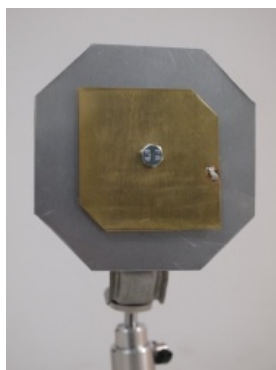
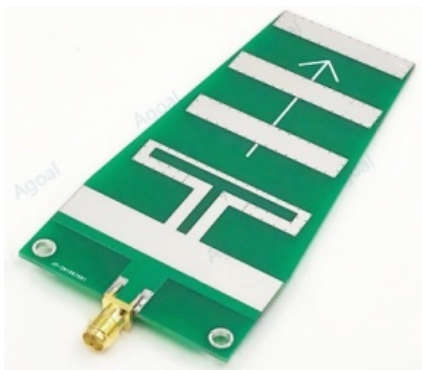


Benchmark test of widely available 2.4 GHz ISM band antennas

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The objective of this study is the comparison of a number of antennas for the 2.4 GHz ISM band, suitable for WiFi, Bluetooth, BLE, LoRa 2.4 GHz, QO-100 Satcom, FPV, that are either commercially available or can be built with moderate effort. The primary issues are the safe matching of the antenna to a transceiver, accuracy of the vendor specifications, and performance comparison between commercial antennas and their DIY competitors.



The first part is a description of each antenna along with a VSWR measurement on the Nano-VNA to check matching with the transceiver; the second part is a comparative test of directivity/gain. The candidates are :

Short rubber antenna $\lambda/4$, nominal 2 dBi

Longer rubber antenna, nominal 5 dBi

Patch antenna QO-100 « Poty »: LHCP feeder for parabolic dish

Modified QO-100 patch antenna with 22 mm washers instead of tube

RHCP patch antenna downsized from Inmarsat antenna

Yagi 17 element 50 cm, alu: advertised gain 16..18 dBi, by some vendors 25 dBi

PCB printed Yagi antenna: gain advertised up to 10.5 dBi

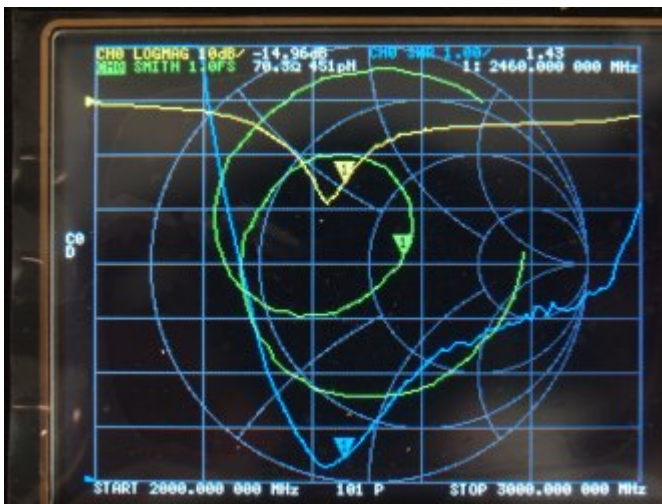
Patch quad array, linear polarisation: gain advertised 14 dBi

Antenna 83 mm diameter, 250 g coffee can

Antenna 97 mm diameter, 500 g coffee can

I. Description of antennas and VSWR measurements

Short rubber antenna 2 dBi



The yellow trace shows the return loss S11 in dB. The VSWR (blue trace) shown here is 1.43 @ 2460 MHz; it is very close to unity in the specified range. Note: the phase of the Smith chart (green) is not correct because the VNA is still calibrated for including the 20 cm cable but the antenna is in this case mounted directly to the VNA without the piece of cable.

The low VSWR is not surprising since these antennas are known to suffer from dissipation, trading gain against good matching.

Long rubber antenna 5 dBi



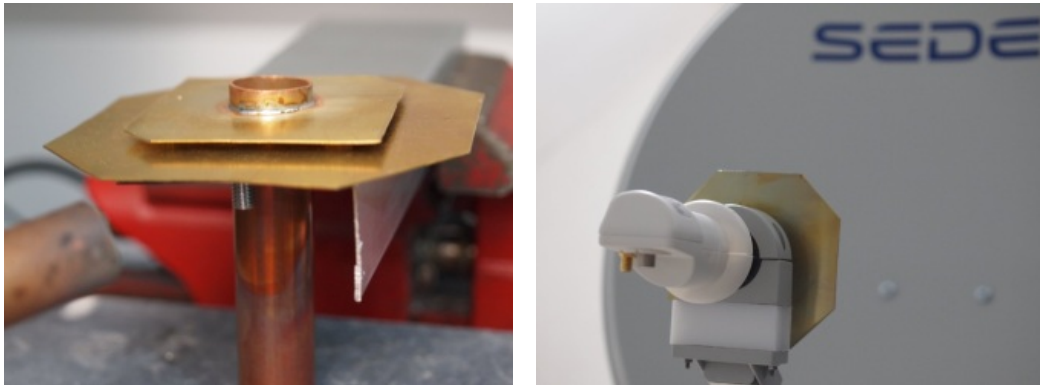
The VSWR minimum is @ 2320 MHz. At 2460 MHz it is 2.92, not good for this kind of antenna that is expected, as its shorter counterpart, to give a perfect match rather than a high gain. It was actually sold as a 433 MHz antenna but there is no VSWR minimum near this frequency either, so we consider it as a typical 5 dBi WiFi antenna. The frequency deviation cannot be attributed to using it with the wrong counterpoise because at this range of frequency it is negligible. The counterpoise is most important in VHF only but not here. A second VSWR dip appears around 2650 MHz : The measurement resolution seems to be insufficient for resolving it because the Smith chart (green) has jumps between 3 measurement points visible as straight lines.

Patch QO-100, metal plates soldered on waveguide tube

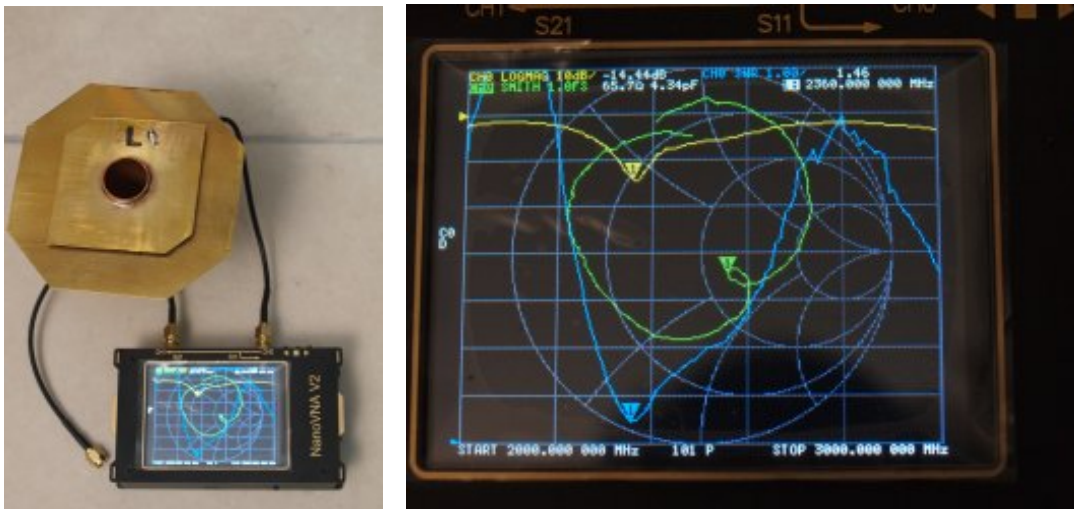
This is the original QO-100 satellite dish feeder for QO-100 uplink at 2.4 GHz, from <http://www.hybridpretender.nl/patch.pdf>

<http://docplayer.net/166276448-Es-hail-2-oscar-100-dual-band-patch-antenna.html>

In summary, it is taken from a ham radio project that consists of converting a parabolic dish antenna into a dual band 2.4 GHz/10.7 GHz antenna for up- and downlink to a geostationary satellite that accommodates (among others) a ham radio transverter.



Left : QO-100 patch feeder being assembled by soldering two brass plates on a copper plumbing tube ; right : QO-100 feeder mounted to a parabolic offset dish, along with a LNB for the 10.7 GHz downlink.

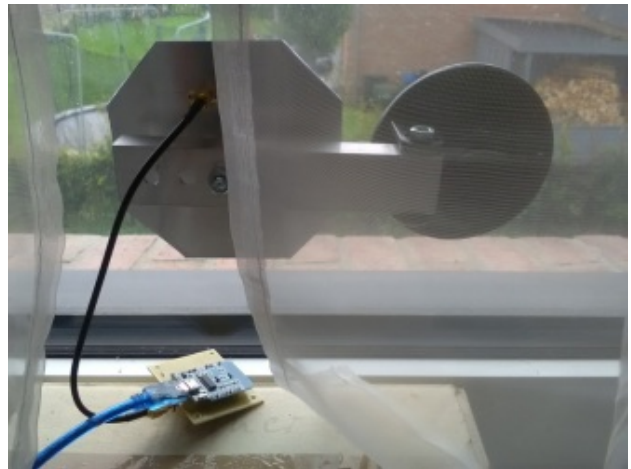
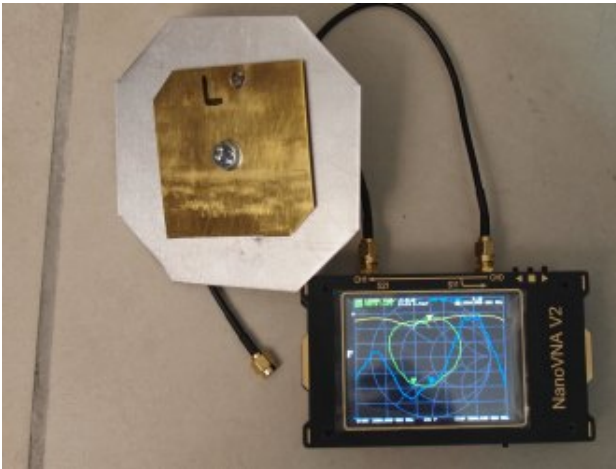


VSWR: 1.9 @ 2400 MHz, 2.77 @ 2500 MHz; minimum 1.44 @ 2360 MHz

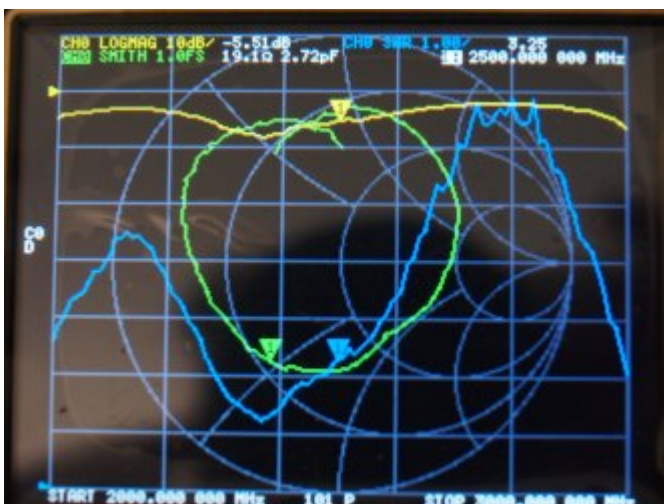
The VSWR minimum is slightly below the target frequency of 2450 MHz. Once soldered, it is difficult to trim and fine tune.

Patch with same dimensions as QO-100, using 22 mm washers instead of the tube

For our purpose the waveguide tube for passing the QO-100 satellite downlink at 10.7 GHz to the LNB is not needed. In a successive version, an electrically identical patch antenna was therefore built by replacing the tube by 22 mm washers, eliminating the critical solder step.



Left : LHCP feeder patch antenna on Nano-VNA ; right : suction cup window version



VSWR: 2.47 @ 2400 MHz; 3.25 @ 2500 MHz, minimum 2.3 @ 2380 MHz

Note that because the antenna is screw mounted instead of soldered, the back plate can be made from aluminum; the radiator still is brass because the center pin of the sma connector is soldered to it.

Patch custom made, downsized from Inmarsat/GPS/Iridium:

Next, an antenna that is not for QO-100 and does not feature the waveguide tube was then made by downscaling to 2450 MHz a L-band Inmarsat antenna, proposed by ham operator Adam 9A4QAV,: <https://www.rtl-sdr.com/building-and-testing-an-l-band-patch-antenna-for-inmarsat-c-reception/>

<https://www.rtl-sdr.com/building-and-testing-an-l-band-patch-antenna-for-inmarsat-c-reception/>
for 1500 MHz:

Reflector Size: 170 mm x 170 mm

Patch Size: 98 mm x 98 mm

Corner Trim: 21 mm from top right and bottom left corners

Coax Connection (Probe): 25 mm from bottom edge

Height of patch from reflector: 7 mm

downscaled 1500 MHz → 2450 MHz

Reflector Size: 104 mm x 104 mm

Patch Size: 60 mm x 60 mm

Corner Trim: 12.8 mm (approx 13 mm) from top right and bottom left corners

Height of patch from reflector: 4.29 mm

trimmed until it works:

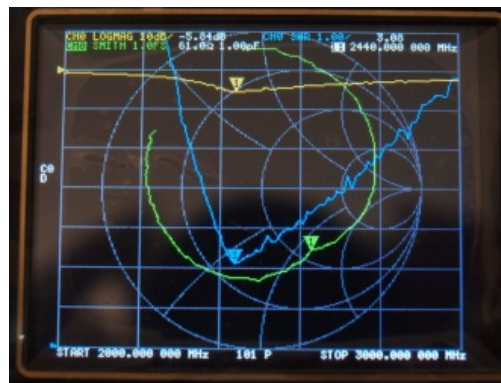
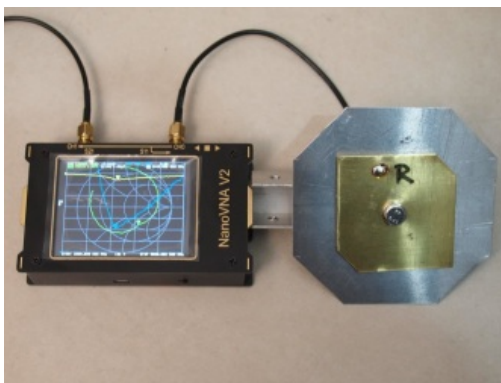
Reflector Size: 104 mm x 104 mm

Patch Size: 58 mm x 58 mm

Corner Trim: 13 mm from top right and bottom left corners

Coax Connection (Probe): 23 mm from left, 8 mm from top (this assymmetric arrangement was inspired from QO-100 antenna)

Height of patch from reflector: 4 mm



Result: VSWR of 3.08 @ 2440 MHz, up to 3.77 within 2400 .. 2500 MHz

The downscaled version is smaller than the version with the tube or 22 mm washer as can be expected. It suggests that if the frequency should be too low, it can be raised by inserting a larger diameter screw or washers in the center.

By the way in the video, Adam says that the center contact is an arbitrary choice to make it DC grounded and protect the LNA input against ESD. The center is a zero impedance spot and for the antenna it is indifferent whether grounded or isolated.

Note that the Inmarsat antenna is RHCP and the feeder for QO-100 is LHCP because the polarisation is flipped by the parabolic dish to RHCP. RHCP is the standard for satcom.

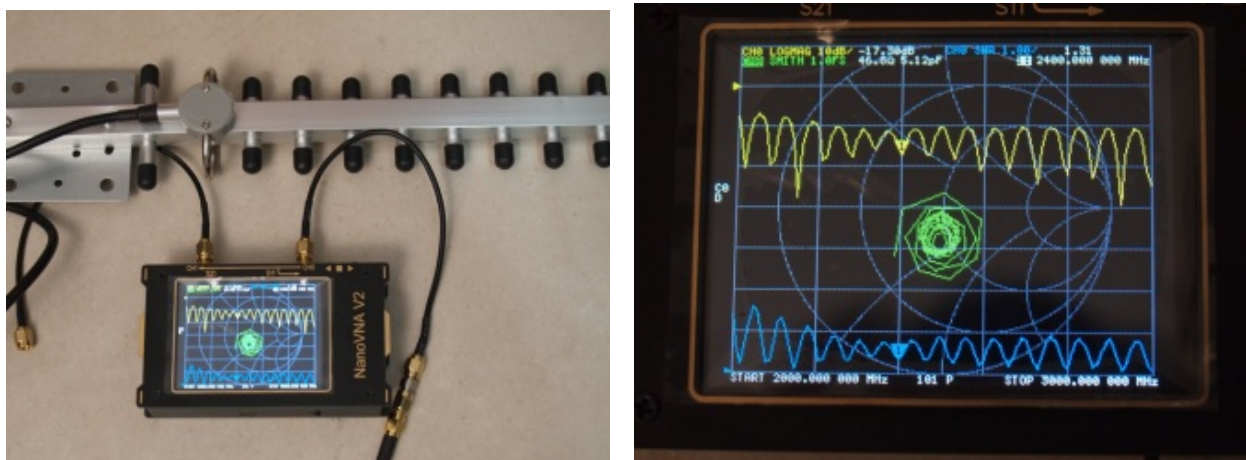
Yagi 50 cm, aluminum, 17 elements, advertised gain 16..18 dBi, by some vendors 25 dBi



The antenna requires extensive repair work before putting into service, exactly as described at <https://hackaday.io/project/158995/logs?sort=oldest>

It seems that the antenna is commercialized since >3 years with a frequently lacking connection between the cable and the driven element. For the antenna to work it is of paramount interest that the feed line is connected to the active element.

Other observations are the equidistant elements of same length, whereas a usual Yagi antenna has different length elements that are not equidistant. In general, the impedance decreases with increasing number of elements, hence a folded dipole with its 300 Ohm is possibly reduced to 50 Ohm with 15 directors. (open dipole: 75 Ohm).



Result: VSWR varies between 1.31 and 1.83, over a range >> 2.4..2.5 GHz; measurement includes the non-detachable cable, 142 cm RG-58. Erratum: previously cable length wrongly given as 60 cm.

Curiosity:

Relation between number of oscillations and cable length: for every wavelength that fits on twice the cable length (back and forth), we get one oscillation of S11 or the VSWR or one turn around the Smith chart:

$cn/f = \lambda$; n is the velocity factor 0.666 of the coax; Z is the number of S11 oscillations

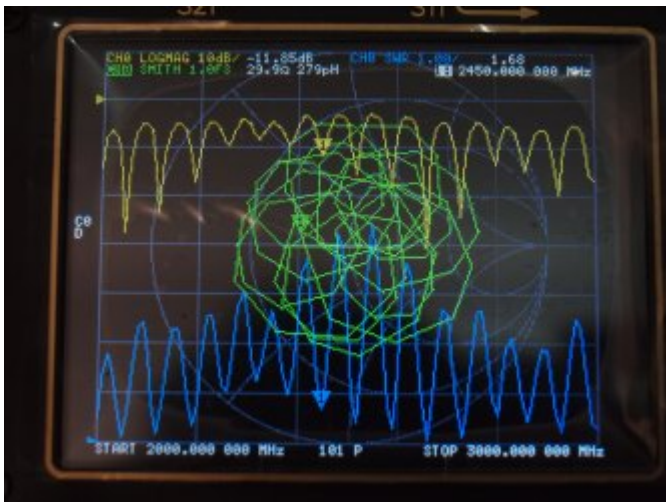
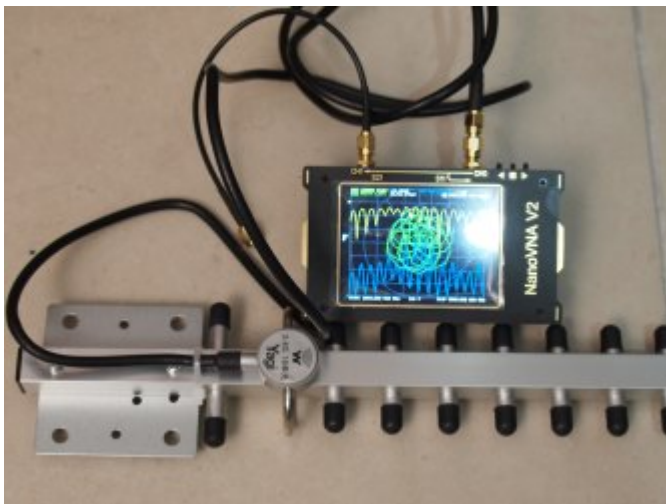
$2L(f_2 - f_1)/(cn) = Z = 15$; $L = Zcn/(2(f_2 - f_1)) = 1.5\text{m}$, determined from number of oscillations

Also note that 1.5 m of RG-58 cable with loss 40 dB/100 ft reduces a feedpoint VSWR of 3 to 1.93

Yagi 50 cm, alu, unmodified as from factory

A second unit of these antennas recently arrived and it turned out that this time the cable is not disconnected because it presents a DC short. It was then characterized as is, to find out whether the piece of mini coax that is believed to act as a stub, would improve the performance beyond the antenna that underwent repair work, sacrificing the stub.

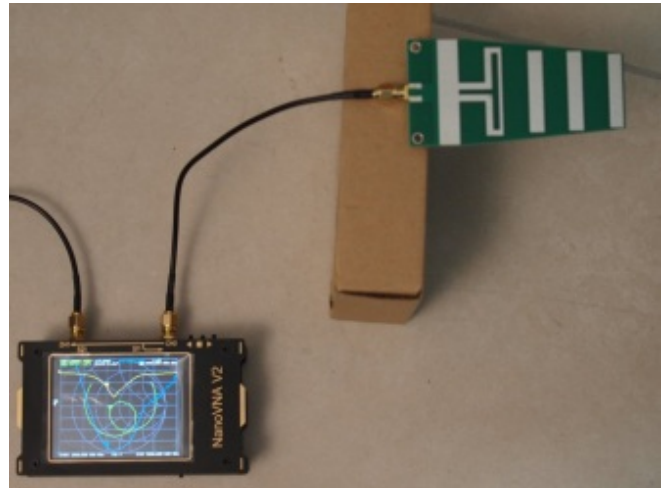
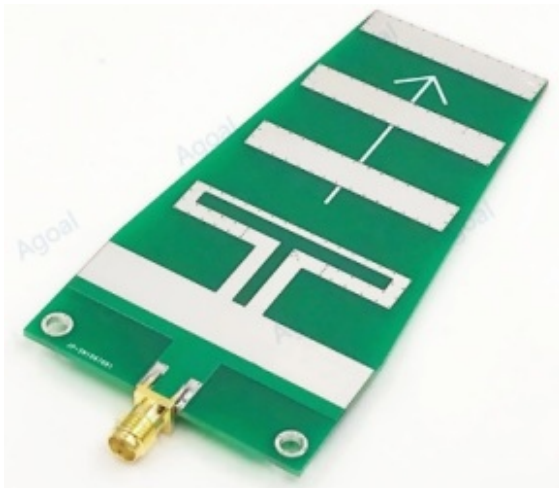
However, it seems that it rather deteriorates the behavior:



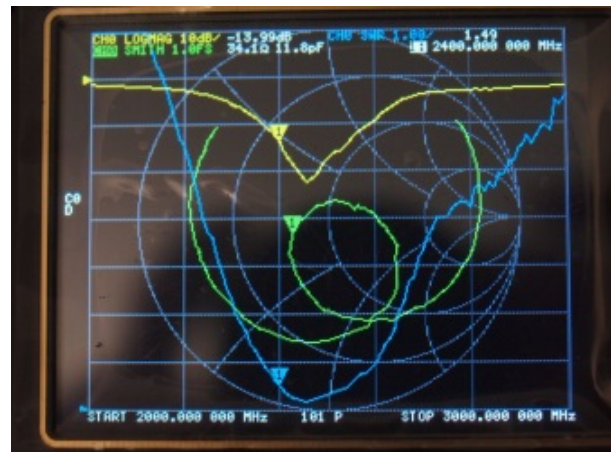
VSWR: 1.68 @ 2450 MHz, 5.2 @ 2480 MHz. The fluctuations of VSWR within the desired frequency range are larger for the unmodified factory configuration containing the 5 cm piece of coax acting as a stub.

Note : during the measurement, the antenna was not laying on the floor ; on the photograph the acquisition is halted and the screen shows the data acquired in free space.

Yagi printed: gain advertised up to 10.5 dBi



Result:



The VSWR has its minimum exactly in the middle of the desired frequency range and is low enough to assure an almost perfect match :
1.18 @ 2450, 1.49 @ 2400, nicely centered around 2450 MHz and useable over a 100 MHz width.

Quad patch array 2 x 2: gain advertised 14 dBi



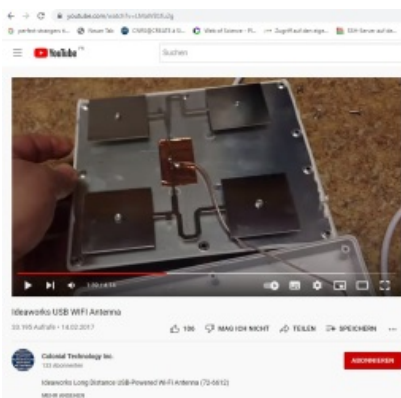
The antenna contains a PCboard consisting of the 4 patches and a feeder network. Apparently it did or still does exist a version made from sheet metal and without PCboard which is possibly even more performant since it avoids distortion of the field by the dielectric at the edges of the patches. Also note that many WiFi routers contain internal patch antennas.

Result:



VSWR 1.03 @ 2400 MHz, 4.6 @ 2480; the dip is not centered at 2450 MHz and very sharp.

Note: before disassembly and reassembly, the VSWR dip was less pronounced (right image). Cured by curiosity ? Apparently the cable was longer while recording the left (additional 20 cm coax?). This antenna is expected to give the best results at the lower end of our desired frequency range.



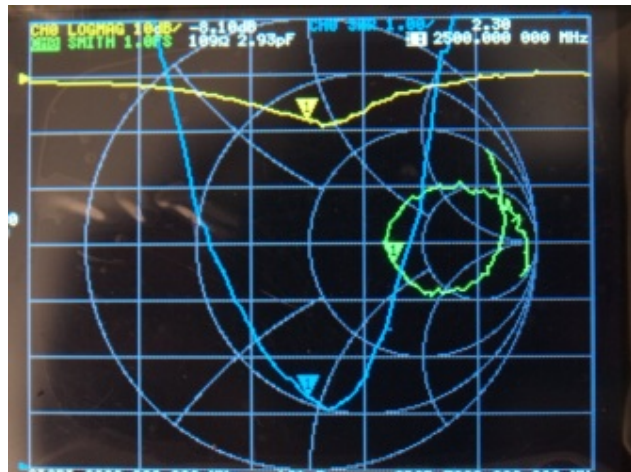
Sheet metal version, Ideaworks USB WIFI Antenna :
<https://www.youtube.com/watch?v=LMalVB1fu2g>

Cantenna 83 mm diameter

250 g coffee can, dimensions : 83 mm diameter, 145 mm height



Result:



VSWR dip unchangeably centered at 2530 MHz : 2.0 @ 2530, 3.48 @ 2400, 2.30 @ 2500; increasing the radiator length from 31 mm to 34 mm does not lower the optimum frequency below 2530 MHz; probably the can is too small.

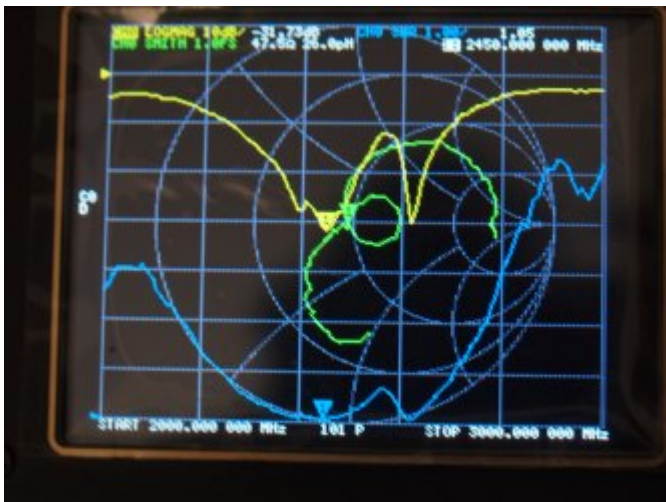
A website :

http://f8kgb.chez-alice.fr/presentation_antenneeh_dipoleetvinverse_antennewifi.htm

gives a length as function of diameter. In contrast to what is stated, it is not the can length, but the wavelength for the TEM₀₀ mode that becomes longer as the can diameter shrinks, because part of the k vector is consumed for fitting the mode into the can. Here for 83 mm diameter, the dipole is placed $\lambda/4 = 66$ mm in front of the bottom (= reflector). This appears (unreasonably?) long compared to the freespace quarter wavelength.

Cantenna 97 mm diameter

Cantenna from 500 g coffee can, dimensions : 97 mm diameter, 185 mm height;
for diameter 97 mm, the above website yields $\lambda/4 = 45.5$ mm for the position of radiator from bottom; the radiator length was shortened until SWR was optimized at 2450 and we find exactly 31 mm;



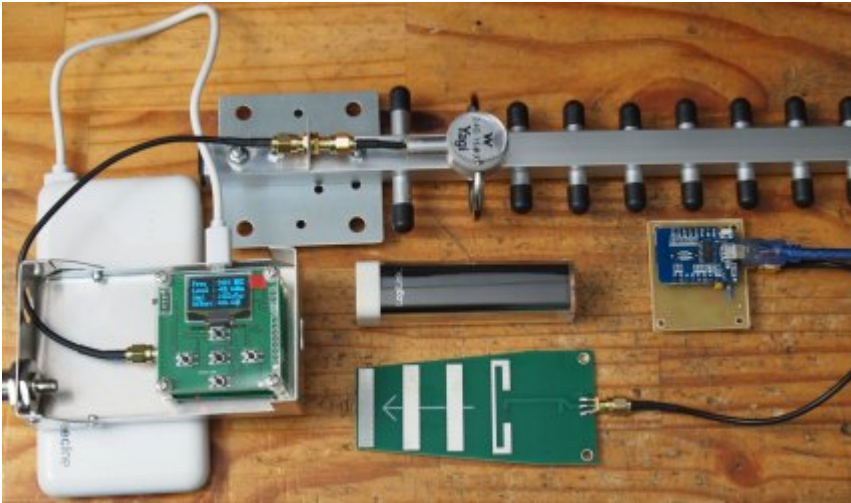
Result :

VSWR: 1.05 @ 2450 MHz, < 1.1 over the entire range 2400 .. 2500 MHz ;

Note that a second VSWR minimum appears at 2620 MHz. This might be the appearance of the next higher mode above TEM₀₀.

II. Relative gain/directivity test for comparing the antennas to each other

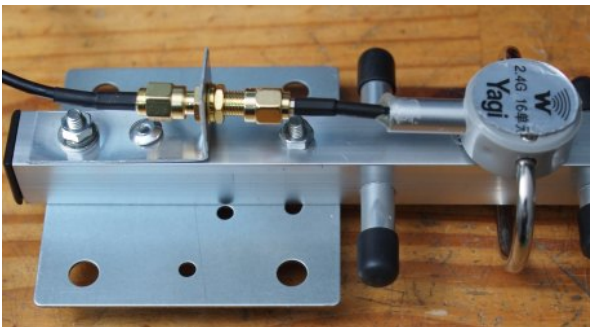
The relative gain of the antennas shall now be compared. To do so, a test transmitter with a SX1281 transceiver module and a printed 5 element Yagi is set to emit in CW mode.



Setup for the field test: antenna gain measurement

Conditions: transmitted power 5 dBm, in CW mode, 2410 MHz, 4 meter distance between transmitting and receiving antenna, transmitter aiming into space, RSSI measured by a power meter with -52 dBm sensitivity

Then, the antennas to be tested are made to face the test transmitter from 4 meters distance, and the incoming signal is measured by a RF power meter. Lacking an anechoic chamber, the transmitter is aiming into the sky/space to avoid reflections and multipath propagation. This leads to RSSI values on the power meter typically of -30 .. -20 dBm, far above the sensitivity of -52 dBm and any unintentional receptions of nearby ISM band devices. Note that the frequency value entered into the power meter seems to be a calibration factor and it does not provide filtering.



Also note that here the Yagi antenna has been modified according to Hackaday and furthermore features a SMA connector near the feedpoint instead of the permanently attached cable, allowing VSWR and gain measurements closer to its feedpoint. The quad patch antenna was modified similarly with a SMA connector.



The test transmitter, 5 dBm aiming at the sky to avoid multipath propagation / reflections. Two printed Yagi antennas were available allowing to keep one as transmitter and use another as DUT.

The antennas were then aimed at the transmitter on the stretched out arm aiming downwards. The linear antennas showed that the emitted polarization was perfectly linear. By rotating e.g. the rubber antenna horizontally, the signal strength dropped below the detection threshold.

The homemade patch antennas that are supposed to have circular polarization were tested in V and H polarization, V meaning that the feedpoint is up or down, and H that it is to the side. Because it had been heard that the polarization is not always perfectly circular. Indeed, most times the V polarization is the preferential one, however only 2 specimen had almost identical values for V and H, showing that it is probably well circularly polarized. This shows that the circular polarization is difficult to achieve and depends critically on the dimensions.

Antennas that are marked (a), (b), (c) are available as several specimen.

The results : raw signal strengths

Received power :

Antenna	RSSI "V"	RSSI "H"
Short rubber, nominal gain 2 dBi:	-36.9 dBm	-52 dBm (noise)
Patch QO-100 Poty:	-25.8 dBm	-30.4 dBm
Patch QO-100 with 22 mm washers (a)	-36.4 dBm	-34.8 dBm
Patch QO-100 with 22 mm washers (b)	-28.1 dBm	-28.3 dBm
Patch RHCP downsized from Inmarsat (a)	-28.6 dBm	-28.3 dBm
Patch RHCP downsized from Inmarsat (b)	-28.6 dBm	-31.4 dBm
Patch RHCP downsized from Inmarsat (c)	-27.7 dBm	-31.0 dBm
Yagi 50 cm, alu: advertised gain 16..18 dBi	-23.7 dBm	
Yagi printed: nominal gain up to 10.5 dBi	-25.5 dBm	
Quad patch array: nominal gain 14 dBi	-21.7 dBm	
Cantenna 83 mm:	-28.1 dBm	
Cantenna 97 mm:	-24.6 dBm	

Discussion

The winner is the quad patch array, followed by the aluminum Yagi. After the test a 2nd patch array was received that does not have the same excellent VSWR value as the first, with no obvious reason, so it must be stated that this antenna might also be subject to tolerance/variations and possibly we had just drawn a perfect specimen. Should the VSWR deteriorate from 1 to 3, this would result in 50 % of reflected voltage amplitude equal to 25 % reflected power, meaning a loss of -1.25 dB in power and gain.

The fact that the winning antenna has 15 dB more gain than the 2 dBi rubber antennas, and that it is advertised as 14 dBi antenna, probably means that the rubber antenna does not have the 2 dBi of a quarter wave because it contains dissipative elements. Otherwise the 14 dBi would rather be dBd, but it is unlikely that the vendor would be understating his antenna. So we shall use the patch antenna as the reference with its nominal 14.0 dBi and obtain the absolute gain of all other antennas relative to it.

The poor value of specimen 'patch QO-100 with 22 mm washers (a)' of -36.4 dBm is not clear. It has to be verified if there was a connection issue with the cable or a reading error occurred (-36 instead of -26). The value shall for the moment be discarded.

The aluminum Yagi antenna has potential for improvement. In a good Yagi antenna the elements are typically of different size and differently spaced, and the intermittent contact of the elements plugged loosely into the boom are possibly a source of loss and fluctuation. The width of the boom is not at all negligible with respect to the element length. The diameter of the passive elements seems to be excessive with respect to their spacing. From VHF and UHF we do know that a gain of 11 dBi can be obtained with a 8-element Yagi. Therefore, the commercial 17-element Yagi does not seem to make good use of its material and lack behind the state-of-art.

Remark about circular polarized antennas and polarization loss : The circular polarized patch antennas were measured here against a linear transmitting antenna. It is known that a circular antenna suffers from 3 dB polarization loss if used against a linear antenna and vice versa. Therefore, in the following gain table, in the case of the two antennas that have almost identical gains in V and H direction, we assume perfect circular polarization and shall add another 3 dB to obtain the gain that would be obtained against a circularly polarized transmitter and put it into the column labeled «gain CC». However for the antennas that have a strong preferential axis and hence elliptical polarisation (at best...), the computation of such a gain value would be more difficult and is therefore not done.

Gains relative to Quad patch array set to 14.0 dBi

Antenna	gain "V"	gain "H"	gain "CC"
Short rubber	-1.2 dBi		
Patch QO-100 Poty:	9.9 dBi	5.3 dBi	
Patch QO-100 with washers (a)	-0.7 dBi	0.9 dBi	
Patch QO-100 with washers (b)	7.6 dBi	7.4 dBi	10.4 dBi
Patch RHCP downsized (a)	7.1 dBi	7.4 dBi	10.1 dBi
Patch RHCP downsized (b)	7.1 dBi	4.3 dBi	
Patch RHCP downsized (c)	8.0 dBi	4.7 dBi	
Yagi 50 cm, alu	12.0 dBi		
Yagi printed	10.2 dBi		
Quad patch array:	14.0 dBi		

Cantenna 83 mm:	7.6 dBi
Cantenna 97 mm:	11.1 dBi

Conclusion

With the winning quad patch array set do 14 dBi, the relative gains of the other antennas are given in the above table. Once again, although number 2 in absolute gain, the Alu Yagi antenna is disappointing for its 17 elements, and overall it is noteworthy that even the best commercial antenna (Quad patch) is only 3 dB above the bigger of the 2 cantennas. The circularly polarized simple patch antennas are predicetd to reach 10 dBi by adding the 3 dB polarization loss. This risks to be exaggerated because single patch antennas are expected to have a gain between 6 and 9 dBi. Hence it can be suspected that their polarization is slightly elliptical/diagonal rather than perfectly circular and the received power under exposure to linear polarized waves had been attenuated by less than 3 dB polarization loss. These antennas may still be quite interesting for air- and spacecraft where a linear polarization cannot be controlled, in particular it may be interesting to minimize weight and size of an onboard antenna e.g. by making a version with metal films on a polystyrene spacer, and using it against a ground station antenna that combines several circular patch antennas in an array. The printed Yagi antenna performs fairly well for its compact dimensions and is expected to give the most reproducible result also with respect to its low VSWR when it is about protecting the transceiver. The 97 mm cantenna is the champion of performance price/ratio. By the way, the quad patch array antenna seems to be most popular in municipal CCTV networks where video signals are transferred between lighting poles and end up in the townhall.

Perspectives

The multi-element Yagi antenna should be optimizeable since 11 dBi are readily achievable by 8 elements and hence 17 elements should alllow to approach the advertised 16 dBi if it was more carefully designed.

Regarding the patch array, it is noteworthy that nowadays the most prominent antenna, the Starlink terminal, comes with 1200 elements whereas our array has only four, leading us to think that there is room to the top. Before comparing our 14 dBi antenna to the Starlink terminal, it has to be noted though that the latter is a phased array featuring beamforming which we would not require, and has a large number of radio frontend modules (FEM), since the Ku-band signal would be difficult to distribute over the array. Instead, a common clock signal is distributed to the FEMs.

<https://www.microwaves101.com/encyclopedias/starlink>

<https://hackaday.com/2020/11/25/literally-tearing-apart-a-spacex-starlink-antenna/>

<https://www.youtube.com/watch?v=h6MfM8EFkGg&t=2s>



Similar to it is the competing project Kuiper by Amazon that is however supposed to work in the Ka band rather than the Ku band :

<https://www.aboutamazon.com/news/tag/project-kuiper>

Before those systems were targeting large scale deployment for rural area coverage and became known to the public via Starlink and 5G, phased arrays with beam steering and beam forming were currently used in satellite communication and solutions were developed for broadband internet for airplanes, by Honeywell-Jetwave/Inmarsat :

<https://aerospace.honeywell.com/us/en/about-us/blogs/ka-band-vs-ku-band-the-difference-between-ku-and-ka>

and the competitor SES by Thales Alenia Space :

<https://www.satellitetoday.com/launch/2019/02/26/ses-12-satellite-now-operational/>

Back to Bluetooth/Wifi/FPV/LoRa : A purely passive array without multiple FEMs might reach its limits at much less than 1200 elements since a large number of elements and a wide frequency coverage get into conflict with a purely passive feeder network, and at some point the multiple radio frontend is required even without the need for beamforming/beamsteering. Anyway, a 4x4 or 5x5 array approaching 20 dBi would probably be feasible without too much change of the technology.

For anything requiring more gain, the questions reduce to which antennas is the most suitable feeder for a parabolic dish reflector, possibly how patch and cantenna compare to a helical antenna as a dish feeder, and what are the alternatives to the parabolic dish itself. For the feeders we do not expect big differences as long as the reflector is illuminated evenly without much spillover.

Alternatives to parabolic dish : in the last years the parabolic dish becomes increasingly replaced by flat panels (mostly known under the brandname Selfsat). These are by no means phased arrays of patch antennas nor active antennas, but merely a parabolic mirror that is made flat in comparable way a bulk lens is transformed into a Fresnel lens, still containing a sort of LNB located at their back, however without the horn antenna in some cases :

<http://www.satmagazine.com/story.php?number=617289206>



As opposed to the parabolic dish, it is however more than uncertain that such a reflector, designed for TV reception in the X..Ku band, is equally suitable for 2.4 GHz operation. In particular a 2.4 GHz feeder would not fit instead of the 10.7 GHz LNB due to its dimensions.

Disclaimer

No warranty of correctness or suitability for a particular purpose is given. Due to fluctuations of values of similar antennas from different manufacturers and even among different specimen from the same manufacturer, it is recommended to perform measurements for each individual implementation. It is the sole responsibility of the user to comply with local legislation regarding spectrum allocation and authorized RF power.

Acknowledgement

This study has been performed in support of the Bluetooth Low energy project « BLE transceiver based on the Semtech SX1281 radio module and the ESP8266 » published in the same GitHub repository. Fruitful discussions with Prof. Guillaume Ferré and Marwane Rezzouki from ENSEIRB-MATMECA, Laboratoire IMS, UMR 5218 CNRS, are gratefully acknowledged.