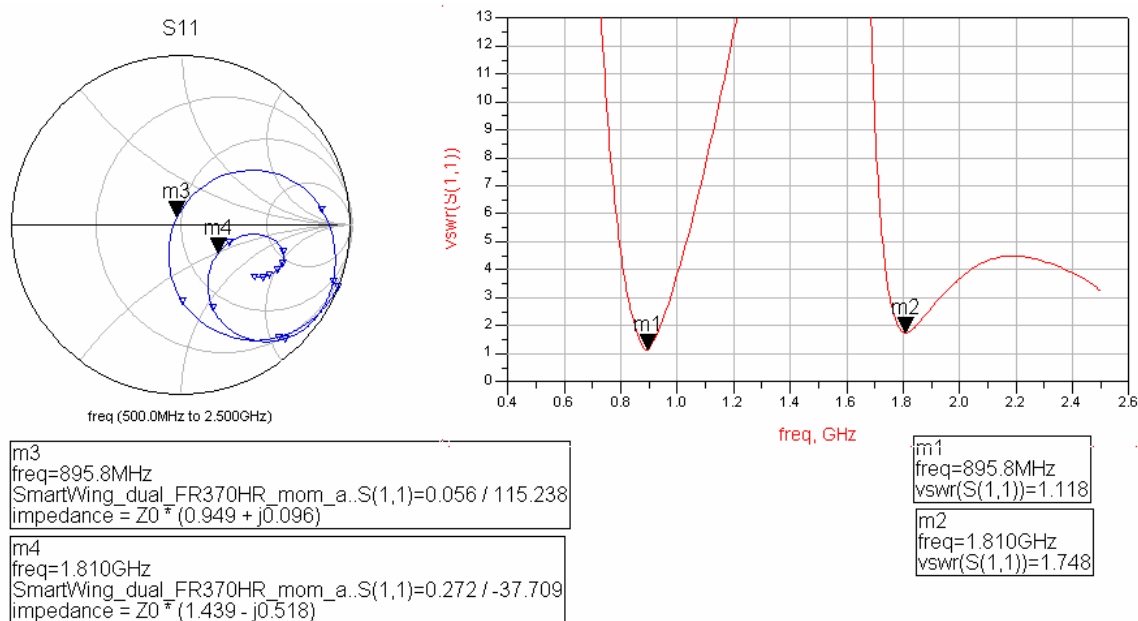


Fig 13. Simulation of SmartWing, dual layer, with GPS patch

As can be seen, the pass bands are centered around 900 MHz and 1800 MHz. But, according to these simulations, we also see that the upper pass band is not perfectly matched to 50 Ω .

4.2 The Patch antenna – a commercial product

Just to compare with another commercial product, and also a different type of antenna, we are including this patch antenna in our project.

We have not simulated this in ADS, and therefore it's only purpose is to be used for comparing the antennas in the Physical Implementation chapter.



Fig 14. The Patch antenna.

4.3 Our first GSM antenna

Using the SmartWing as starting point, we designed our first antenna which is shown in the figure below.

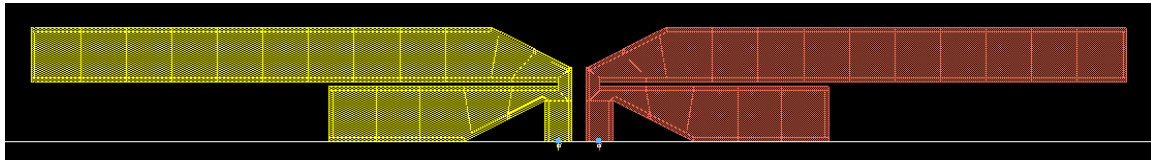


Fig 15. Our first GSM antenna in ADS.

The shorter part (2.5 cm) of the wing is receiving/transmitting the higher frequency and the longer part (5.8 cm) the lower frequency.

4.3.1 Simulation in ADS

The following test results were retrieved from ADS.

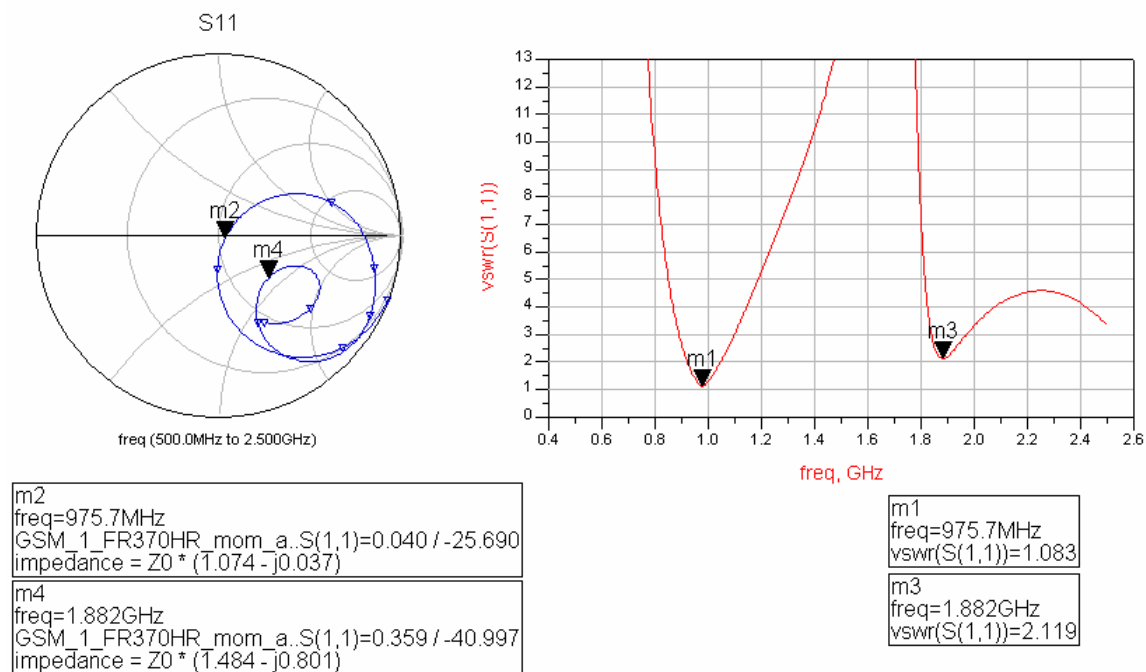


Fig 16. Simulation of our first GSM antenna in ADS.

This antenna behaves far from perfect. The lower frequency band is centered almost at 1 GHz and none of the bandwidths (VSWR < 2) are very impressive. From this design we decided to test several variations to see how these results could be improved.

Theoretically, the lengths should correspond to the center frequencies. Given the center frequencies in simulations, the calculated lengths should be:

$$l_{f_high} = 0.44 \cdot \frac{c}{f} = 0.44 \cdot \frac{c}{1.88 \cdot 10^9} = 7.02 \text{ cm}$$

$$l_{f_low} = 0.44 \cdot \frac{c}{f} = 0.44 \cdot \frac{c}{975 \cdot 10^6} = 13.54 \text{ cm}$$

In ADS, $l_{f_high} = 5.57 \text{ cm}$ and $l_{f_low} = 12.16 \text{ cm}$ which not corresponds to our calculations, as previously noticed in section 3.

4.4 Improving the GSM antenna design

Here, all steps that improved the antenna are presented (the simulations of these versions can be seen in Appendix I). The changes in each step are highlighted with red circles and arrows.

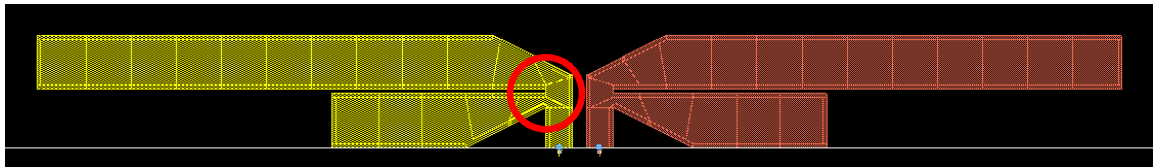


Fig 17. GSM2, changing width between the longer and shorter antenna parts.

This change improved matching and VSWR on the upper frequency band.

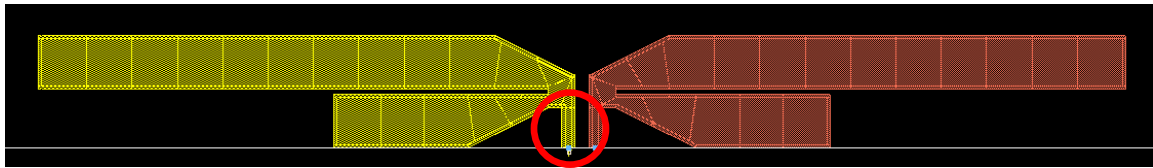


Fig 18. GSM3, changing the feeder widths.

This further improved the matching, since making the feeders more narrow results in a less capacitive load and the center frequencies moves up on the smith chart.

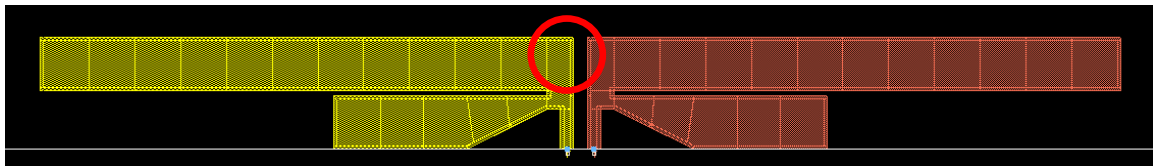


Fig 19. GSM4, adding corners.

By adding corners, this also improved the matching and VSWR on the upper band.

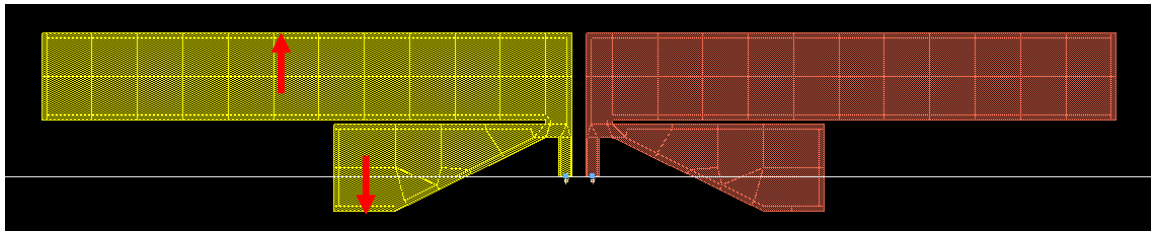


Fig 20. GSM5, changing antenna widths from 6 mm to 10 mm.

Changing the widths actually got the matching a little worse, but the upper and lower band widths were improved dramatically.

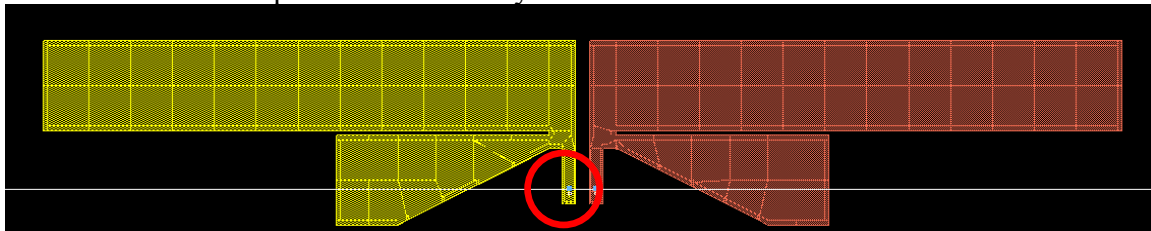


Fig 21. GSM6, changing feeder lengths and port positions.

Here, the feeder lengths were changed and the ports moved up on the feeders a little. The purpose of this was to try to adapt a bit to reality where the connectors are soldered a few millimeters in on the feeders.

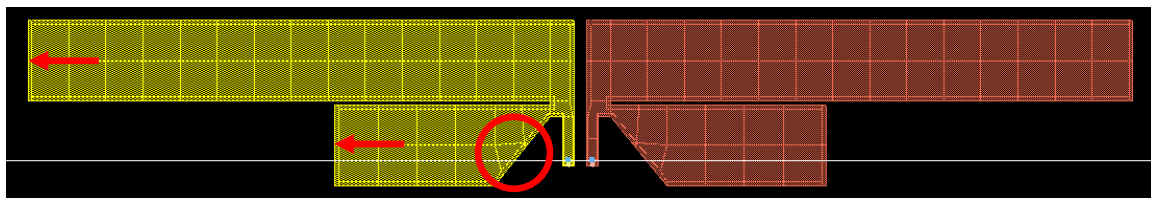


Fig 22. The final design, changing wing lengths and new angle for shorter antenna part.

Finally, the lengths were changed to move the pass bands to the correct GSM frequencies. Also, the width of the shorter part of the antenna further improved the upper pass band.

We also tried a few things that didn't improve the design but rather made it worse:

- Moved the wings closer to each other
- Reduced antenna widths from 6 mm to 3 mm
- Put both wings in same layer
- Moving the ports further up on the pad

4.4.1 Simulation of the final design in ADS

In the figure below, the simulation results of our final GSM antenna are shown.

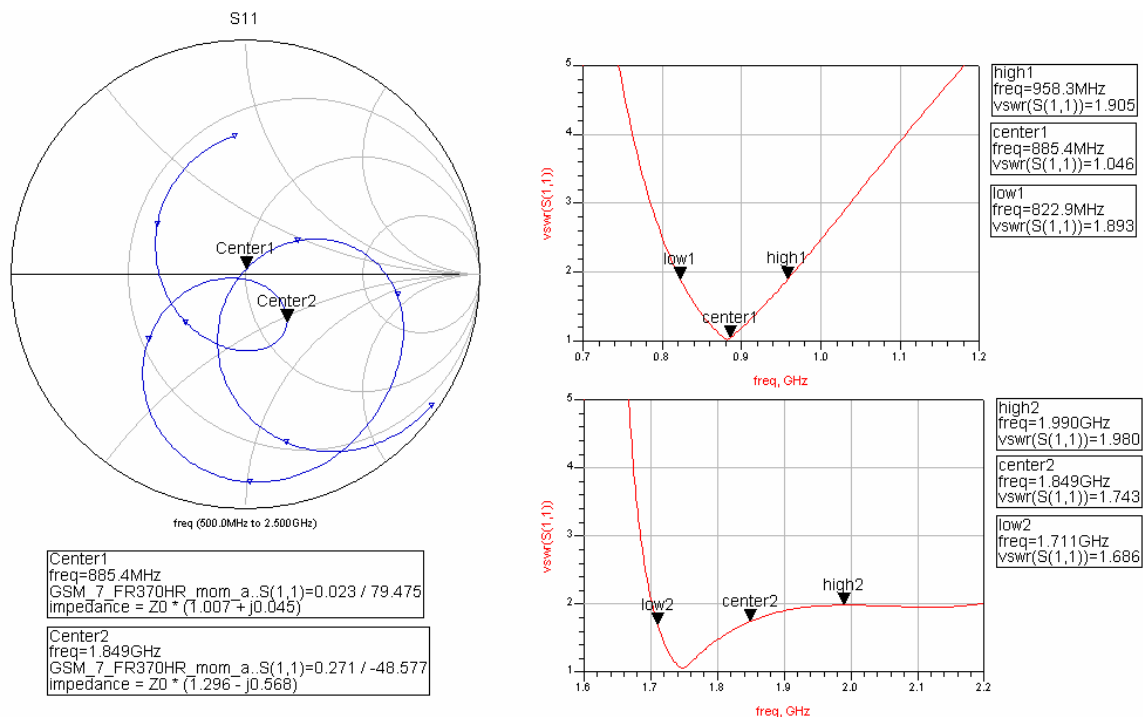


Fig 23. Simulation results of the final design.

As can be seen, we now have a much better bandwidth in both the lower and upper pass band. Both the dips are very close to VSWR = 1, which is as good as it possibly gets. Compared to our first design, the pass bands are now also centered at the correct GSM frequencies. From ADS, we retrieved the directivity to be $D = 3.42$ dB and the gain to be $G = 2.51$ dB. In the figure below, the radiation pattern is shown.

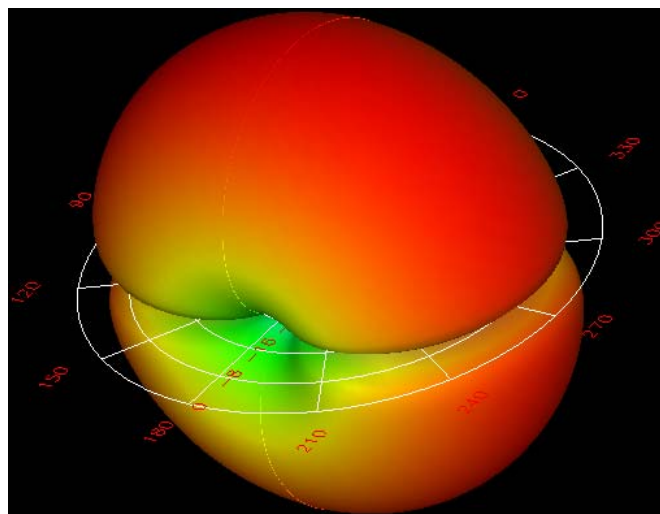


Fig 24. Radiation pattern.

5 Physical implementation of antenna

In the figure below, a picture of our final antenna is shown. In order to realize the antenna, gerber files were exported from ADS and sent to a contractor. The substrate is the same used in the simulations, FR370HR (see Appendix II).

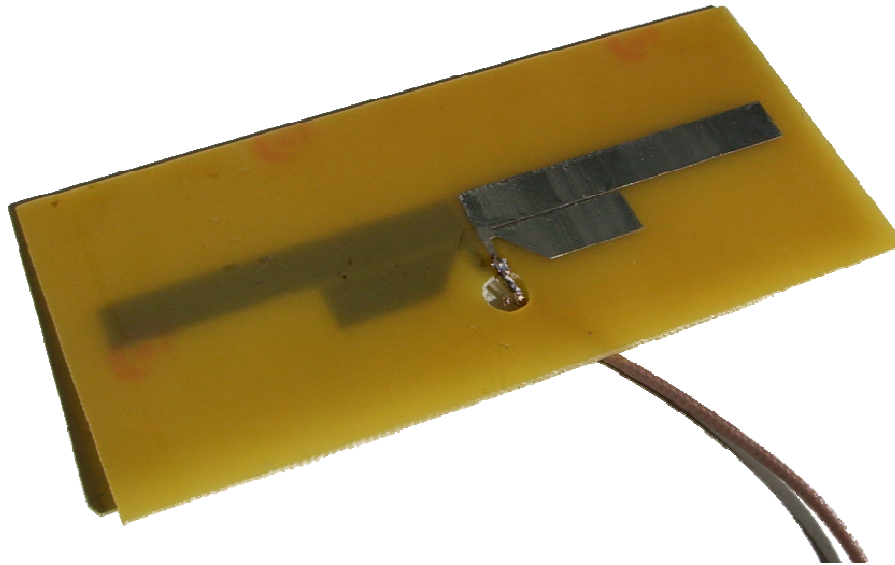


Fig 25. Picture of our final antenna.

To be able to carry out measurements of the antenna, a $50\ \Omega$ cable was soldered to the feeder.

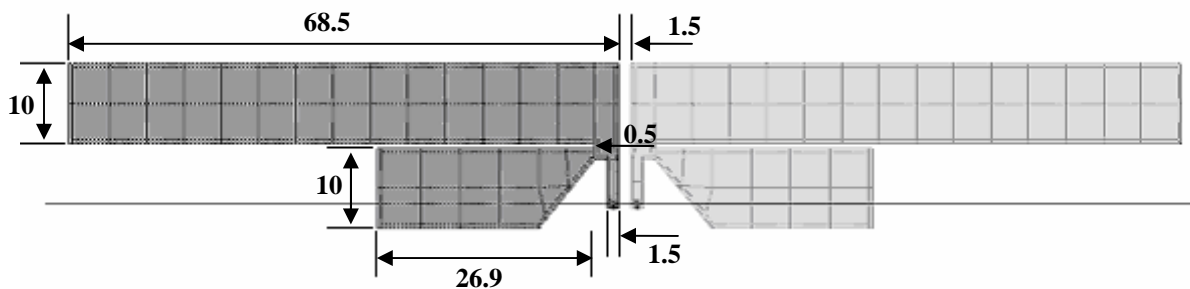


Fig 26. Our final antenna (mm).

5.1 Testing the antenna

Using a Network Analyzer, we got the following measurements shown in the figure below.

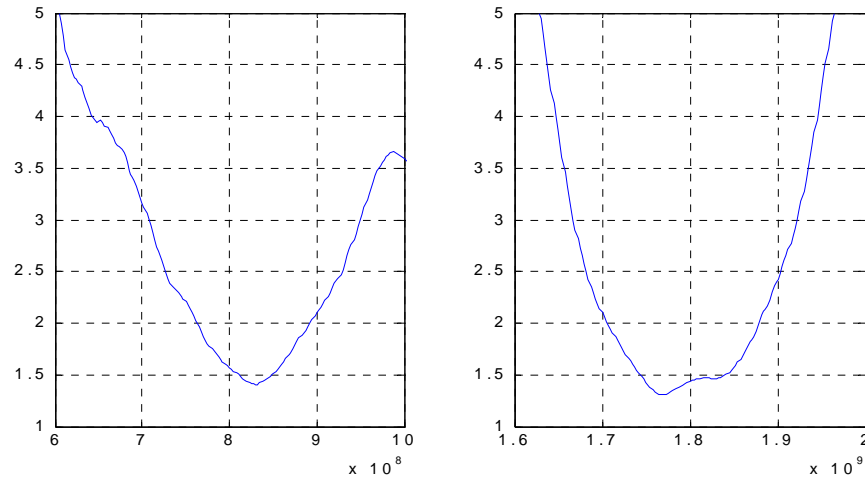


Fig 27. Plot showing lower (left) and upper (right) pass bands of our GSM antenna.

As can be seen, we got quite good pass bands in reality too, even though the plot doesn't look exactly the same as it did in the simulations. One thing that differs significantly though, is that the lower pass band has moved down in frequencies compared to the ADS simulations. Also the upper pass band has moved down a bit.

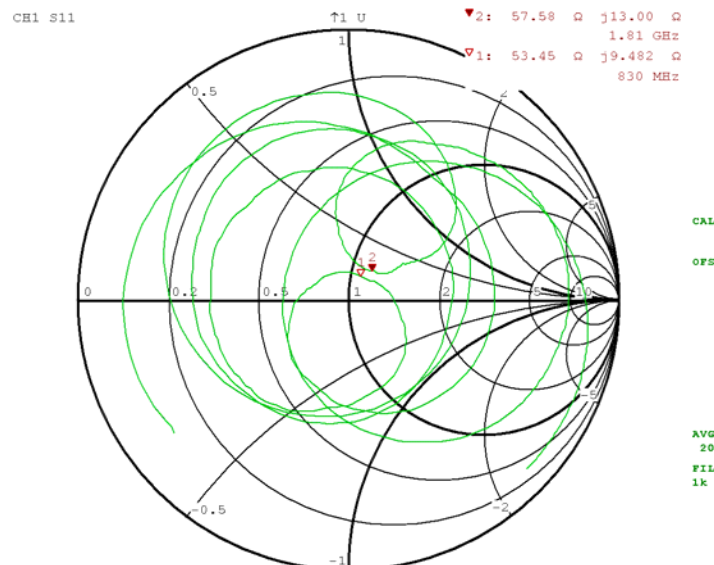


Fig 28. Smith chart plot of our GSM antenna.

As we see in the figure above, the center frequencies of the pass bands are well matched to 50 Ω .

5.2 Comparing with commercial products

Finally, we have compared our antenna to the previous mentioned commercial antennas, as can be seen in the figure below. Compared to the SmartWing, our pass bands (@ $VSWR < 2$) are wider. We also note that the SmartWing pass bands are placed a bit to high frequency wise.

The patch antenna seems to work extremely well according to the VSWR plot. This way to measure its performance is a bit misleading though, the cable is long (leading to losses) and the antenna itself is probably pretty lossy as well (see theory in section 2.1.4).

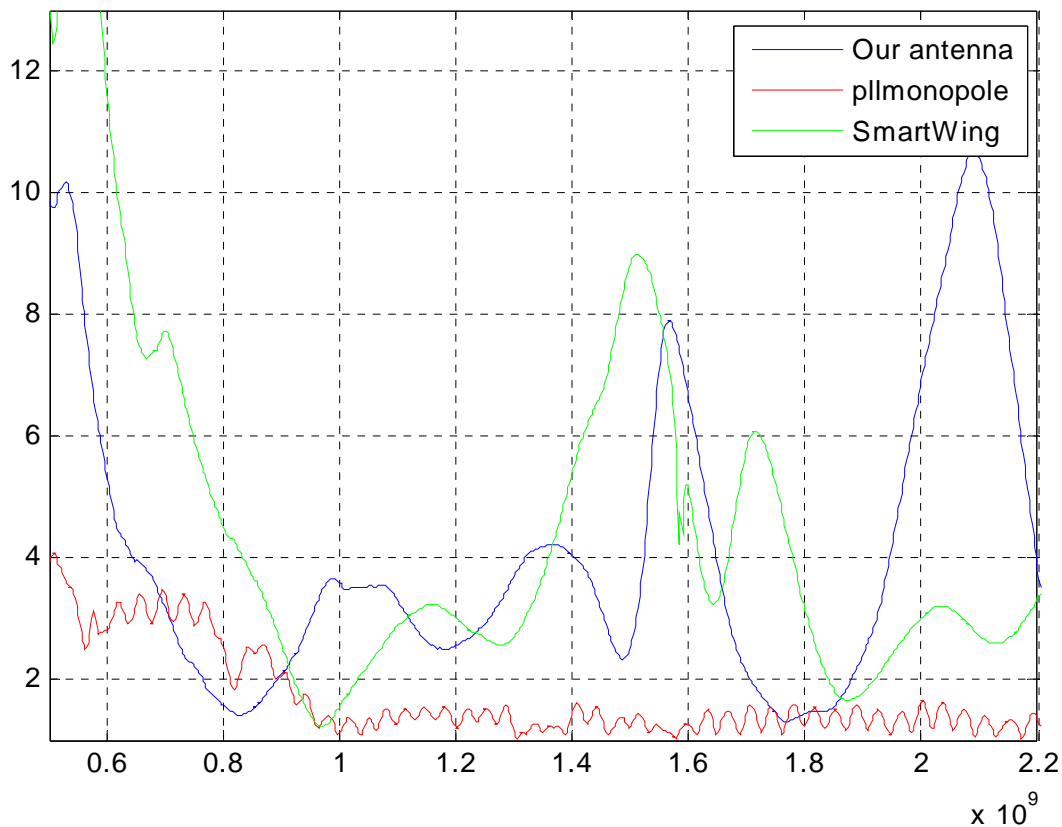


Fig 29. VSWR measurements of all three antennas.

6 Discussion and conclusions

The simulation differs significantly from the actual antenna and this might happen because of several reasons. First of all, during the measurement we used a single ended 50 ohm port, not a balanced port which was used in simulations. To avoid this problem, a balun should have been used. One other reason might be that the simulation is ideal and the reality is not. The physical environment may be noisy and the reflection is utterly dependent of the surroundings of the antenna. If an object came close to the antenna during measurements the VSWR plot was instantly affected. Therefore it was challenging to achieve accurate test results. Another reason might be that we have no cables connected in the simulation. The attachment of the matched cables may alter the out comings, and they may also not be soldered exactly where the ports are placed in the simulation. The difference in propagation velocity, v_p , in metal between the simulations in ADS and reality may also be a reason for the dislocation of center frequencies of the pass bands. In ADS an estimated propagation velocity is used.

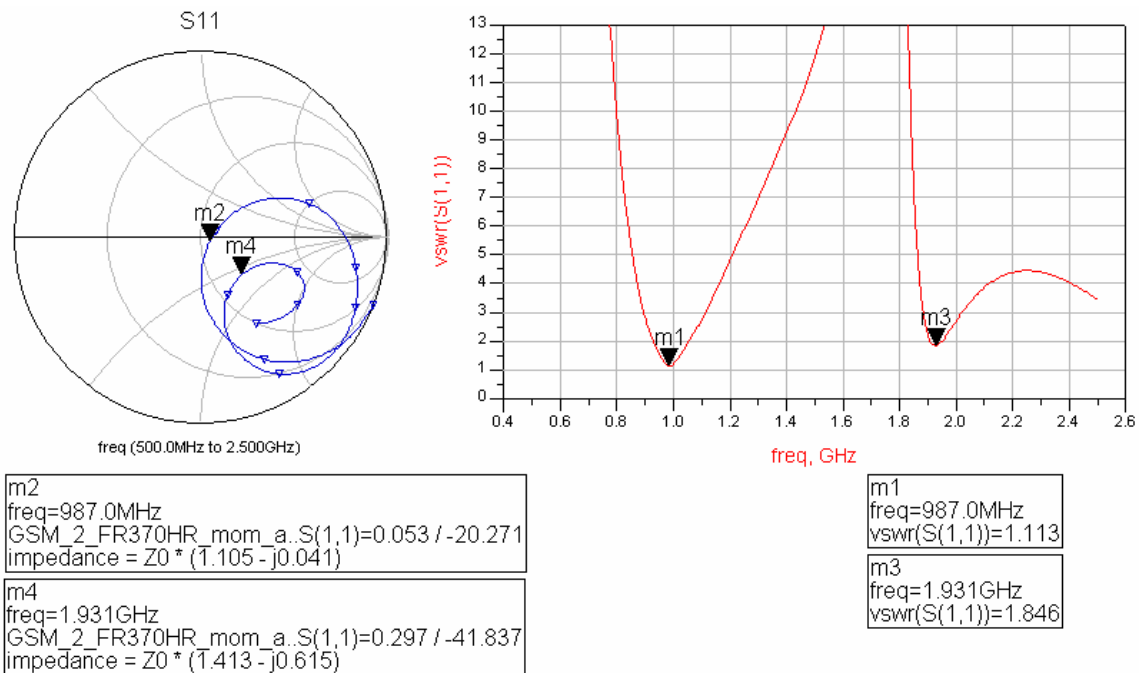
Since our final antenna isn't exactly what we anticipated, some changes ought to be made. By shortening the length of the wings in small steps iteratively and performing new tests continuously, the antennas can be tuned to the right center frequencies.

References

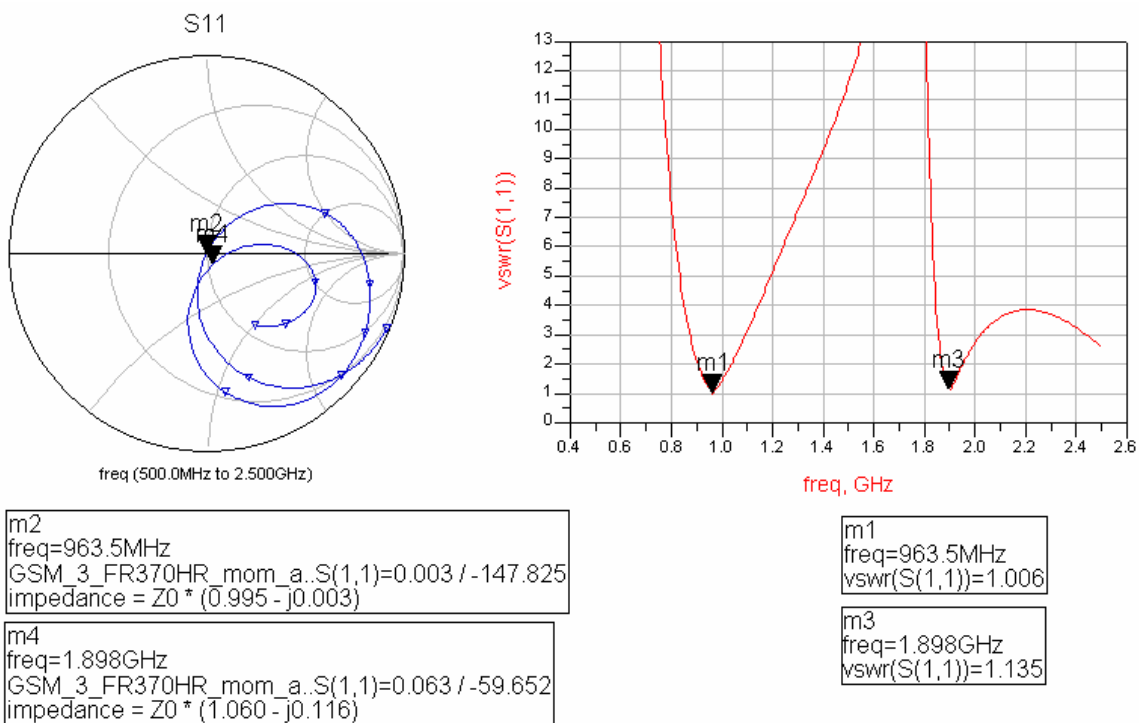
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<http://en.wikipedia.org/wiki/GSM>

Appendix I – Improving GSM antenna simulation results

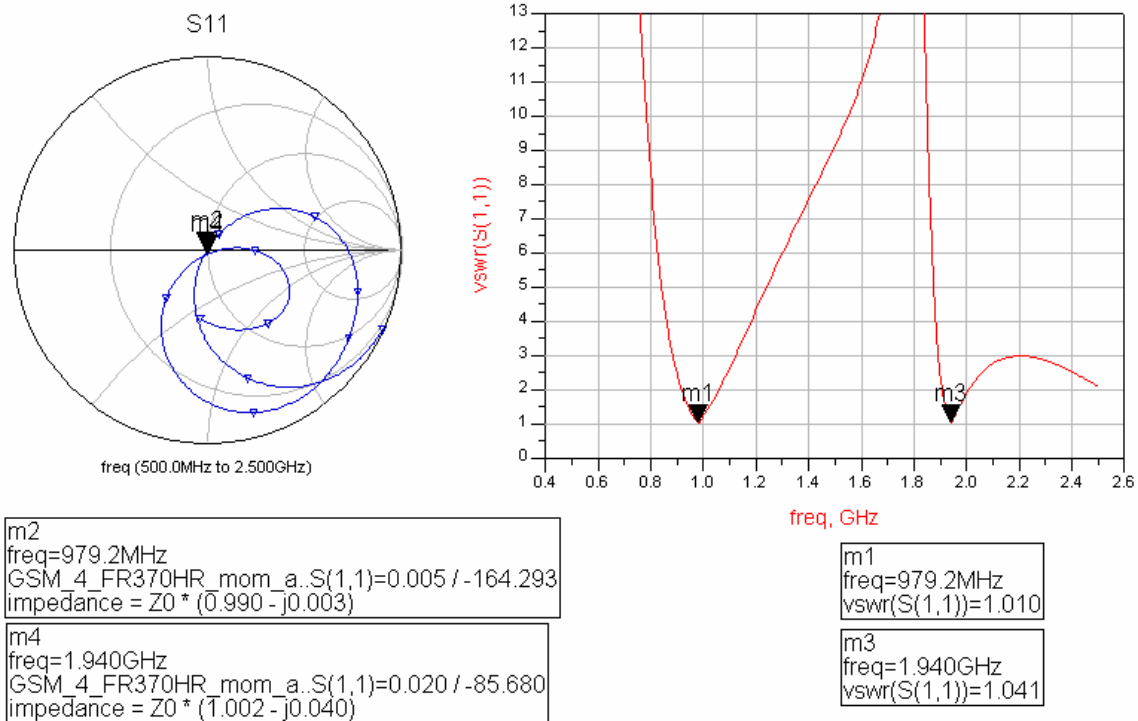
GSM2



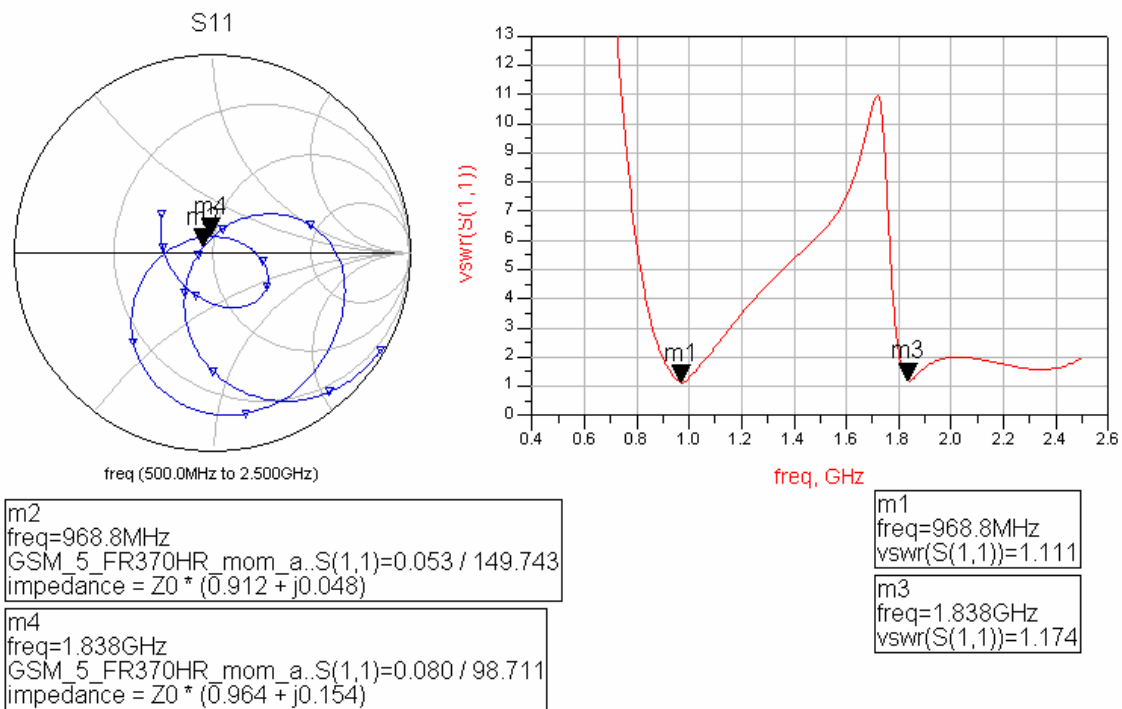
GSM3



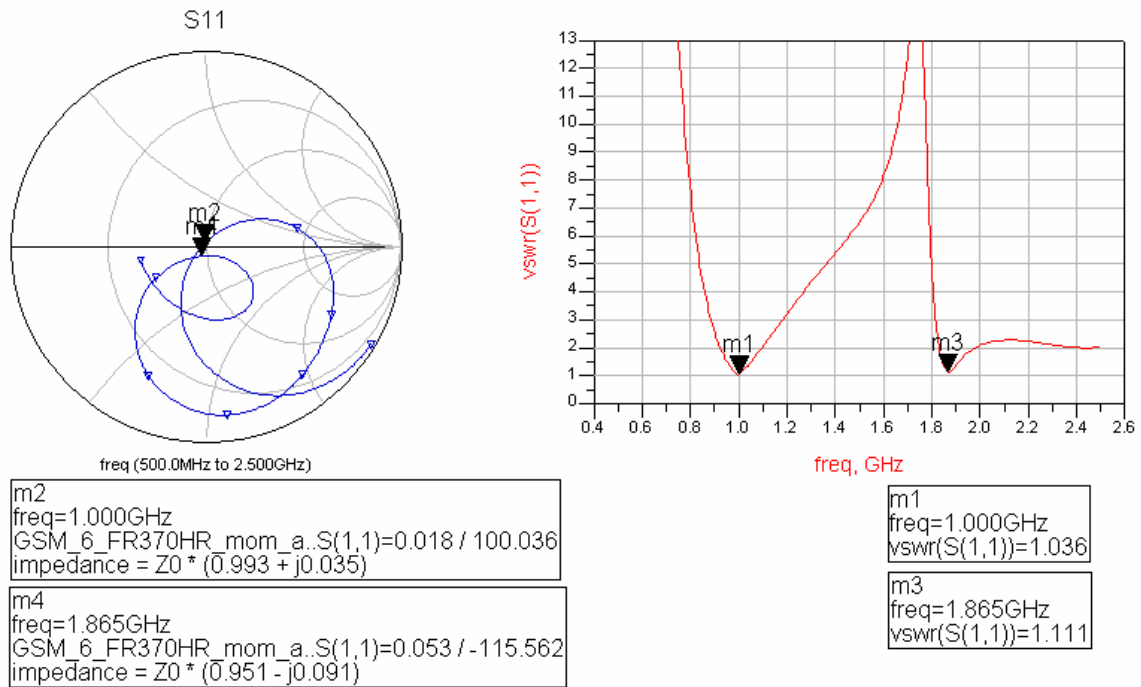
GSM4



GSM5



GSM6



Appendix II – Substrate parameters

FR370HR parameters

Substrate

- Thickness: 1.2 mm
- Permittivity: Real = 4.04, Loss Tangent = 0.021
- Permeability: Real = 1, Loss Tangent = 0

Laminate

- Type: Sheet Conductor, Copper foil
- Thickness: 25 μm
- Conductivity (Sigma): Real = 5.7E+008, Im = 0 Siemens/m
- Overlap Precedence: 1

RO4350B parameters

Substrate

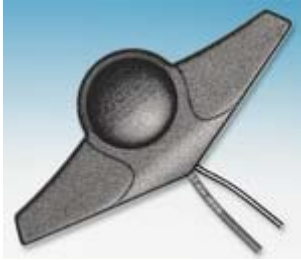
- Thickness: 1 mm
- Permittivity: Real = 3.48, Loss Tangent = 0.04
- Permeability: Real = 1, Loss Tangent = 0

Laminate

- Type: Sheet Conductor, Copper foil
- Thickness: 25 μm
- Conductivity (Sigma): Real = 5.7E+008, Im = 0 Siemens/m
- Overlap Precedence: 1

Appendix III – SmartWing specifications (in Swedish)

SmartWing, GSM/GPS



Fabr Smarteq

Bilantenn för mobiltelefoner GSM 900/1800 och GPS-mottagare. Monteras på insidan av bilens framruta. Spänningsmatning till den aktiva GPS-antennen sker från ansluten GPS-mottagares antennanslutning.

Tekniska data:

Frekvensområde

GSM:	824–960 MHz / 1710–1990 MHz
GPS:	1572,42 MHz

Antennvinst

GSM:	0 dBd
GPS:	Passiv=2 dBic @ zenith ; Aktiv=27 dB

Max effekt (GSM): 10 W

Spänningsmatning (GPS): 3–5 V

Impedans: 50 Ω

Anslutning/Kontakt

GSM:	2,5 m kabel, FME/f
GPS:	2,5 m kabel, SMA/f

Dimensioner/Vikt: L135×B58×H18 mm/110 g

Färg: Svart

Reference:

<http://www.elfa.se/elfa-bin/dyndok.pl?lang=se&dok=7011.htm>

Appendix IV – GSM frequency bands

There are fourteen frequency bands defined in 3GPP TS 45.005, which succeeded 3GPP TS 05.05:

System	Band	Uplink (MHz)	Downlink (MHz)	Channel Number
T-GSM 380	380	380.2 - 389.8	390.2 - 399.8	Dynamic
T-GSM 410	410	410.2 - 419.8	420.2 - 429.8	Dynamic
GSM 450	450	450.4 - 457.6	460.4 - 467.6	259 - 293
GSM 480	480	478.8 - 486.0	488.8 - 496.0	306 - 340
GSM 710	710	698.0 - 716.0	728.0 - 746.0	Dynamic
GSM 750	750	747.0 - 762.0	777.0 - 792.0	438 - 511
T-GSM 810	810	806.0 - 821.0	851.0 - 866.0	Dynamic
GSM 850	850	824.0 - 849.0	869.0 - 894.0	128 - 251
P-GSM 900	900	890.0 - 915.0	935.0 - 960.0	1 - 124
E-GSM 900	900	880.0 - 915.0	925.0 - 960.0	975 - 1023, 0-124
R-GSM 900	900	876.0 - 915.0	921.0 - 960.0	955 - 1023, 0-124
T-GSM 900	900	870.4 - 876.0	915.4 - 921.0	Dynamic
DCS 1800	1800	1710.0 - 1785.0	1805.0 - 1880.0	512 - 885
PCS 1900	1900	1850.0 - 1910.0	1930.0 - 1990.0	512 - 810

Note: The table shows the extents of the band and not center frequency.

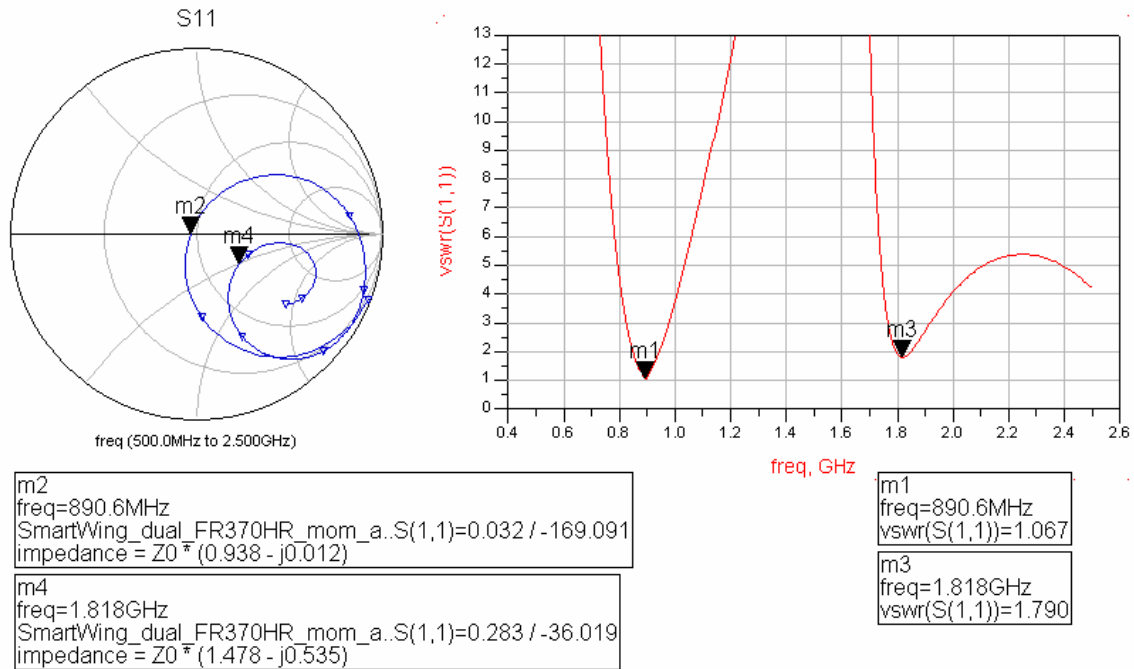
- P-GSM, Standard or primary GSM 900 Band
- E-GSM, Extended GSM 900 Band (includes Standard GSM 900 band)
- R-GSM, Railways GSM 900 Band (includes Standard and Extended GSM 900 band)
- T-GSM, TETRA-GSM

Reference:

<http://www.answers.com/topic/gsm-frequency-bands?cat=technology>

Appendix V – Simulation of SmartWing variations

Simulation of SmartWing, dual layer, without GPS patch



Simulation of SmartWing, single layer, without GPS patch

