The myth of reflected power

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A common topic among ham radio operators is about power lost due to high VSWR when feeding an untuned antenna. A very frequent explanation about why this should (or should not) be a concern, is more or less like this:

The power generated by the transmitter enters the coaxial cable and runs towards the antenna. When it reaches the load (the antenna) it encounter a mismatch; due to this mismatch, some power is transferred to the antenna, while the rest is reflected back and therefore lost. A tuner can be added between the transceiver and the line, but it will just "fool" the transceiver to believe the load is 50Ω: nevertheless the mismatch is still there with all of its consequent losses.

The amount of reflected (thus supposedly lost) power is directly related to VSWR and usually quantified in tables like this:

VSWR (:1)	Return Loss (dB)	Reflection Coefficient	Mismatch Loss (dB)	Match Efficiency (%)
1.011	45	0.006	0.000	100.00
1.020	40	0.010	0.000	99.99
1.036	35	0.018	0.001	99.97
1.065	30	0.032	0.004	99.90
1.074	29	0.035	0.005	99.87
		...		
2.61	7	0.447	0.967	80.05
3.01	6	0.501	1.256	74.88
3.57	5	0.562	1.651	68.38
4.42	4	0.631	2.205	60.19
5.85	3	0.708	3.021	49.88

Match Efficiency - e.g. 100 Watts Forward Power at 1.33:1 VSWR Yields 98 Watts Output (ie. 2 Watts Reflected).

The Mismatch Loss in dB is calculated with the formula below:

$$ML_{\mathrm{dB}} = -10\log_{10}\left(1 - \left(\frac{VSWR-1}{VSWR+1}\right)^2\right)$$

For example, with VSWR=5.85, according to this approach, more than 50% of the power should be lost (-3.021 dB).

Where does the energy go?

Many sources do not even bother to consider where the "lost power" is supposed to go: simply, it disappears. However we all learned in our high school Physics class that energy can not disappear into nothing.

Some more advanced sources, instead, explain that the reflected power runs back into the transmission line until it bangs against the transmitter, whose internal resistance dissipates it. And if it bangs too hard, it can destroy the transmitter, like a train crashing into a wall.

According to this theory, the complete process should be:

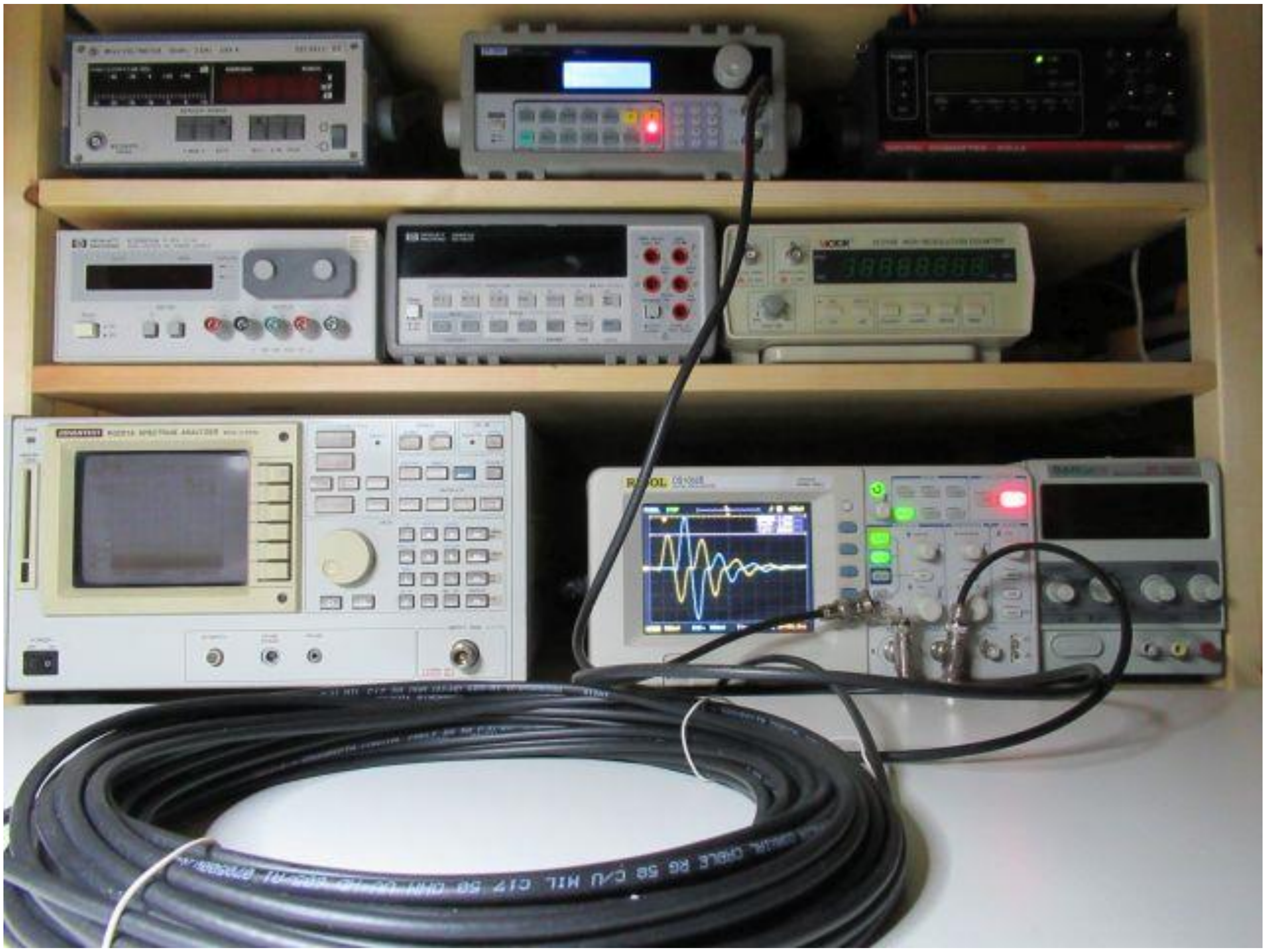
- energy leaves the transmitter and enters the coaxial cable;
- while running in the transmission line, some energy is dissipated as heat (all hams are aware of the dBs lost for every 100m/100ft at a given frequency of their favorite coaxial cables);
- the surviving energy hits the mismatch point, where the high-VSWR antenna is connected to the coax;
- given a VSWR value, a fixed percentage of energy goes to the antenna, while the remaining is "sent back" on the same coax;
- the returning energy runs back on the cable and gets dissipated again by the same cable attenuation that it met on its forward run;
- finally, the remaining reflected energy hits the transmitter and it is completely dissipated by the generator internal resistance;

Let us make an example. We have a cable that has 1dB of attenuation at the frequency in use and we have an antenna presenting VSWR=5.85, thus a Mismatch Loss of 3.021dB: we should expect to have 3.021dB+1dB=4.021dB attenuation, i.e. only 40W out of 100 that go on the air.

But… is that true?

Experiments setup

In order to verify the theory above, I connected my function generator to channel #1 of my oscilloscope; after that, I connected 24.9m of RG-58, then channel #2 of the scope and finally the load resistor representing the antenna. This setup will allow us to see the **voltage entering the line** and the **voltage entering the load** after having traversed the entire cable.

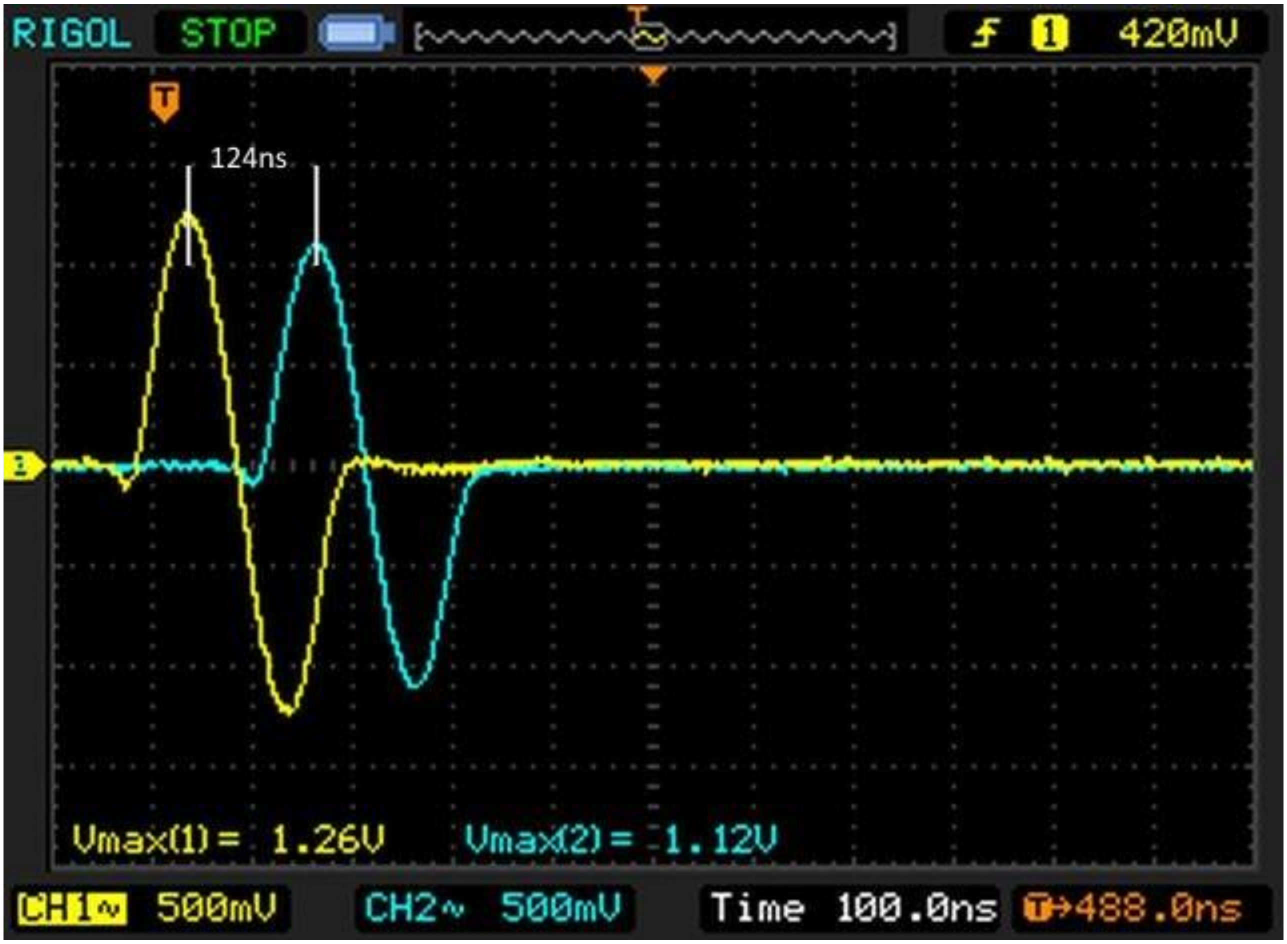


Knowing the voltage V and the complex impedance Z, we can calculate the resulting power with $P=V^2/Z$. Thus, with this setup and the help of a VNA, we can measure the **power entering the coax** and the **power received by the load** without impedance restrictions. The difference will reveal us the **real power loss**.

Before starting the experiments, I carefully measured this test cable with my network analyzer. It resulted having a velocity factor of 0.6636 and, at 5MHz, an attenuation of 0.823dB.

Experiment 1: matched load

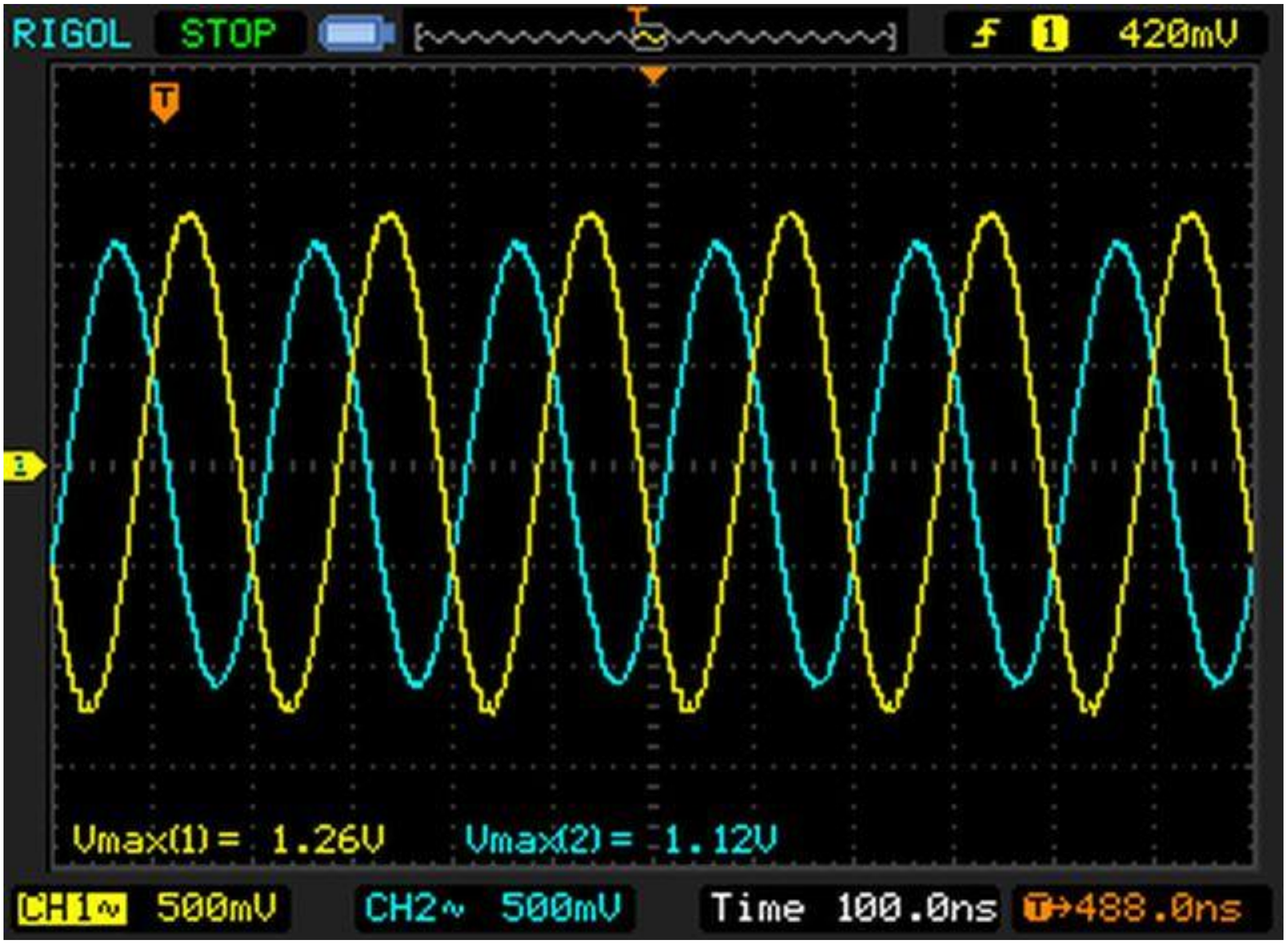
In this experiment, the line is terminated with a 50Ω load, thus it is perfectly matched. In the picture below we can see the function generator sending a **single 5MHz sine wave:**



As expected, we have the generated pulse (yellow) developing on the 50Ω characteristic impedance of the coaxial cable. After 124ns, the same pulse reaches the 50Ω load. Considering that light travels 300mm every 1ns, we have 124 * 300 * 0.6636 = 24686mm = 24.7m, which is fairly close (±1ns) to the measured length of 24.9m.

Being R the same on both sides (i.e. 50Ω), we can calculate the power ratio squaring the ratio of peak voltages: $(1.12/1.26)^2$=0.79, which is a loss of 1.02dB, which is the same as the VNA measure ±0.2dB.

Now we can set the generator to send a **continuous stream of sinewaves** at 5MHz:



As expected, we obtain the same pattern as before but **repeated over and over**: voltages and timings are absolutely identical.

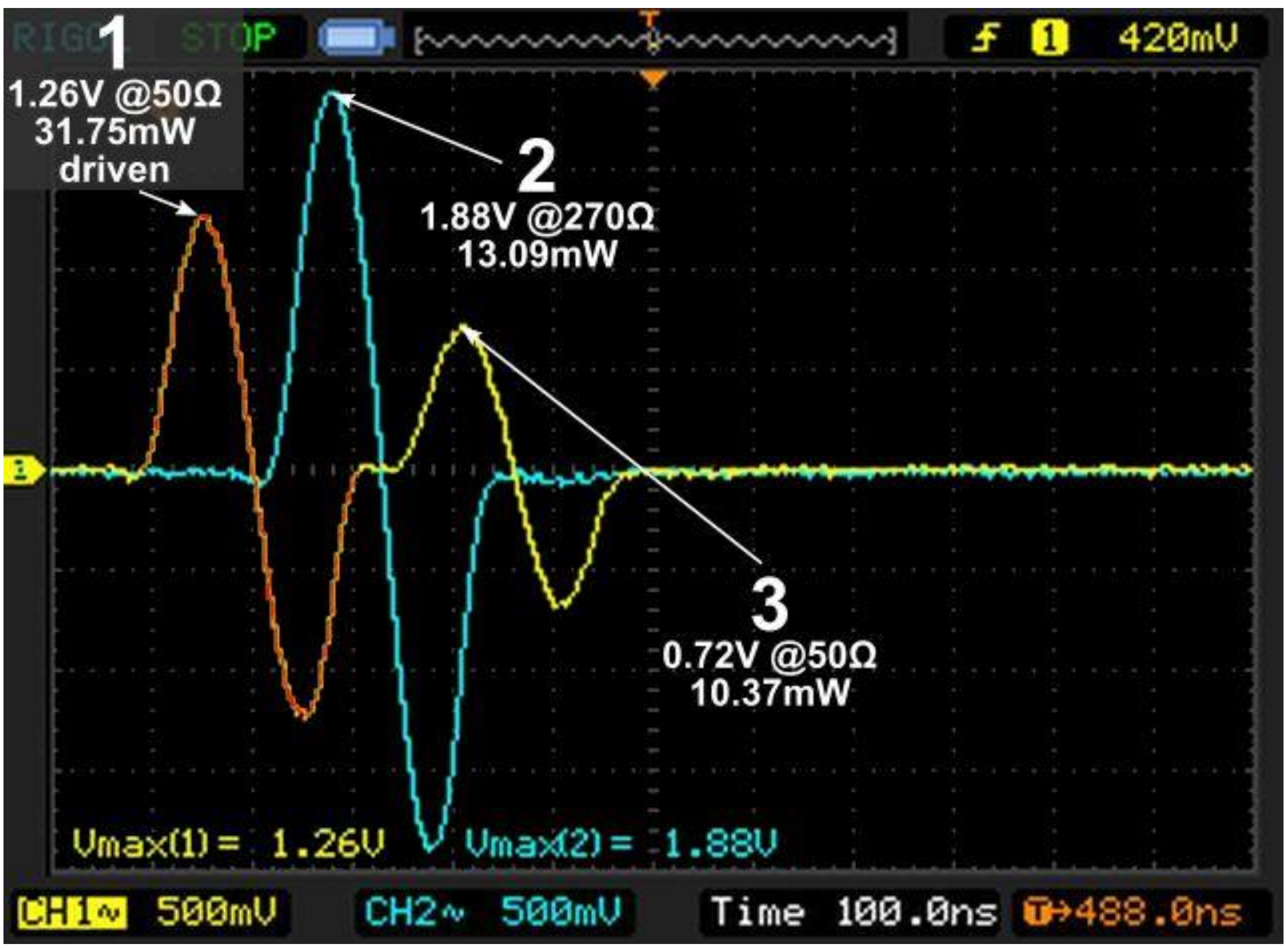
So far so good.

Experiment 2: mismatched load

In order to test the behavior of the transmission line when loaded with high VSWR, I prepared a female SMA connector with a 270Ω SMD resistor soldered on it:

This load produces VSWR=5.403 and, according to the Mismatch Loss table above, a loss of 2.779dB (53% to the antenna, 47% lost).

Let us now send again a **single 5MHz pulse** and see what happens:



What we see now is something a bit different than before. The **initial pulse (1) is identical as the one of experiment #1** (1.26V peak). When it arrives to the 270Ω load (2) 124ns later, the

voltage is much higher (1.88V peak). Then, after 124ns, a **new peak** (3) **appears on channel 1**, the load side.

Let’s see what happened. The initial pulse (1) is driven on the transmission line, that **at that time appears as a 50Ω load**. There should be no surprise to observe that the first pulse **is always identical** among all the experiments: since information can not travel at infinite speed, the generator can not know instantly that at the end of the line that there is a different load than before. Therefore, the first peak must be identical to the ones we have seen before when we had the 50Ω load – and so it is.

The peak power sent by the generator in the coaxial cable is 1.26V on 50Ω (1), which makes 31.75mW. The peak then travels along the line generating heat; when reaches the other end, after 124ns, it should have lost 0.823dB: the power available at (2) should be 26.27mW.

At this point the wave encounters the mismatch. The tables say that, due to VSWR=5.403, only 52.7% of this power should be delivered to the load, that is 13.85mW. If we look at the 1.88V peak on 270Ω we have 13.09mW **which confirms it**.

We have now a remainder of 12.42mW that have not been delivered to the 270Ω load. This power is bounced back and travels the coaxial cable in the other direction, loosing again 0.823dB. The power that reaches back the generator should be 10.28mW: the value at point (3) is 0.72V @50Ω, which makes 10.37mW, again **perfectly in line with expectations**.

At this point the returning peak (3) encounters the function generator output port which offers 50Ω, i.e. a perfect match: the returning wave heats up the 50Ω resistor inside the function generator and disappears.

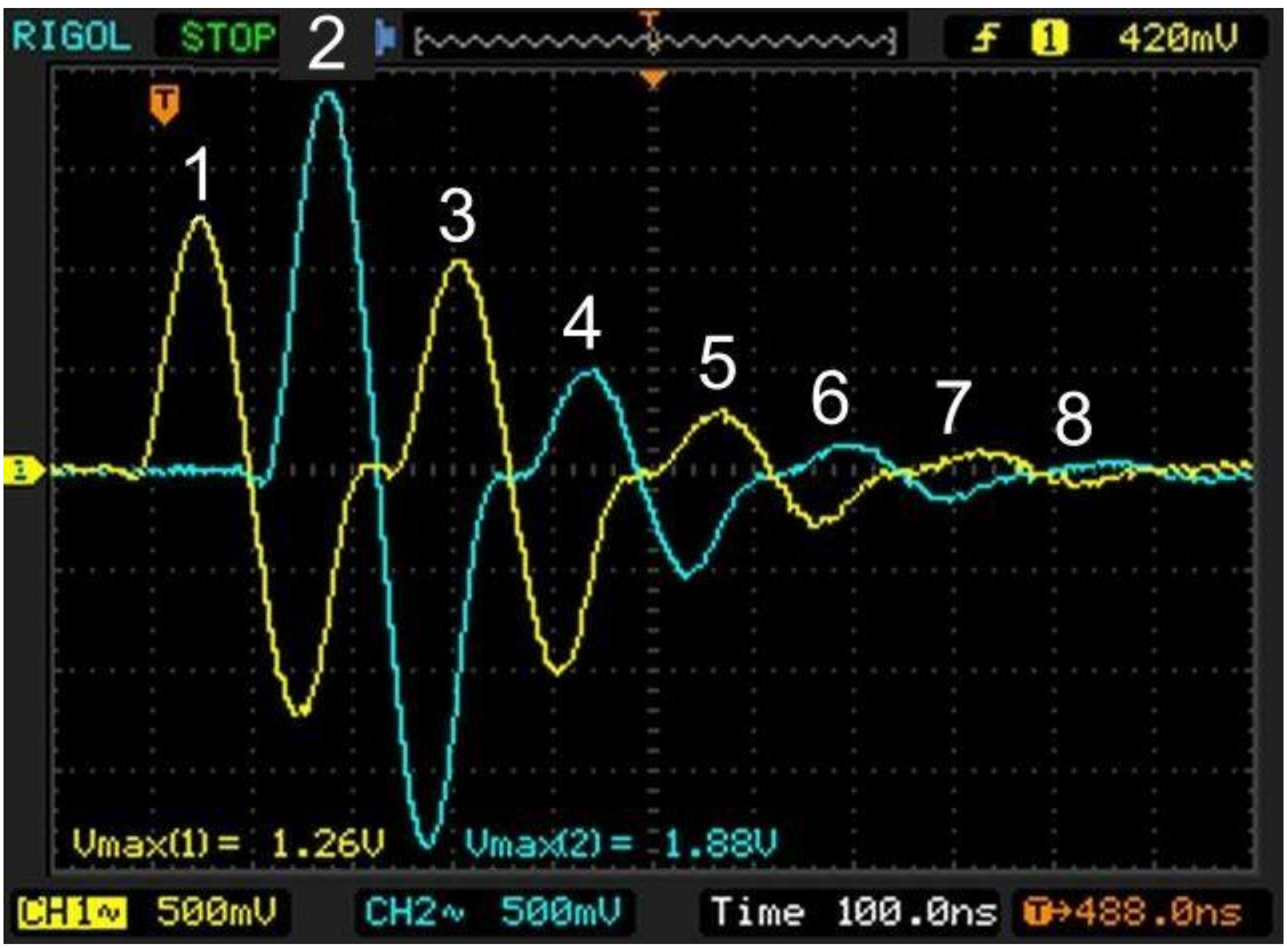
So far, the initial theory is perfectly confirmed: the mismatched load has consumed the **exact percentage of power** and the rest has been bounced back and **dissipated in the generator.**

The power delivered to the load was expected to be attenuated of 0.823dB (cable loss) + 2.779dB (mismatch loss)=**3.602dB**. Using a script and the binary data downloaded from the oscilloscope, I integrated the energy contained in the driven curve (orange, 3.040429nJ) and the load curve (blue 1.313286nJ): their ratio, 0.4319, accounts to 3.646dB of attenuation, which is almost a **perfect match with the expected 3.602dB!**

Experiment 3: mismatched load and generator

This time we shall repeat the experiment 2, but instead of having a 50Ω generator, we shall use a different impedance. In order to attain it, I prepared a matching attenuator with 10.28dB of attenuation and a reverse impedance of 144.5Ω. This is like to have a generator which output impedance is not 50Ω anymore, but 144.5Ω.

I increased the function generator voltage to compensate the attenuator so the same 1.26V initial peak was generated again in the transmission line. This is what happened:



Here we can see a **different story**. The initial stimulus (1) **is the same as before** as predicted; it travels until it reaches the 270Ω load (2) which reacts exactly as in experiment #2, reflecting the 47.3% of the received power. However this time the power coming back **finds another mismatch**, the 144Ω attenuator pad (3), and **it is reflected back again** towards the 270Ω load (4). Then it bounces back and forth over and over until all the power is gone. As it appears clearly, this time **more energy is delivered to the load**, although in multiple steps.

Using the energy integration method, I calculated the energy actually delivered to the 270Ω load. This time the loss is only 3.271dB: i.e. the load **received 0.37dB more than before**.

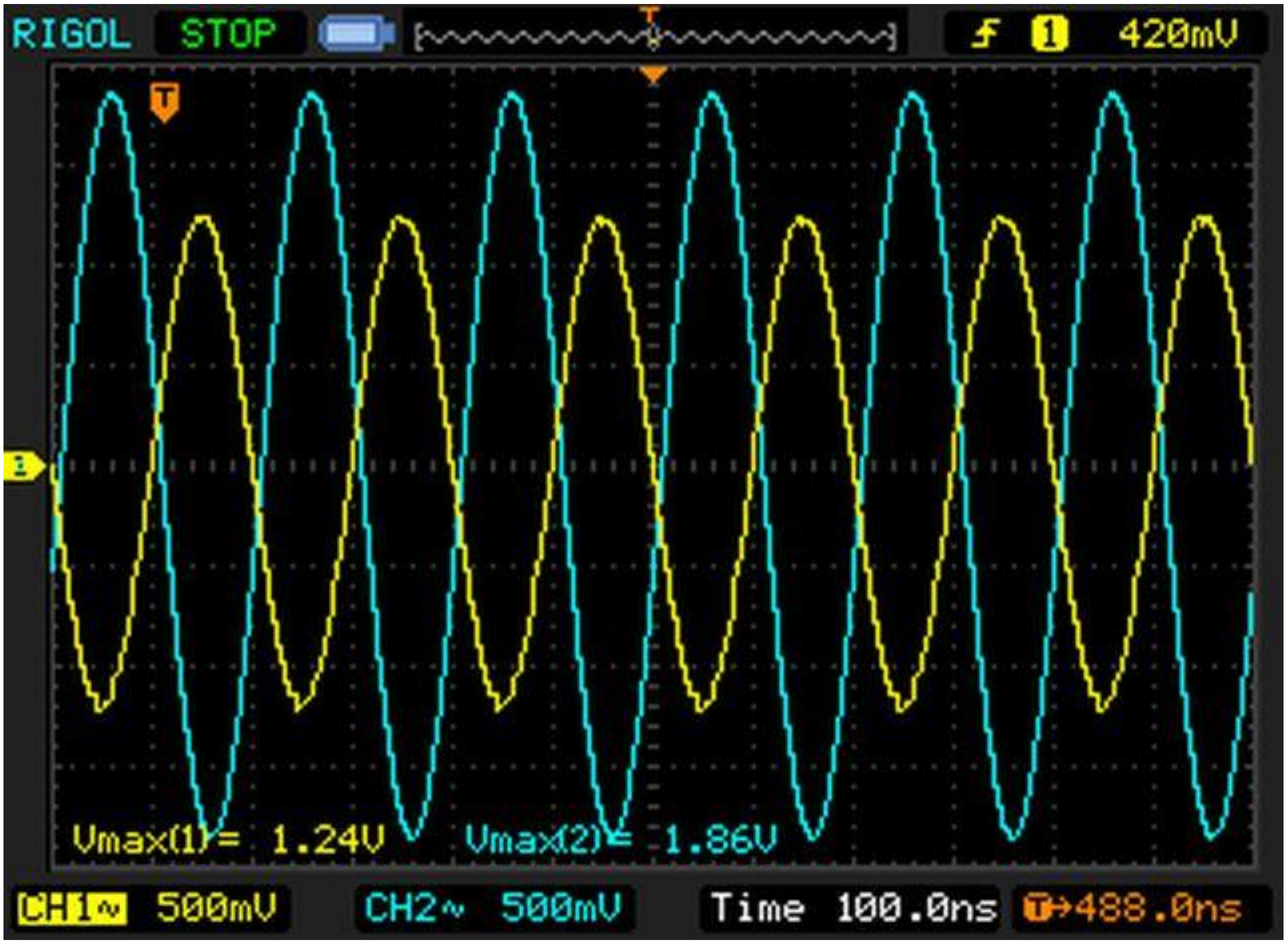
The **first cracks in the initial theory begin to appear**. The initial claim is founded on a fixed relation VSWR->loss, but a very simple experiment like this shows **a case where it does not work**. Same identical initial wave, same line, same load, same VSWR, two different results just by changing the impedance of the generator?

Experiment 4: let's the magic begin

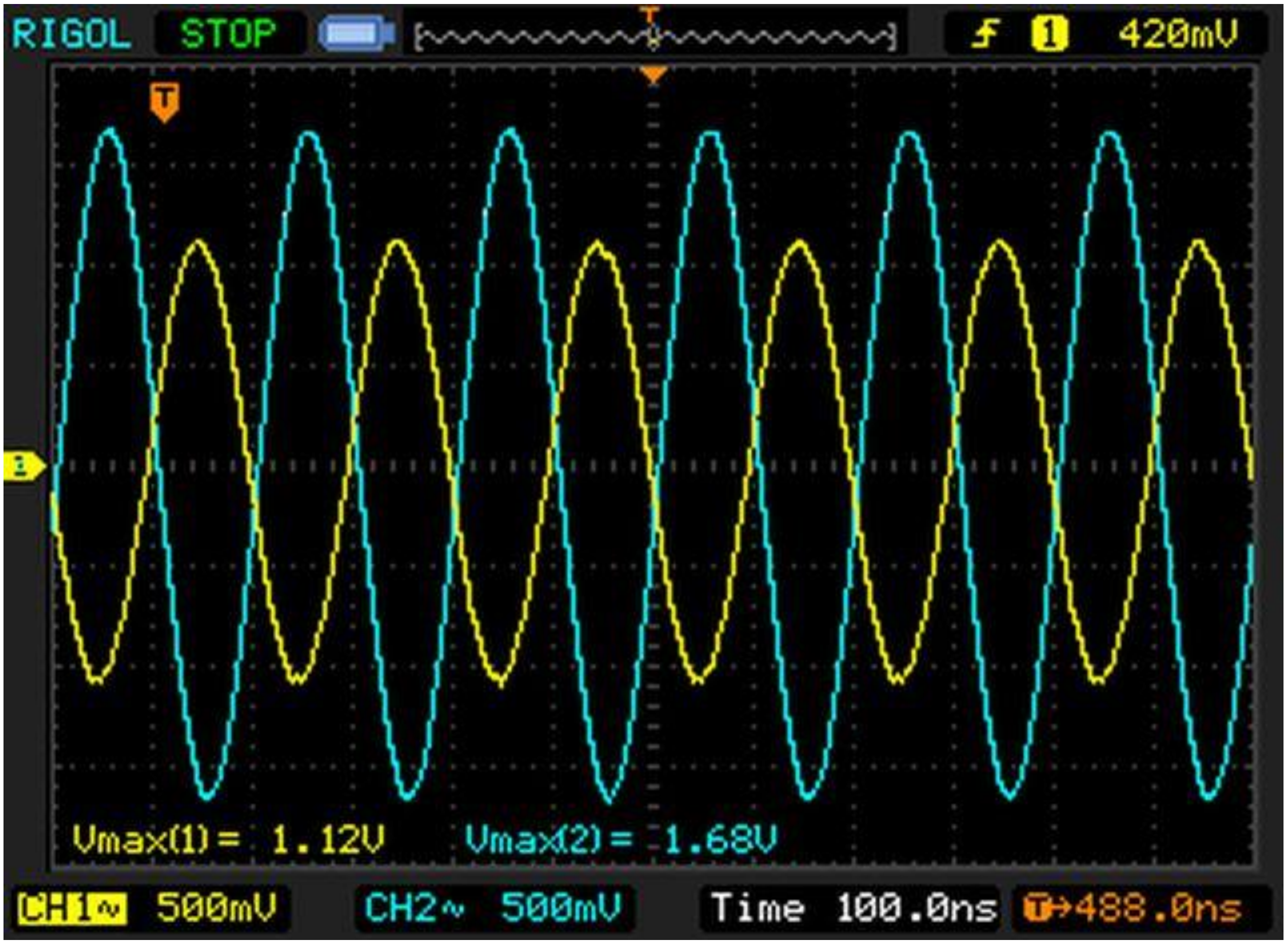
So far we have seen with that same setup, **two different generator impedances** feeding exactly the same power **can change the amount of power delivered to the load**. The experiment above shows that the power not delivered to the load is dissipated as heat by the cable itself and by the internal resistance of the generator.

We shall now execute another experiment: this time, we will repeat experiments #2 (50Ω generator, 270Ω load) and #3 (144Ω generator, 270Ω load) but **feeding a continuous sine wave**. In both tests, the generator is set with the identical voltage level that in the previous tests generated the 1.26V initial peak.

Here they are:



Test with 50Ω generator, 270Ω load



Test with 144Ω generator, 270Ω load

When feeding the circuit with a **continuous sine wave**, something weird seems to happen. First we note that by looking at these screenshot, there is **no clue of any bouncing anymore**: both tests generate a nice yellow sine wave that propagates 124ns ahead to a nice blue sine wave on the load.

Even more interesting is that the peak CH1/CH2 voltages, although not identical among the two tests, **hold exactly the same ratio**:

- 1.86/1.24 = 1.5
- 1.68/1.12 = 1.5

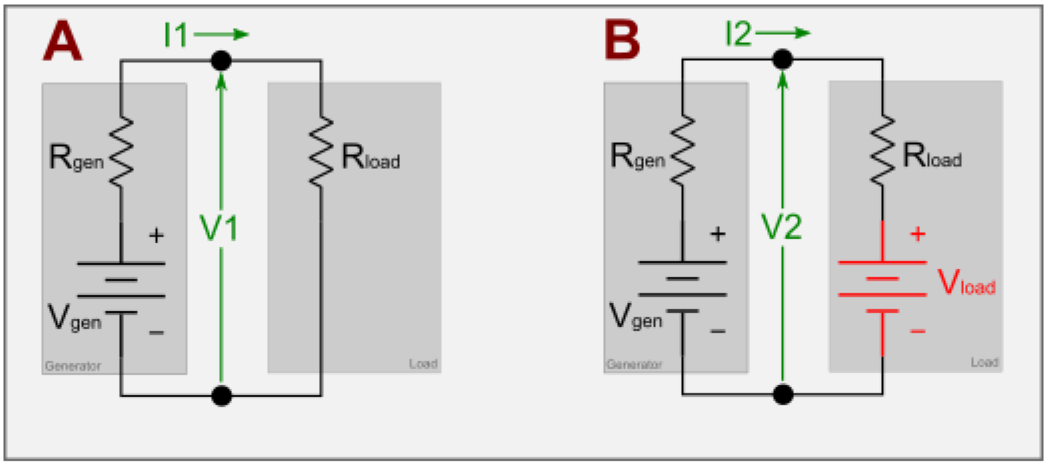
Unlike the single-shot tests #2 and #3, the continuously fed lines **are delivering exactly the same amount of power**, **no matter what the generator impedance is**.

In other words, when the generator sends a single shot, part of the energy is bounced back and dissipated by its internal impedance. As we saw, different generator impedance, different amount of energy dissipated, different amount of energy successfully delivered to the load. But if the generator sends a **continuous flow** of sine waves, we experience a completely dissimilar behavior: **no matter of which is the generator impedance**, **the very same percentage of the power** that enters the coaxial cable **is delivered to the load**.

So, what's going on?

Behavior of a transmission line

Without entering into the details, we can have an hint of the reason why a transmission line fed continuously behaves differently from one that receives a single pulse from the picture below:



In picture "A" we have a voltage generator V_{gen} with its internal resistance R_{gen} feeding a load made of the resistance R_{load}. What the generator will see is a voltage V1 and a current I1 developing on its terminals: therefore, it will see an impedance Z1=V1/I1 which, in this case, is the same as R_{load}.

The reflected power forms a voltage wave that travels back on the line until reaching the generator. This wave is seen as a voltage generator was added at the feed point (picture "B"). If we calculate the V2 voltage and I2 current we shall see that, due to the contribution of V_{load}, they will not match I1 and V1 anymore. The generator will **see a new impedance value** Z2=V2/I2, this time not equal to R_{load} anymore.
In other words, the reflections **change the impedance of the transmission line** at the feed point.

The resulting effect is that the transmission line now **acts as a impedance transformer**. The power lost in this process is only the one dissipated by the transmission line as heat: no matter what the VSWR is, if we could have a perfect line, all the power would be transferred to the load.

Whatever formula that calculates power loss **using only VSWR** as a parameter, like the one at the beginning, **it obviously flawed**.

Measuring real losses

So far, we have established that the Mismatch Loss formula shown at the beginning **does not really tell how much power is lost due to mismatch**. So, how much power do we really loose?

To have an answer, I prepared another experiment of measurement of power entering and exiting a transmission line terminated with a mismatched load (the same 270Ω load). To achieve the best precision, instead of using the oscilloscope, I used a much more accurate Rohde&Schwarz RF millivoltmeter. The test cable was made of 6.22m of RG-58 terminated with SMA connectors. I made two microstrip fixtures that could host the 1GHz probe of the RF millivoltmeter, which adds about 2pF. I then made an S11 and S21 measurement of this setup, including fixtures and probe, to know the impedance values needed to calculate the power levels.

At 20MHz my 6.22m test cable has a matched loss of 0.472dB.

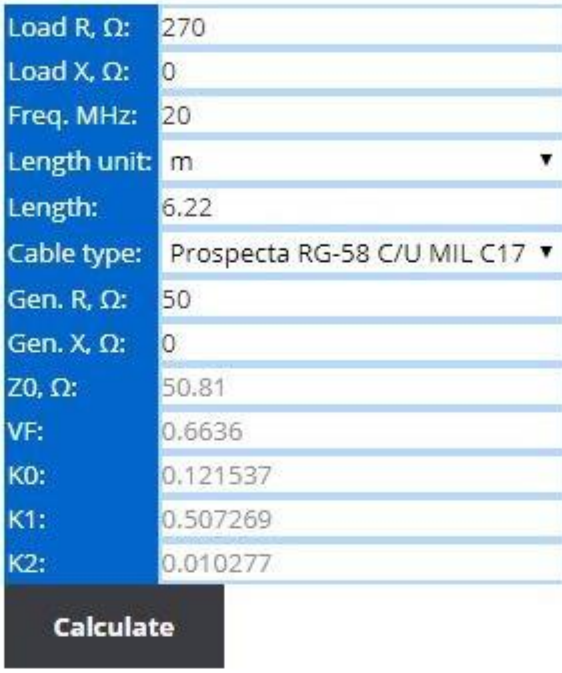
Then I set my signal generator at 20MHz and measured input and output voltage:

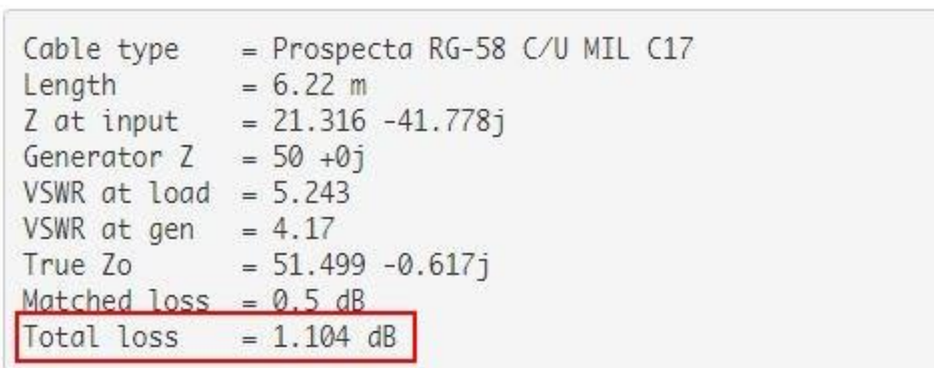
The measured impedance at 20MHz is 18.590 -j36.952; on that impedance, a voltage of 241.5mV$_{RMS}$ amounts to 0.634mW$_{RMS}$ (-1.981dBm); the output voltage is 364.1mV$_{RMS}$ on 270Ω, which is 0.491mW$_{RMS}$ (-3.092dBm).

The overall power lost in this cable at this frequency is 1.110dB, i.e. only **0.638dB** more than the 0.472dB that this cable would have normally dissipated due to line attenuation. This is **significantly different than the 2.779dB loss** foreseen by the “Mismatch Loss” method.

Calculating mismatch losses

Is there a formula that allows us to estimate the loss of a mismatched transmission line? Yes, there is. You can find a complete explanation in the very interesting AC6LA’s site. These formulas require some parameters of the transmission line to be measured with a network analyzer. I measured my “Prospecta RG58” with two S11 runs (open/short) and I fed the S11 files to ZPLOT, which gave me back the nominal Zo, nominal VF, K0, K1 and K2 parameters for my line. I fed those parameters to the IZ2UUF Transmission Line calculator, which gave me the following results:





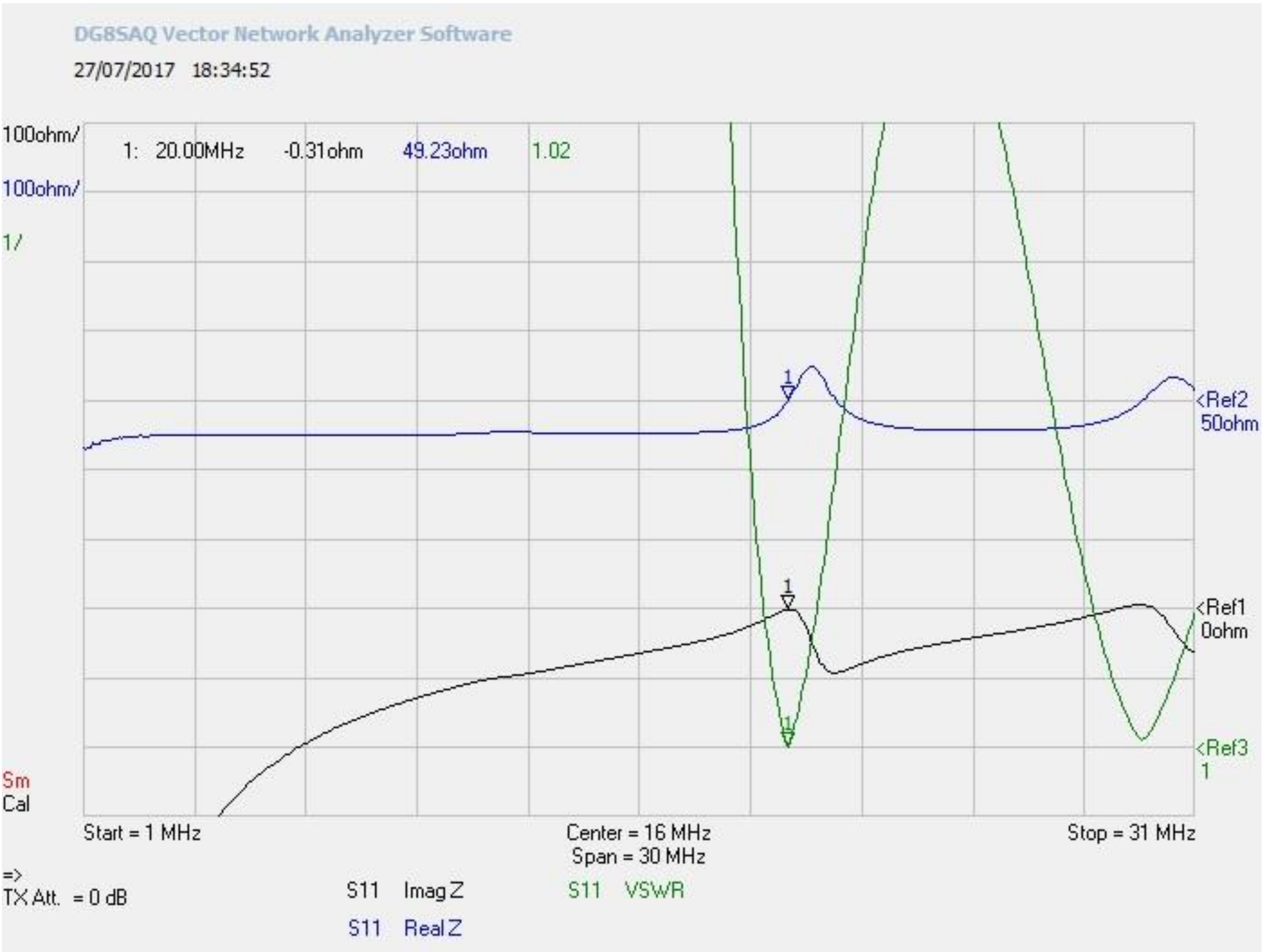
```
Cable type    = Prospecta RG-58 C/U MIL C17
Length        = 6.22 m
Z at input    = 21.316 -41.778j
Generator Z   = 50 +0j
VSWR at load  = 5.243
VSWR at gen   = 4.17
True Zo       = 51.499 -0.617j
Matched loss  = 0.5 dB
Total loss    = 1.104 dB
```

The software calculated a matched loss of 0.500dB (I measured 0.472dB) and a total loss of 1.104dB (I measured 1.110dB), which makes it a stunning “perfect match” with only 0.006dB of difference!

So far I got very good results comparing real and predicted loss figures up to VHF, with discrepancies of cents of dB. To test higher bands I shall do further work to cancel out the impact of measurement fixtures and probes.

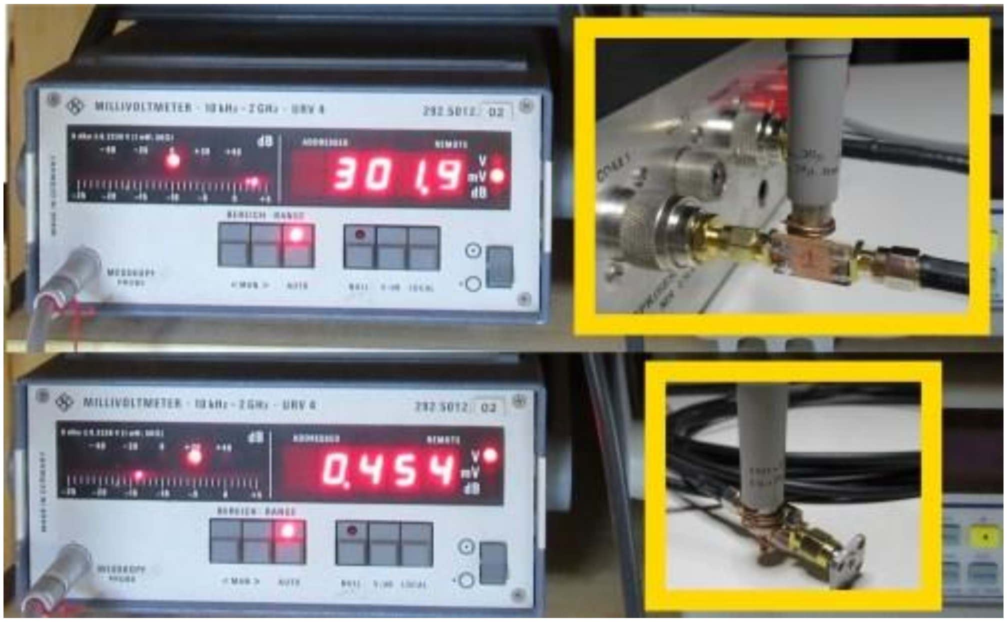
Adding a tuner

What happens if we add a tuner between the transmitter and the transmission line, as most hams do? In order to verify this, I connected the same 6.22m RG-58 line terminated with the 270Ω load to my MFJ-949E tuner and, with the help of my network analyzer, I tuned it to reach a perfect 50Ω match including the millivoltmeter probe:



Then, I connected it to the signal generator and, using the RF millivoltmeter at the feed point of the tuner as a reference, I increased the generator power to compensate the extra cable I added. With 0.4dBm set on the signal generator, I had perfect 0dBm at the perfectly tuned 50Ω tuner input. As far as the signal generator is concerned, it is feeding a perfect load.

Let us see the voltage entering the line after the tuner and the voltage reaching the load:



We have 301.9mV on the beginning of the line, where the impedance is 18.59-j36.952: solving the complex numbers calculation tells that my **tuner is pumping on the line 0.990mW (-0.043dBm)**. At the end we have 0.454mV, which **delivers to the 270+j0 load 0.763mW (-1.173dBm)**. This means that the line dissipated 1.130dB, which is almost identical to the 1.110dB measured in the previous example (difference is only 0.02dB!) and almost identical the 1.104dB calculated by the online calculator.

In these measurements we see that in this case the **tuner received 0dBm** and produced on its **output -0.043dBm**, thus **dissipating as little as 0.043dB of power** (<1%).

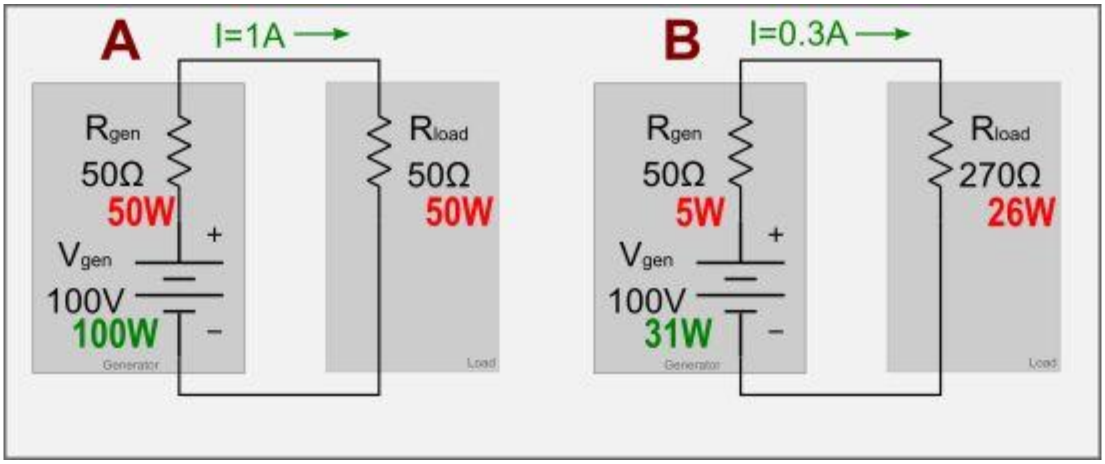
If we would have fed a perfectly matched 50Ω load with this 6.22m long RG58 line, we would have lost 0.472dB due to normal line attenuation. Feeding the same line with a VSWR>5 load and a tuner, we have lost 1.173dB, which means a **net cost of only 0.701dB.**

Be aware that such a low loss in a tuner is not a general rule, since tuning other impedances could cause greater heat dissipation, but it is very common.

Back to the Mismatch Loss

After all the experiments above, we have established beyond all reasonable doubt that the Mismatch Loss formula shown at the beginning of the article **does not indicate the power lost when feeding a mismatched antenna**. So, what is it for?

Let us consider these two simple circuits:



Picture "A" shows a 100V voltage generator with its internal 50Ω resistance R_{gen} feeding a 50Ω load R_{load}. Using Ohm's law, we can calculate $I=V/R=V_{gen}/(R_{gen}+R_{load})=1A$. Given that $P=I^2R$, we can calculate the power dissipated by the load: $P_{load}=I^2R_{load}$=**50W**. The generator itself is generating $P=V_{gen}I$=100W and 50W are dissipated by the internal resistance R_{gen}.

Now we can do the same calculation on "B", where R_{load} is 270Ω. We have that $I = V_{gen}/(R_{gen}+R_{load}) = 100/(50+270)=0.3125A$. Hence, the power consumed by the load is I^2R_{load}=**26.367W**. The generator is generating $P=V_{gen}I$=31.25W and R_{gen} is dissipating 4.883W.

We see that in circuit A the **load is receiving more power**: 50W vs. 26.367W: due to the [maximum power transfer theorem](), we get the maximum power (in this case 50W) when $R_{load}=R_{gen}$. For any other value, the power going to the load will be less. The "A" condition is defined as "**matched**".

If we calculate the ratio of the power delivered on B and the maximum possible delivered power A, we have that 26.367 / 50 = 0.527; if we transform it in dB, we have **2.779dB** which is **exactly the Mismatch Loss** we calculated before for the 270Ω load.

The Mismatch Loss value does not tell how much power is actually lost due to other dissipated, but it represents the **inability of the generator to generate power due to mismatch**.

Note also that the **Mismatch Loss is not an index of efficiency**: with matched load, we got the highest power on the load (50W) but **efficiency was at 50%** (100W produced, 50W used on the load). In the mismatched circuit, the generator produced 31.25W of which 26.367W were delivered to the load, holding an efficiency of **84.3%**!

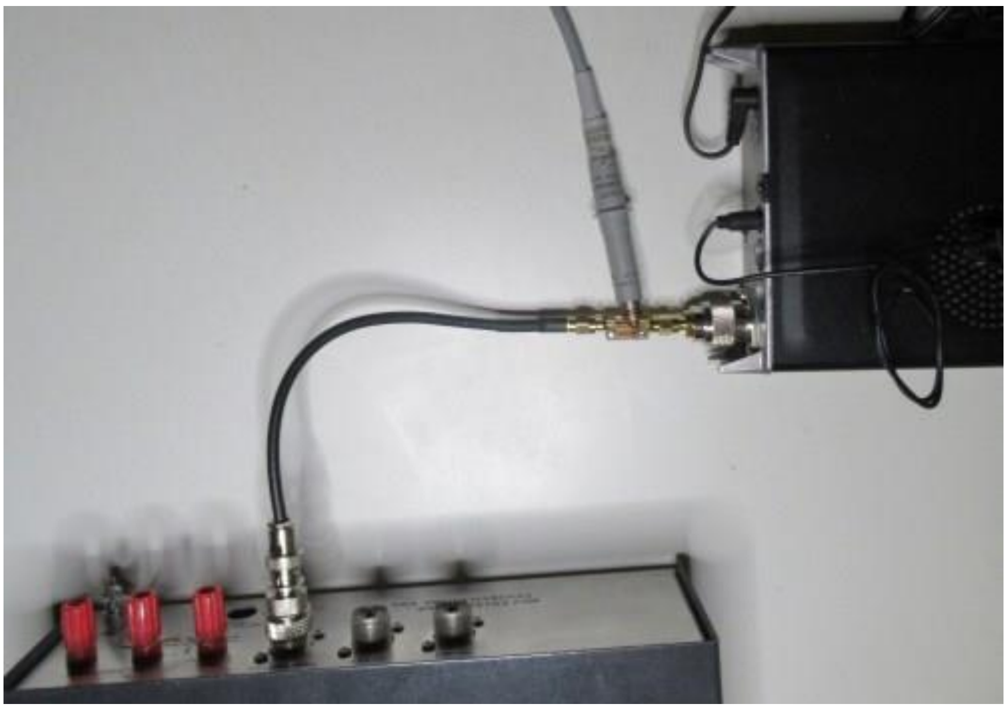
We can see this effect on the power that the R&S SMS2 signal generator has been able to deliver into the mismatched line with or without the tuner:

The difference in power between the two is 1.94dB: if we calculate the mismatch for the impedance being fed (note the reference impedance is 18.590 -j36.952 presented at the input of the line, not 270+j0 at load!), we have VSWR=4.3 and Mismatch Loss=2.13dB, again another almost perfect match to the measured values. Without the tuner, due to the mismatch, the signal generator was not able to generate the whole power it would have produced on a matched load: **power is not lost, is simply not generated**.

That is like when a biker is pedaling with the wrong gear: great effort, little performance. The tuner adapts the impedance at the input, exactly like the biker that shifts on the right gear.

Mismatch on real transceivers

Note that the mismatch effect that prevented the signal generator to generate the full power is mostly due to the fact that **laboratory signal generators are designed to behave as close as possible as an ideal 50Ω generator**. But being an ideal 50Ω generator, as we have seen, means low efficiency. **Real transmitters** are indeed **designed to work on a 50Ω load**, but not necessarily **to present back 50Ω** impedance when transmitting. Modern transceivers are able to compensate some degree of mismatch by feeding different voltages/currents to make the load happy. My FT-817 sends out the same power no matter of the load: changing the load, changes the voltage but the resulting power is almost the same until the HIGH VSWR protection kicks in by cutting the power. This kind of radio can feed mismatched lines within their VSWR tolerance without suffering loss of power, thus without the need of a tuner (I have planned to write another post reporting on this).



Conclusions

- the claim that **a given VSWR values gives a fixed loss of power is a myth** deriving from a misinterpretation of the concept of "Mismatch Loss";
- if all the people that published such claim would have ever measured input and output power from a mismatched transmission lines, they would have immediately realized that true figures on power loss are most of the times very distant from their forecasts;
- the power lost in the transmission line is the result of a **function that combines the mismatch and the normal loss** of the line in matching conditions; an ideal (lossless) line would have no loss at all no matter of the VSWR;
- **do not assume that feedline loss due to mismatch is always low**: severe mismatches, like feeding a 40m 1/2 wave dipole on the 20m band, **may cause very high losses** in the transmission line;
- a **transmission line is an impedance transformer**;
- unless transmitting single bursts, the impedance of the transmitter has no relevance in the calculation of the power dissipated by the transmission line;
- the mismatch between the transmission line and the transmitter might prevent it to generate its maximum power but many transmitters might be able to compensate the mismatch;
- a tuner is not *fooling the transceiver to believe the antenna is tuned*, it is simply adapting two different impedances (after all, not many hams would describe their power supplies as objects *fooling the radio to believe that the 220V AC power line is actually 13.8V DC*, won't they?);
- tuner is not *wasting huge amounts of power* as commonly believed: many times its insertion loss is negligible (tenths of dB) even with high VSWR.