Influence of the cable

on L-band link between antenna converter and modem

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Due to simple fact that satellite antenna must be located outdoor and the modem is usually located indoor or at some distance there will always be a need to connect the two with a length of RF cable.

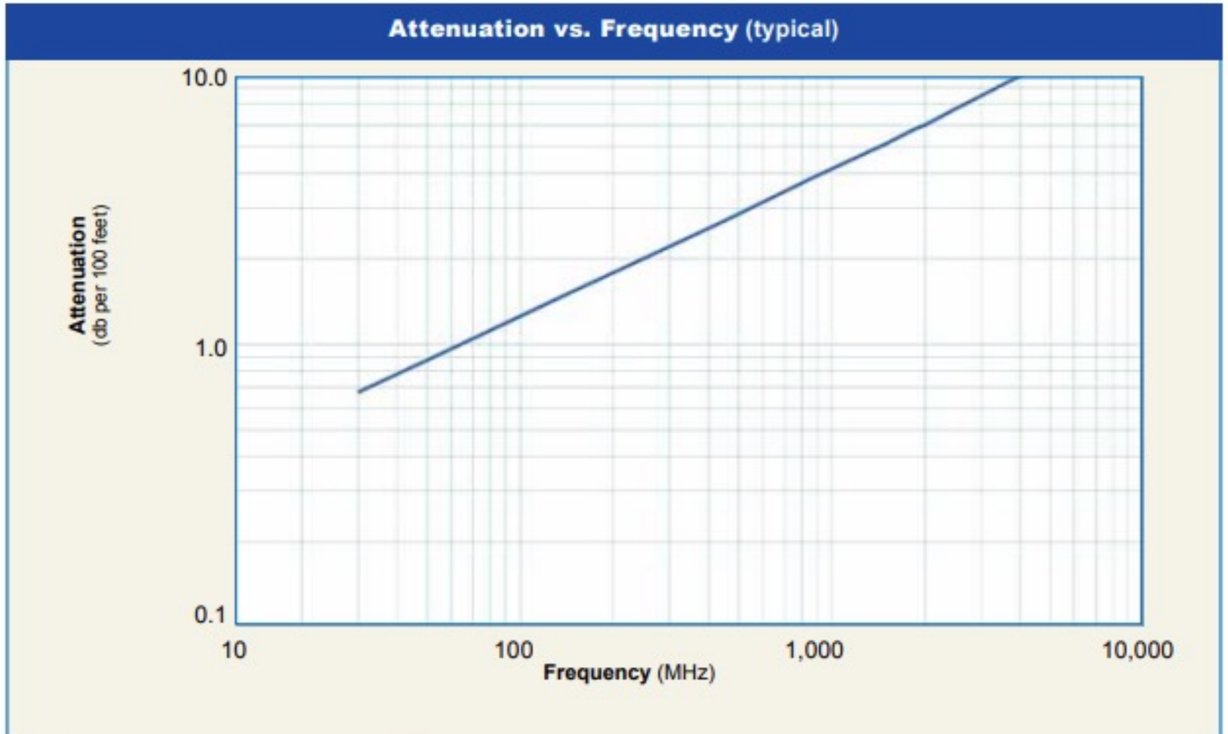
Below we take a look at how this cable can affect the L-band link, analyze the differences between cables, and finally look for solutions to problems that arise from using long cables.

- Modern satellite communication uses microwave frequencies in the range from 4 to 40 GHz.
- There are many reasons for that, such as antenna size, beam forming and propagation through atmosphere.
- Except for the low end of the range (4-6GHz) modems and software defined radios today are unable to demodulate and process such high frequency signals directly.
- Therefore frequency converters (up and down) are used to translate signals from satellite band to modem and vice versa.
- The cables connecting converters to modems also carry DC power, reference and control signals for the converters.
- Often antenna and modem are so far apart that cable lengths between them reach dozens of meters.
- Whereas DC, reference and control signals are not affected much by the long cables, L-band signals are.

TIMES MICROWAVE SYSTEMS

LMR-400

Typical signal attenuation of RF cable



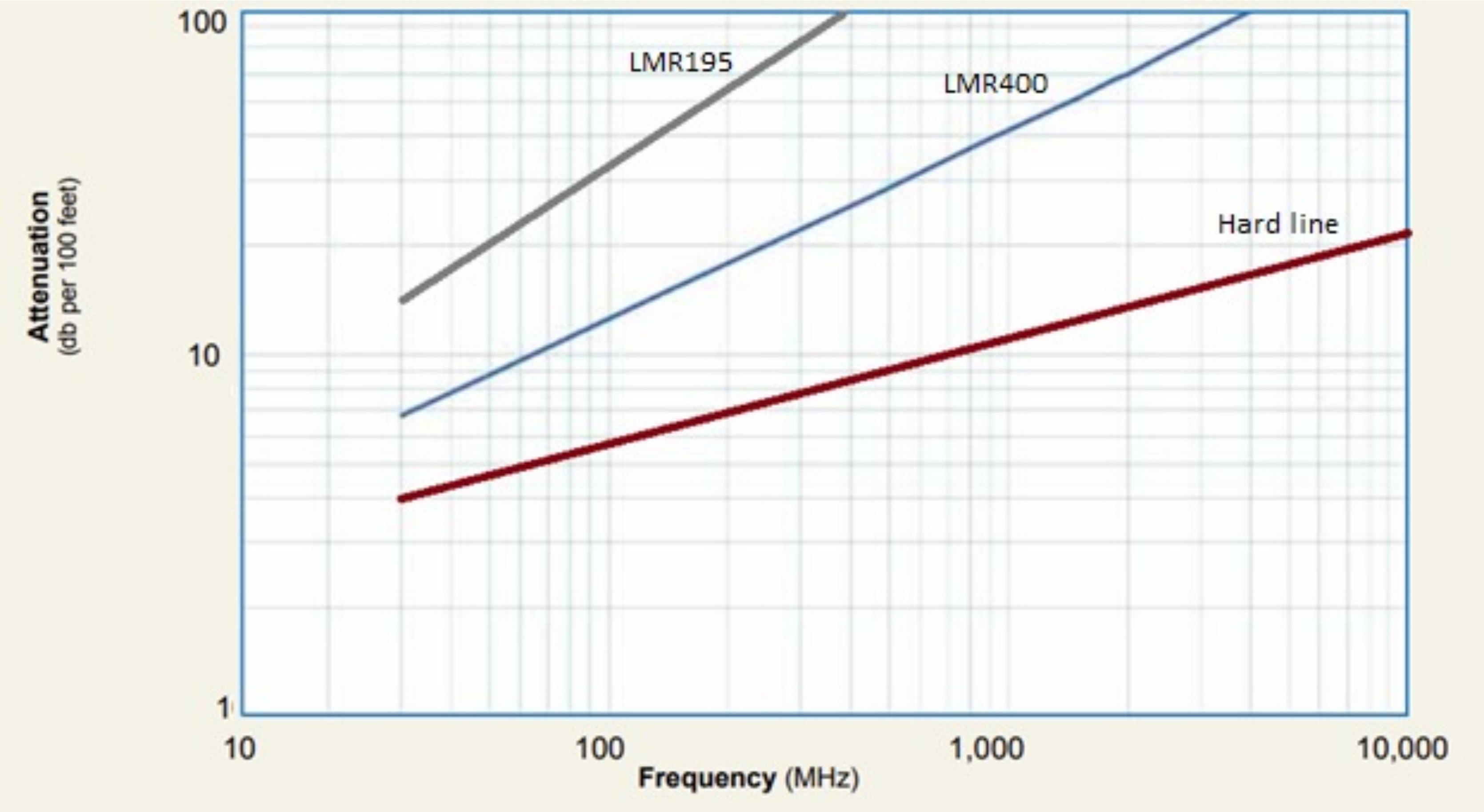
Frequency (MHz)	30	50	150	220	450	900	1500	1800	2000	2500	5800	8000
Attenuation dB/100 ft	0.7	0.9	1.5	1.9	2.7	3.9	5.1	5.7	6.0	6.8	10.8	13.0
Attenuation dB/100 m	2.2	2.9	5.0	6.1	8.9	12.8	16.8	18.6	19.6	22.2	35.5	42.7
Avg. Power kW	3.33	2.57	1.47	1.20	0.83	0.58	0.44	0.40	0.37	0.33	0.21	0.17

Let’s take a look at typical RF cable built by Times Microwave

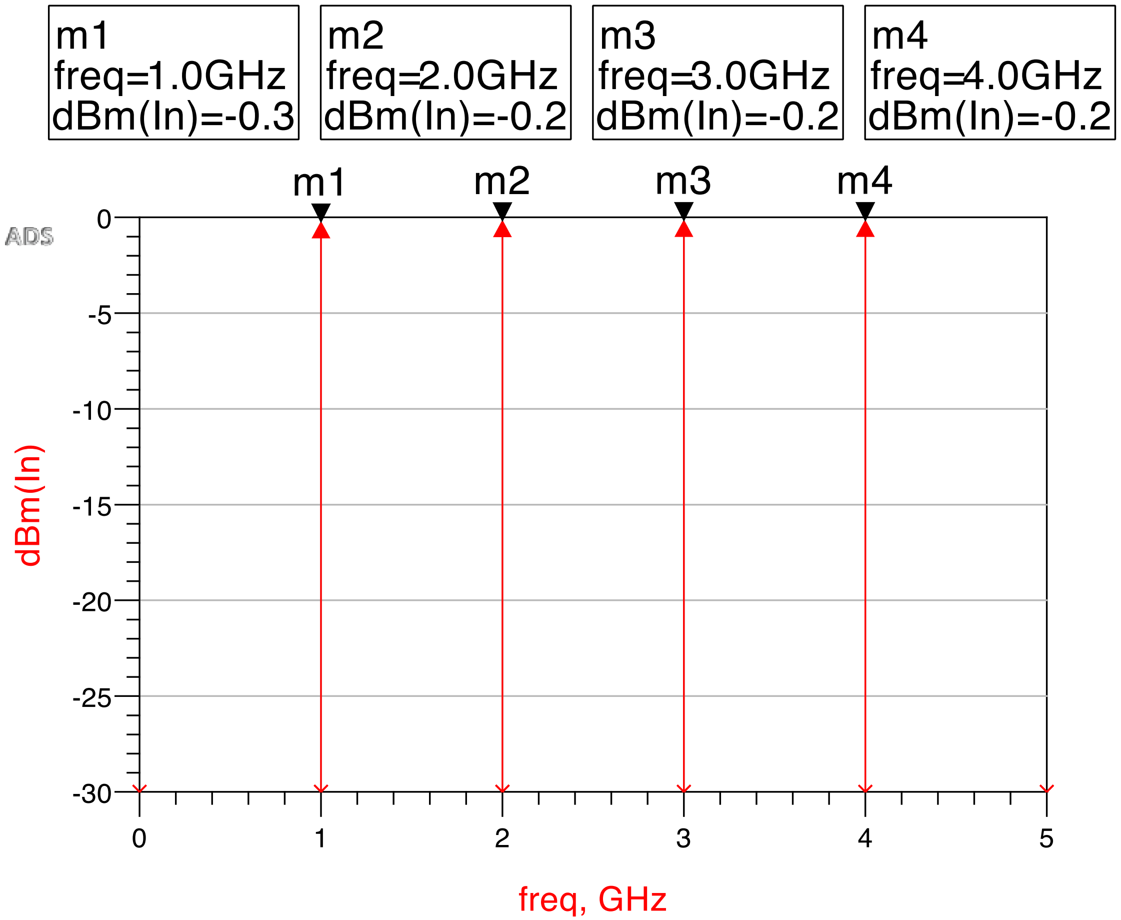
What can we tell from this graph?

1. Attenuation is proportional to frequency
2. This dependency is clearly linear (log – linear)

Different cables have different slopes

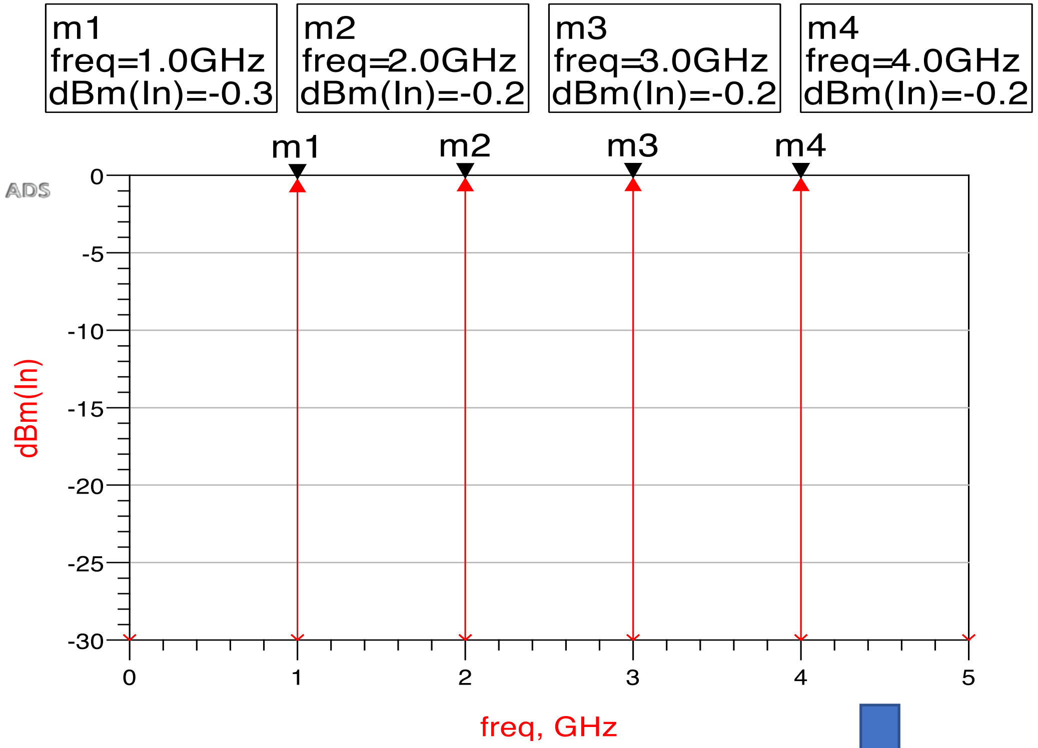


We shall connect the cable to the source L-band signal, such as LNB

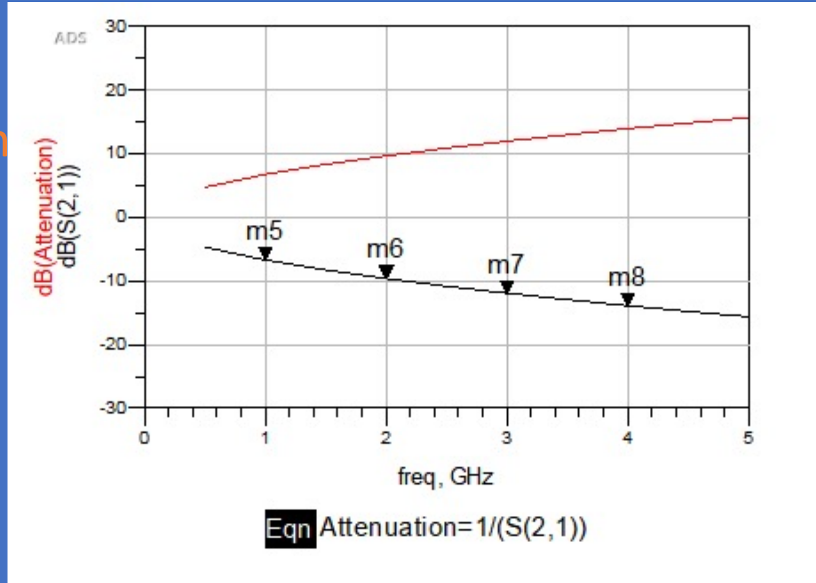


This is the example of L-band spectrum
With four carriers from 1 to 4 GHz
In an ideal case all carriers from LNB to Modem should be delivered without amplitude distortion.

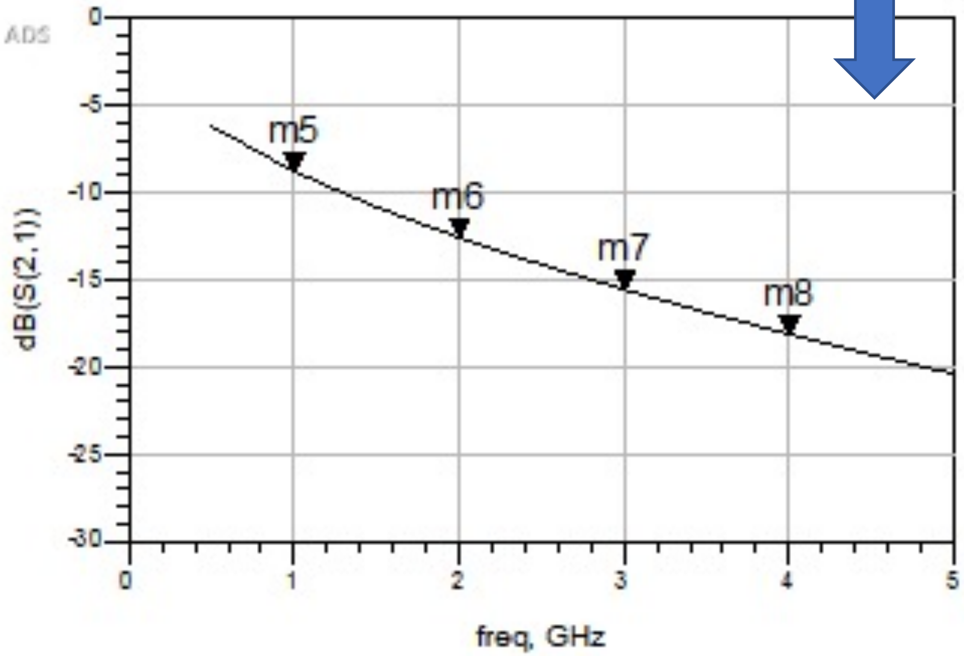
The phase distortion in cable is usually very small so we will only focus on amplitude

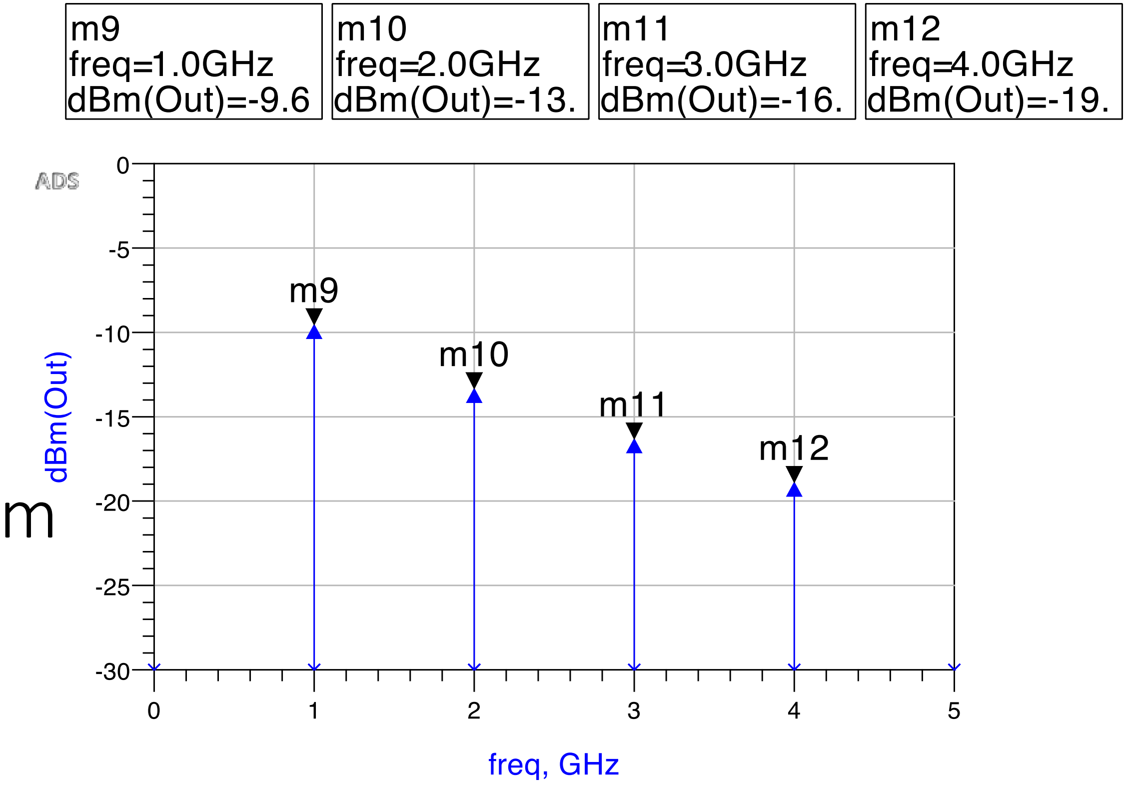


Let's not forget that attenuation is inverse of the transfer function S(2,1)



When we add a length of cable with following through loss…





the spectrum clearly distorts

Let us study the cables closer and find differences between them

LMR400

Construction Specifications			
Description	Material	In.	(mm)
Inner Conductor	Solid BCCAl	0.108	(2.74)
Dielectric	Foam PE	0.285	(7.24)
Outer Conductor	Aluminum Tape	0.291	(7.39)
Overall Braid	Tinned Copper	0.320	(8.13)
Jacket	(see table)	0.405	(10.29)

Electrical Specifications			
Performance Property	Units	US	(metric)
Velocity of Propagation	%	84	
Dielectric Constant	NA	1.38	
Time Delay	nS/ft (nS/m)	1.20	(3.92)
Impedance	ohms	50	
Capacitance	pF/ft (pF/m)	23.9	(78.4)
Inductance	uH/ft (uH/m)	0.060	(0.20)
Shielding Effectiveness	dB	>90	
DC Resistance			
Inner Conductor	ohms/1000ft (/km)	1.39	(4.6)
Outer Conductor	ohms/1000ft (/km)	1.65	(5.4)
Voltage Withstand	Volts DC	2500	
Jacket Spark	Volts RMS	8000	
Peak Power	kW	16	

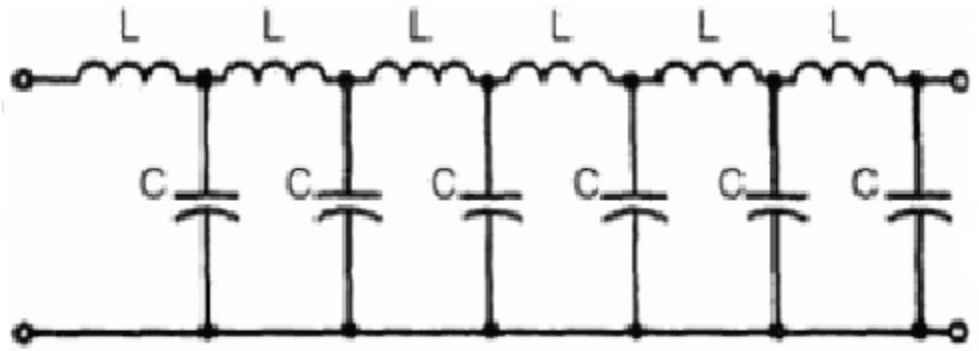
LMR195

Construction Specifications			
Description	Material	In.	(mm)
Inner Conductor	Solid BC	0.037	(0.94)
Dielectric	Foam PE	0.110	(2.79)
Outer Conductor	Aluminum Tape	0.116	(2.95)
Overall Braid	Tinned Copper	0.139	(3.53)
Jacket	(see table)	0.195	(4.95)

Electrical Specifications			
Performance Property	Units	US	(metric)
Velocity of Propagation	%	80	
Dielectric Constant	NA	1.56	
Time Delay	nS/ft (nS/m)	1.27	(4.17)
Impedance	ohms	50	
Capacitance	pF/ft (pF/m)	25.4	(83.3)
Inductance	uH/ft (uH/m)	0.064	(0.21)
Shielding Effectiveness	dB	>90	
DC Resistance			
Inner Conductor	ohms/1000ft (/km)	7.6	(24.9)
Outer Conductor	ohms/1000ft (/km)	4.9	(16.1)
Voltage Withstand	Volts DC	1000	
Jacket Spark	Volts RMS	3000	
Peak Power	kW	2.5	

The equivalent circuit of the cable – Telegrapher's model

was originally developed in 1876 for describing behavior of long transmission lines

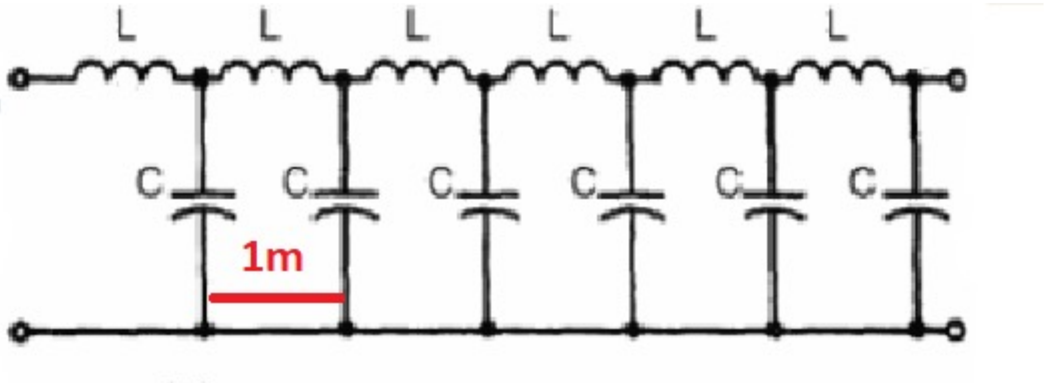


(A) ARTIFICIAL TRANSMISSION LINE

What are these components?

<u>LMR400</u>

L=0.2uH
C=78.4pF



(A) ARTIFICIAL TRANSMISSION LINE

<u>LMR195</u>

L=0.21uH
C=83.3pF

Electrical Specifications

Performance Property	Units	US	(metric)
Velocity of Propagation	%	84	
Dielectric Constant	NA	1.38	
Time Delay	nS/ft (nS/m)	1.20	(3.92)
Impedance	ohms	50	
Capacitance	pF/ft (pF/m)	23.9	(78.4)
Inductance	uH/ft (uH/m)	0.060	(0.20)
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Outer Conductor	ohms/1000ft (/km)	1.65	(5.4)
Voltage Withstand	Volts DC	2500	
Jacket Spark	Volts RMS	8000	
Peak Power	kW	16	

Electrical Specifications

Performance Property	Units	US	(metric)
Velocity of Propagation	%	80	
Dielectric Constant	NA	1.56	
Time Delay	nS/ft (nS/m)	1.27	(4.17)
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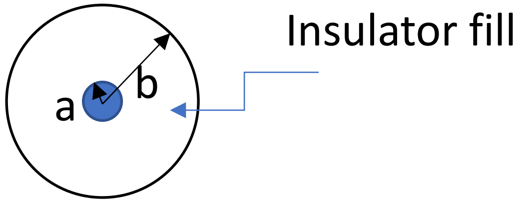
Voltage Withstand	Volts DC	1000	
Jacket Spark	Volts RMS	3000	
Peak Power	kW	2.5	

Definitions



- a (d) – radius (diameter) of inner conductor
- b (D) – radius (diameter) of outer conductor (inner surface of it)
- ε – dielectric constant of insulator
- μ – magnetic permeability of conductors
- Z_0 - characteristic impedance of the cable $Z_0 = \sqrt{\frac{L}{C}} = \frac{138}{\sqrt{\varepsilon \cdot \mu}} \cdot \log(\frac{b}{a})$
- ν – velocity of propagation $\nu = \frac{1}{\sqrt{L \cdot C}} = \frac{c}{\sqrt{\varepsilon \cdot \mu}}$
- Δt – time delay through length of cable $\Delta t = \frac{l}{\upsilon}$

Fun fact: Z_0 is not frequency dependent. So 50 Ohm impedance of the cable can be measured with DC ohm-meter…… the only catch is: the cable has to be infinitely long!

Back to our cables

LMR400

L=0.2uH
C=78.4pF

$$Z_0 = \sqrt{\frac{L}{C}} = \sqrt{\frac{0.2E^{-6}}{78.4E^{-12}}} = 50.5(ohm)$$

or

$$Z_0 = \frac{138}{\sqrt{\varepsilon \cdot \mu}} \cdot \log\left(\frac{b}{a}\right) = \frac{138}{\sqrt{1.38 \cdot 1}} \cdot \log\left(\frac{7.24}{2.74}\right) = 49.6(ohm)$$

$$v = \frac{1}{\sqrt{L \cdot C}} = \frac{1}{\sqrt{0.2E^{-6} \cdot 78.4E^{-12}}} = 252{,}538{,}136.138\ (m/s)$$

Velocity of Propagation in % = $\frac{252{,}538{,}136.138}{299{,}792{,}458.000} = 84.2\%$
is a comparison with speed of light in free space

Time delay of 1m cable: $\Delta t = \frac{l}{v} = 3.96\ (ps)$

Construction Specifications

Description	Material	In.	(mm)
Inner Conductor	Solid BCCAl	0.108	(2.74)
Dielectric	Foam PE	0.285	(7.24)
Outer Conductor	Aluminum Tape	0.291	(7.39)
Overall Braid	Tinned Copper	0.320	(8.13)
Jacket	(see table)	0.405	(10.29)

Electrical Specifications

Performance Property	Units	US	(metric)
Velocity of Propagation	%	84	
Dielectric Constant	NA	1.38	
Time Delay	nS/ft (nS/m)	1.20	(3.92)
Impedance	ohms	50	
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Inductance	uH/ft (uH/m)	0.060	(0.20)
Shielding Effectiveness	dB	>90	
DC Resistance			
Inner Conductor	ohms/1000ft (/km)	1.39	(4.6)
Outer Conductor	ohms/1000ft (/km)	1.65	(5.4)
Voltage Withstand	Volts DC	2500	
Jacket Spark	Volts RMS	8000	
Peak Power	kW	16	

...back to our cables

LMR195

L=0.21uH
C=83.3pF

$$Z_0 = \sqrt{\frac{L}{C}} = \sqrt{\frac{0.21E^{-6}}{83.3E^{-12}}} = 50.2(\text{ohm})$$

or

$$Z_0 = \frac{138}{\sqrt{\varepsilon \cdot \mu}} \cdot \log\left(\frac{b}{a}\right) = \frac{138}{\sqrt{1.56 \cdot 1}} \cdot \log\left(\frac{2.79}{0.94}\right) = 52.2(\text{ohm})$$

$$v = \frac{1}{\sqrt{L \cdot C}} = \frac{1}{\sqrt{0.21E^{-6} \cdot 83.3E^{-12}}} = 239{,}093{,}545.358\ (\text{m/s})$$

Velocity of Propagation in % = $\frac{239{,}093{,}545.358}{299{,}792{,}458.000} = 79.8\%$
is a comparison with speed of light in free space

Time delay of 1m cable: $\Delta t = \frac{l}{v} = 4.18$ (ps)

Construction Specifications

Description	Material	In.	(mm)
Inner Conductor	Solid BC	0.037	(0.94)
Dielectric	Foam PE	0.110	(2.79)
Outer Conductor	Aluminum Tape	0.116	(2.95)
Overall Braid	Tinned Copper	0.139	(3.53)
Jacket	(see table)	0.195	(4.95)

Electrical Specifications

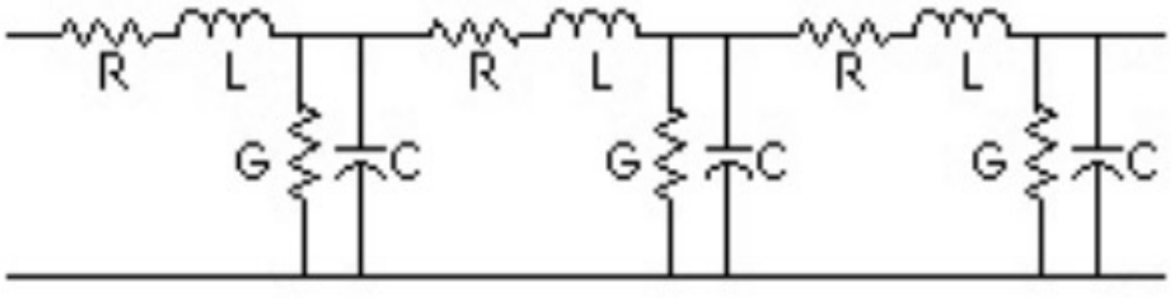
Performance Property	Units	US	(metric)
Velocity of Propagation	%	80	
Dielectric Constant	NA	1.56	
Time Delay	nS/ft (nS/m)	1.27	(4.17)
Impedance	ohms	50	
Capacitance	pF/ft (pF/m)	25.4	(83.3)
Inductance	uH/ft (uH/m)	0.064	(0.21)
Shielding Effectiveness	dB	>90	
DC Resistance			
Inner Conductor	ohms/1000ft (/km)	7.6	(24.9)
Outer Conductor	ohms/1000ft (/km)	4.9	(16.1)
Voltage Withstand	Volts DC	1000	
Jacket Spark	Volts RMS	3000	
Peak Power	kW	2.5	

- We can tell from above that the Telegrapher's model components L and C are good for calculating some properties of the cable such as characteristic impedance (Z_0), velocity of propagation (ν).

- Can we calculate loss based on the simple Telegrapher's model?

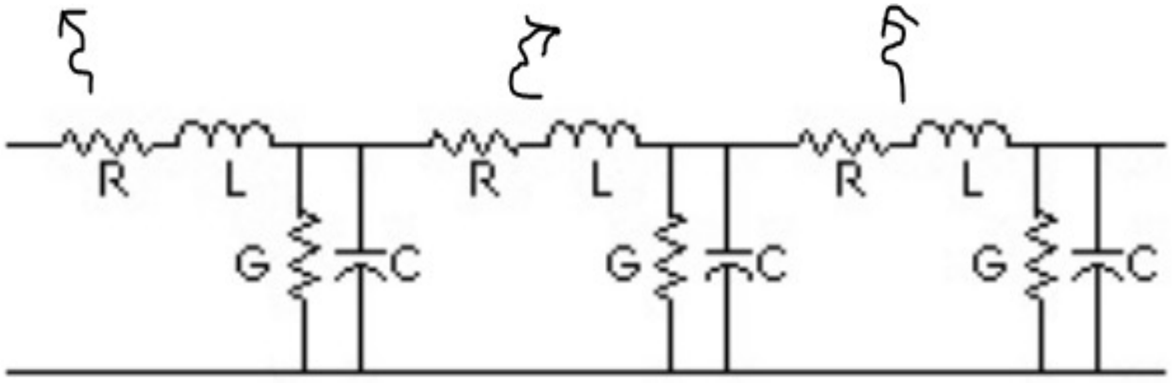
The answer is NO. The LC components used above are lossless.

- The lossy Telegrapher's model looks like that:



From this model we can tell that the losses in the cable come from losses in metal conductors (R) and conduction losses of the dielectric (G)

- What is missing in this model?



Cables radiate. We must add radiation losses.
Dielectric has losses expressed in tanδ

- Total losses of the cable: $\alpha = \alpha_C + \alpha_D + \alpha_R + \alpha_G$

α_C - Loss due to metal conductivity (R)

α_D - Loss due to dielectric loss tangent

α_G - Loss due to conductivity of dielectric (G)

α_R - Loss due to radiation

α_C - Loss due to metal conductivity:

$$\alpha_C = 8.686 \cdot \frac{Resistance\ per\ unit\ length}{2 \cdot Z_0}$$

- Resistance per unit length: $\sqrt{\frac{f \cdot \mu_0}{\pi}} \cdot \left\{\frac{\sqrt{\mu_{r1} \cdot \rho_1}}{D} + \frac{\sqrt{\mu_{r2} \cdot \rho_2}}{d}\right\}$ (ohms/meter)

The resistance and resistive loss are frequency dependent

- D-outer conductor diameter = 2b
- d-inner conductor diameter = 2a
- μ_{r1}, ρ_1 properties of outer conductor
- μ_{r2}, ρ_2 properties of inner conductor

Typical loss for LMR400, Cu center conductor, Al foil

Frequency, MHz	100	500	1000	2000	5000
α_C, dB/meter	0.041	0.091	0.128	0.182	0.287

α_D - Loss due to dielectric loss tangent:

$$\alpha_D = 92.0216 \cdot 10^{-9} \cdot \sqrt{\varepsilon_r} \cdot \tan\delta \cdot f \quad \text{(dB/meter)}$$

Loss due to tanδ is also frequency dependent

Typical numbers for α_D:

Foam polyethylene tanδ = 0.0001, ε_r=1.38 (LMR400 cable)

Frequency, MHz	100	500	1000	2000	5000
α_D, dB/meter	0.0010	0.0054	0.0108	0.0216	0.0541

α_G - Loss due to dielectric conduction:

$$\alpha_G = \frac{1636 \cdot \sigma}{\sqrt{\varepsilon_r}} \text{ (dB/meter)}$$

- Loss dielectric conduction is only a function of bulk material properties of the dielectric.
- σ – conductivity of polyethylene < 10^{-15} s/m

Therefore: $\alpha_G = \frac{1636 \cdot 10^{-15}}{\sqrt{1.56}} = 1.3 \cdot 10^{-12}$(dB/meter)

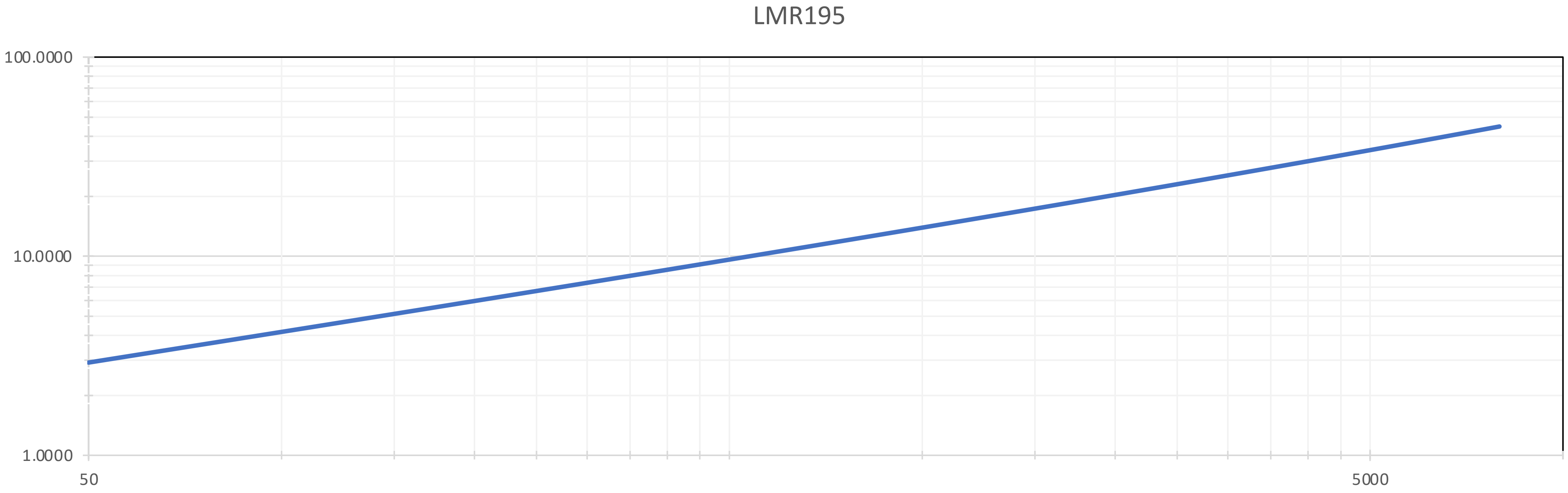
No dielectric that is used in a good RF cable has noticeable conduction loss

α_R - Loss due to radiation

- Loss due to radiation can be derived from specified shielding effectiveness.
- In case of LMR195 it is >90dB
- $shielding\ effectiveness = 10 \cdot \log(\frac{Incident\ power}{Radiated\ power})$ (dB)
- $\frac{Power\ radiated}{Incident\ power} = 10^{-9}$
- Radiation loss $\alpha_R = 10 \cdot \log(\frac{1}{1-1\cdot 10^{-9}}) = 4.3 \cdot 10^{-9}$ (dB)

Just like dielectric conduction loss, radiation of a good RF cable plays no significant role in overall cable loss.

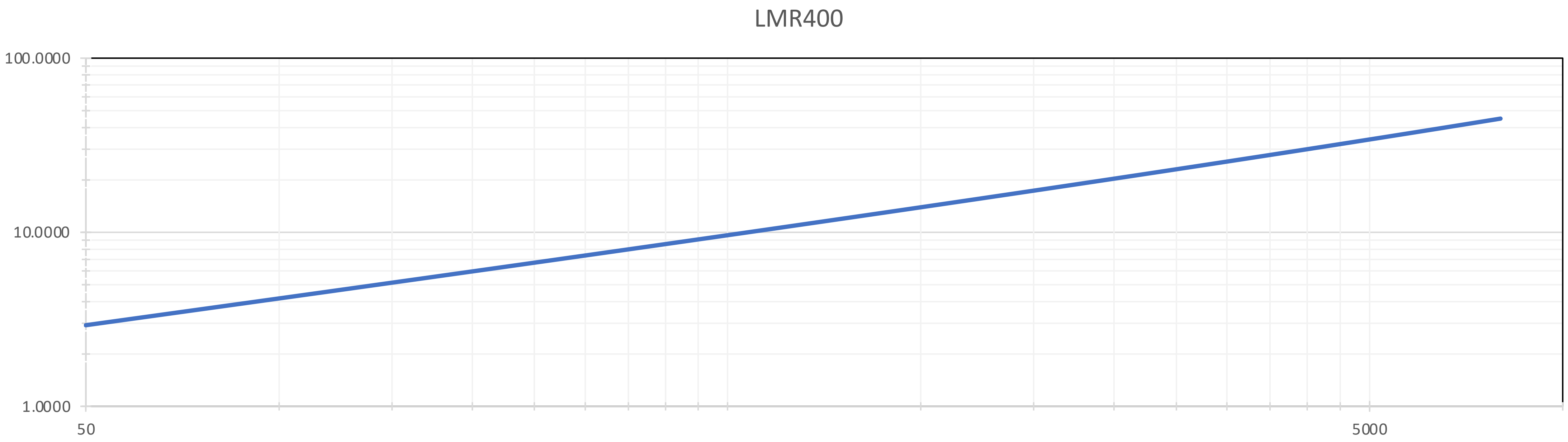
Let’s calculate cable loss vs frequency by adding α_C and α_D



Frequency, MHz	30	50	150	250	450	900	1500	1800	2000	2500	5800
Attenuation, dB/100m	6.2	8.1	14.1	18.4	24.9	35.8	47.0	51.8	54.8	61.8	98.5

And compare it with datasheet for LMR195

Attenuation dB/100 m	6.5	8.4	14.6	17.7	25.5	36.5	47.7	52.5	55.4	62.4	98.1



Frequency, MHz	30	50	150	250	450	900	1500	1800	2000	2500	5800
Attenuation, dB/100m	2.3	2.9	5.1	6.7	9.1	13.1	17.3	19.2	20.3	23.0	37.2

Comparing with datasheet for LMR400

Attenuation dB/100 m	2.2	2.9	5.0	6.1	8.9	12.8	16.8	18.6	19.6	22.2	35.5

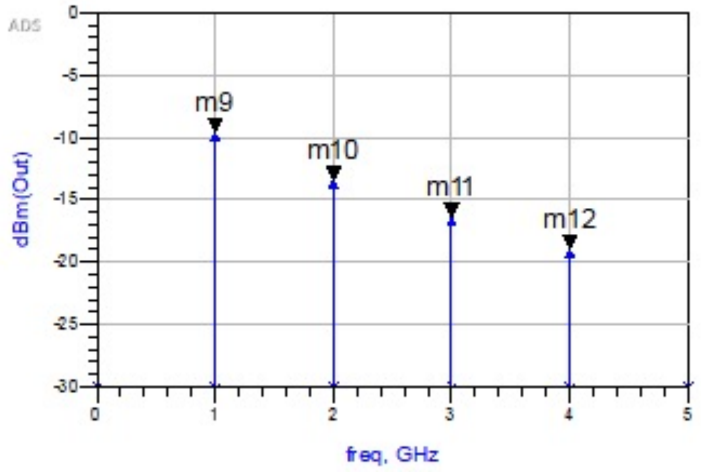
So what is the difference between the cables?

- Thicker cables are less resistive because they have larger conductors: $\sqrt{\frac{f\cdot\mu_0}{\pi}}\cdot\left\{\frac{\sqrt{\mu_{r1}\cdot\rho_1}}{D}+\frac{\sqrt{\mu_{r2}\cdot\rho_2}}{d}\right\}$ → the larger D and d (or b and a) the smaller the resistance. The current density is smaller in larger conductor.
- Thicker cables have less tanδ. Even if the same dielectric is used (foam PE or PTFE) the foaming in a larger cable is easier to achieve, more porosity → less dielectric loss. Tiny amount of foamed dielectric in thin cable is unable to hold the center conductor in place. Therefore foam is more dense in thin cables (which we can tell from dielectric constant ε: 1.38 in LMR400 and 1.56 in LMR195)
- Thicker cables have less dielectric conductive loss. The dielectric in thicker cable is more porous and conductors are farther apart. Even though the cables in our examples above have no noticeable loss there may be some cables with solid dielectrics where conduction starts to play role
- Thicker cables have less radiation loss, also because large surface area of outer conductor presents less current density. In some poorly shielded cables this will play role too.

So this is how to chose cable more minimum amplitude distortion:

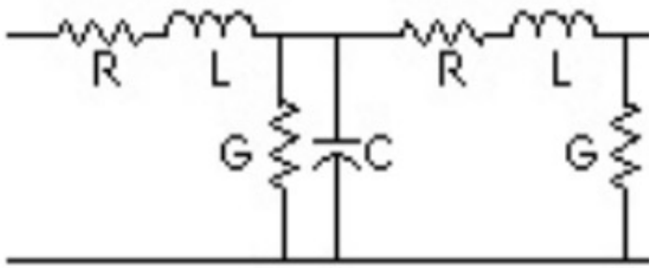
- The thicker the better
- Solid center conductor has less resistivity than stranded. Same applies to the outer conductor (rigid cables have less resistive loss)
- Pay attention to the dielectric (foam has less loss)
- Good cables have few layers of outer conductor. This helps the shielding effectiveness and maintains the integrity of the cable when bent.

But in the end any cable of significant length will have frequency dependent loss and will produce amplitude distortion of the signal

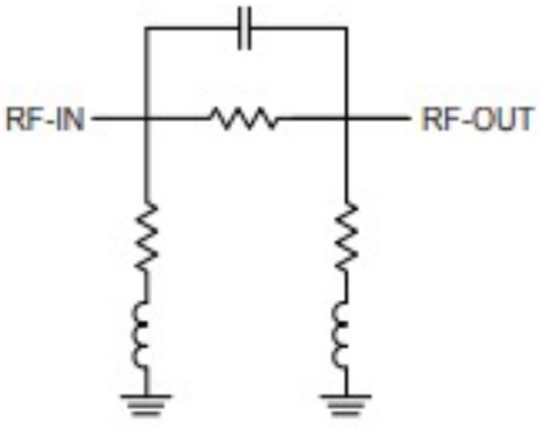


What can be done about amplitude distortion caused by the cable?

In order to compensate frequency dependent loss of this circuit (our cable):

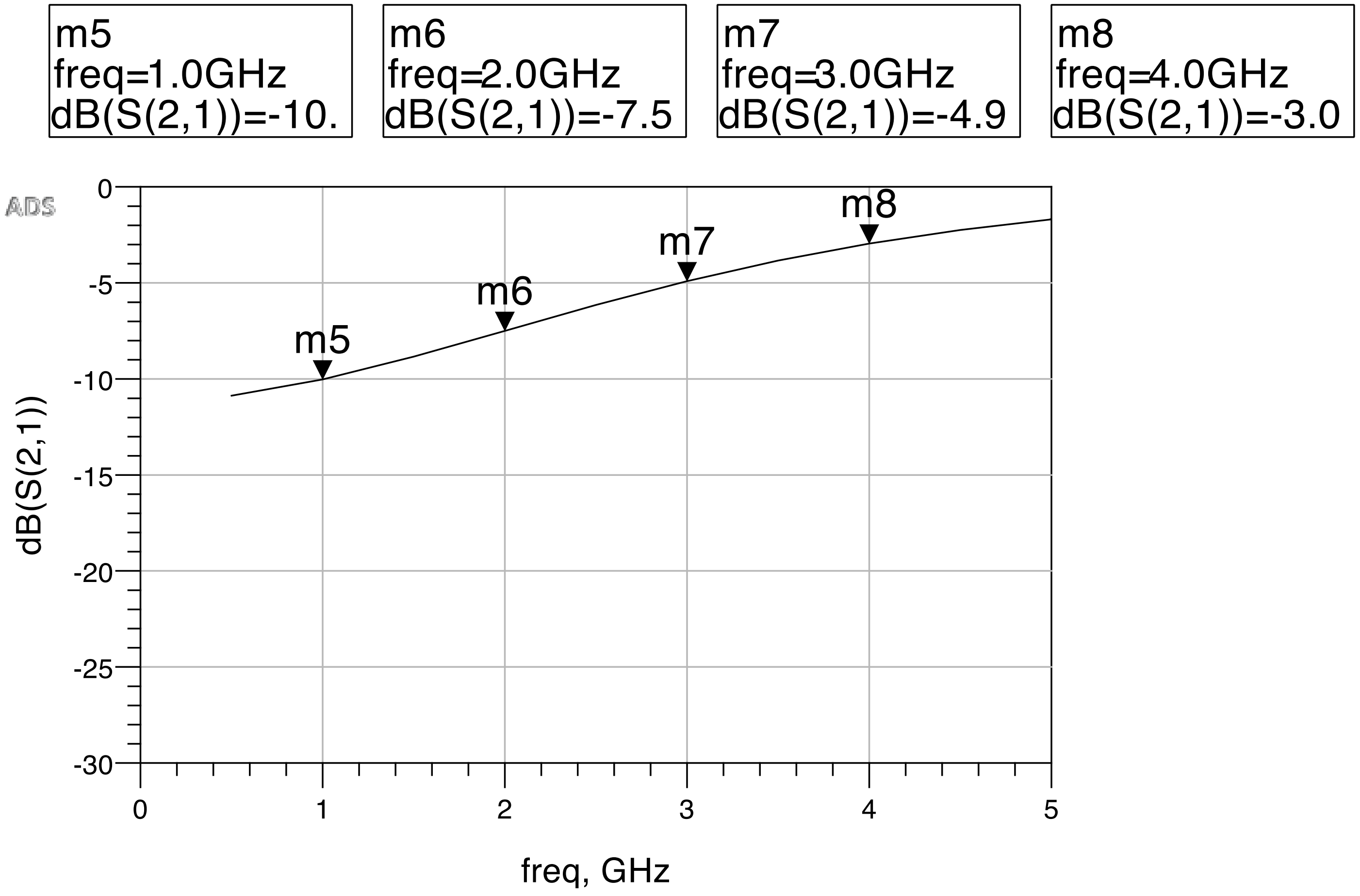


An obvious solution would be to design this circuit:

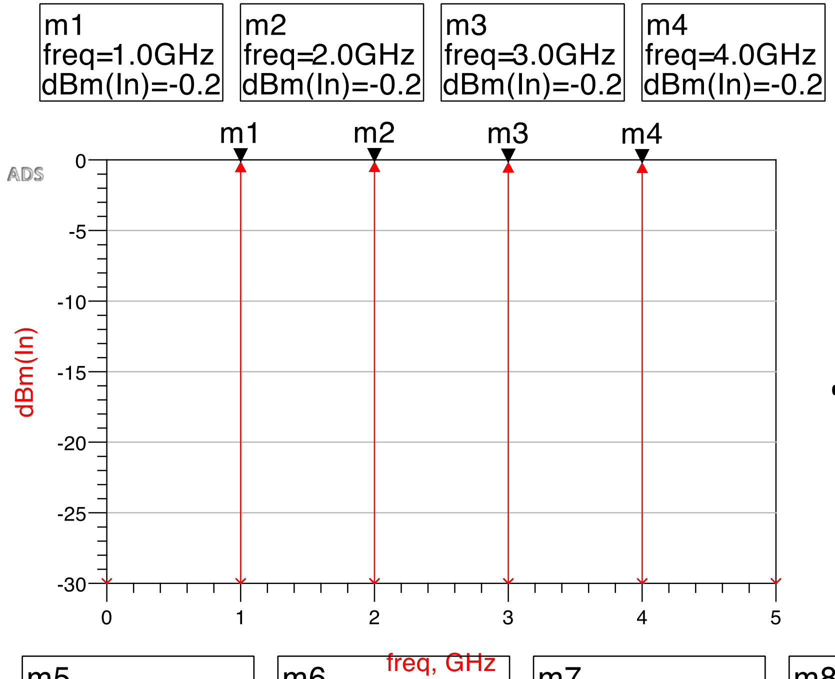


Such circuits are called frequency equalizers

The frequency response of equalizer:



LNB output



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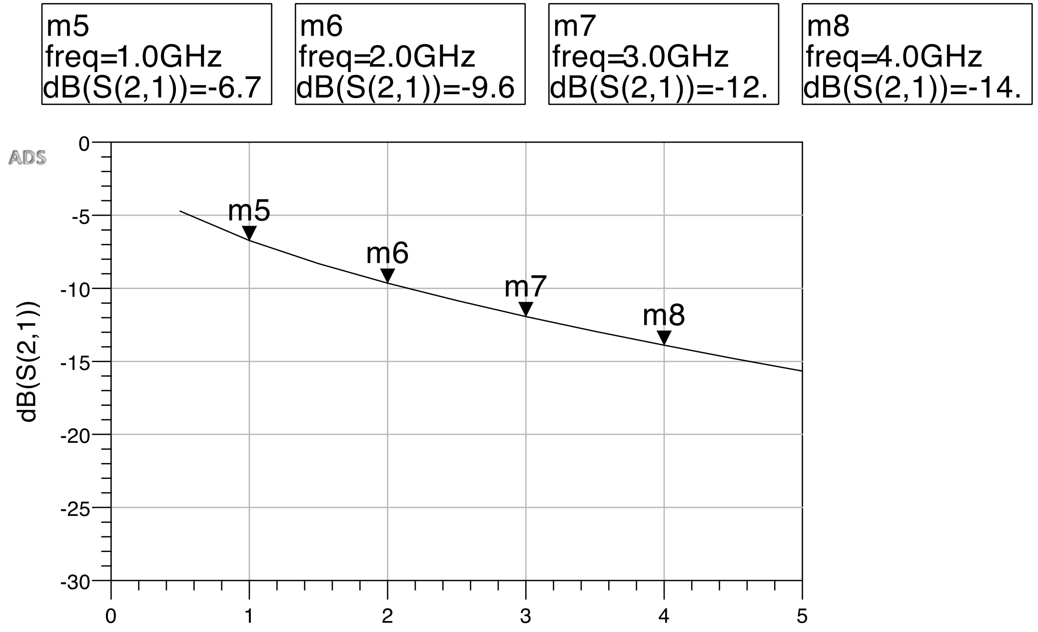
Cable loss



Let's simulate it with the cable

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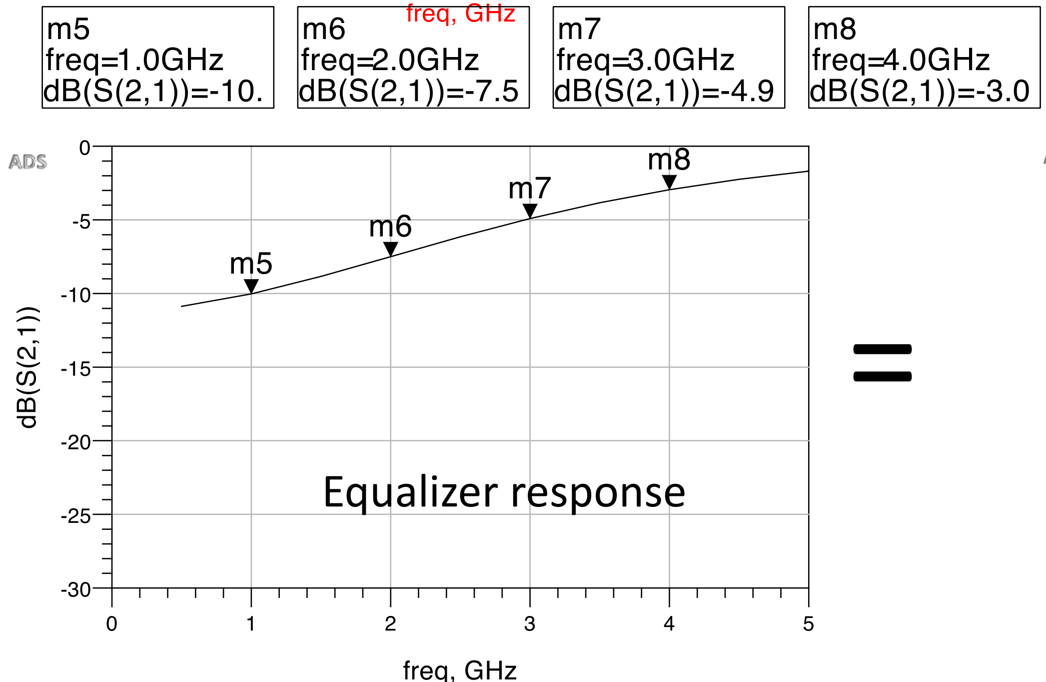

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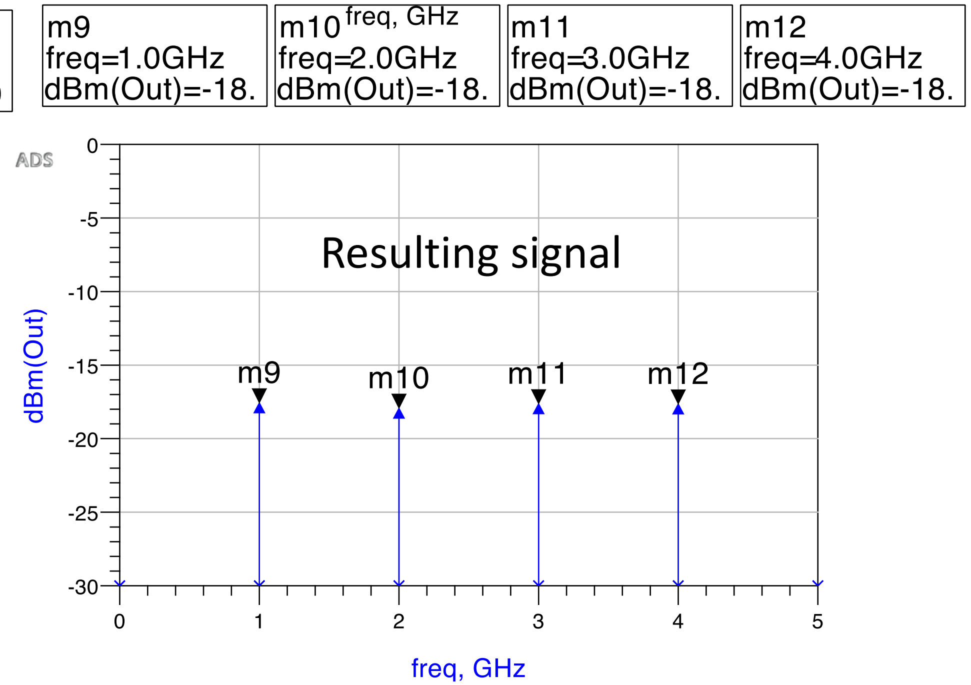
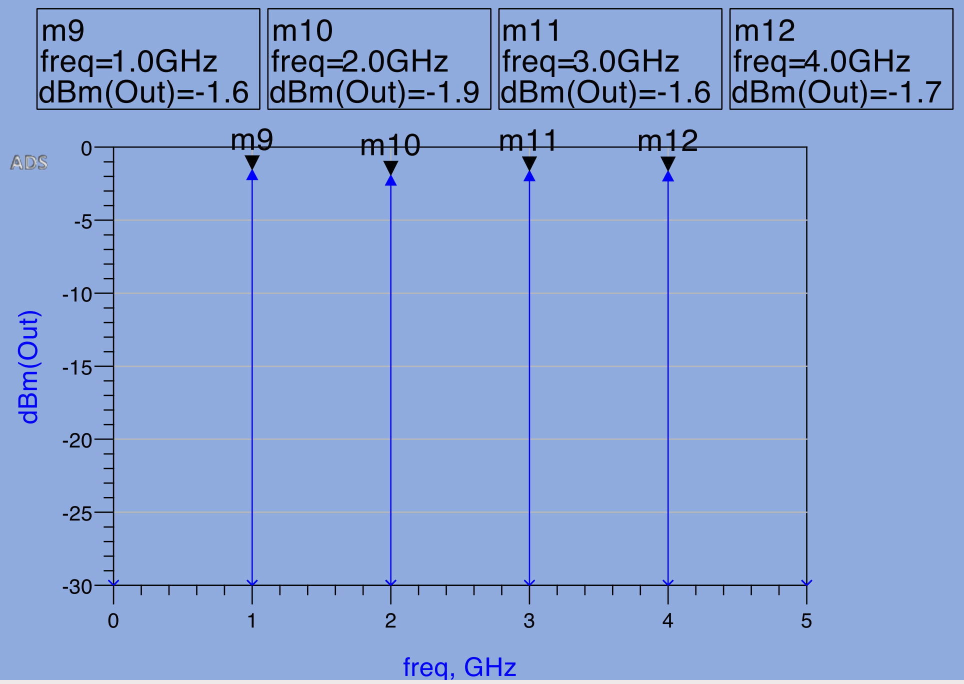
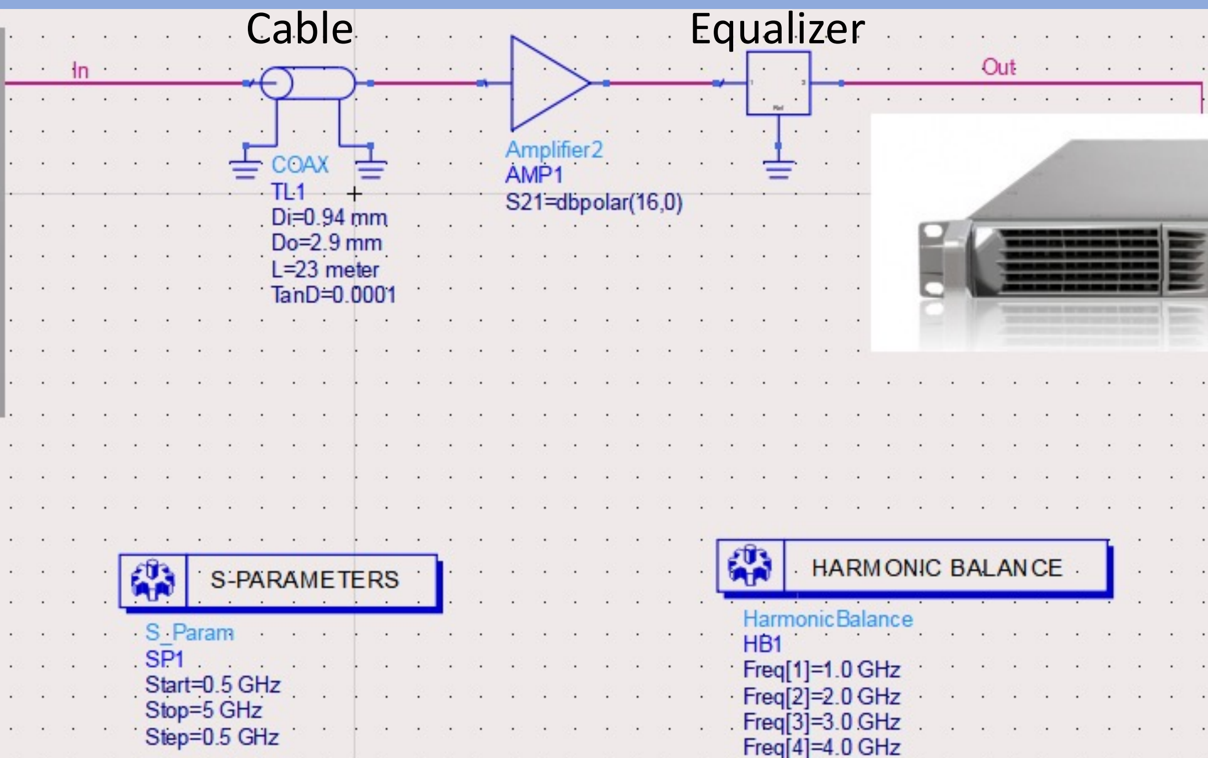


the only problem is…
now all carriers have low albeit equal power levels

As we can see using the passive equalizer will only attenuate the signal further.



The solution to this to add an amplifier:

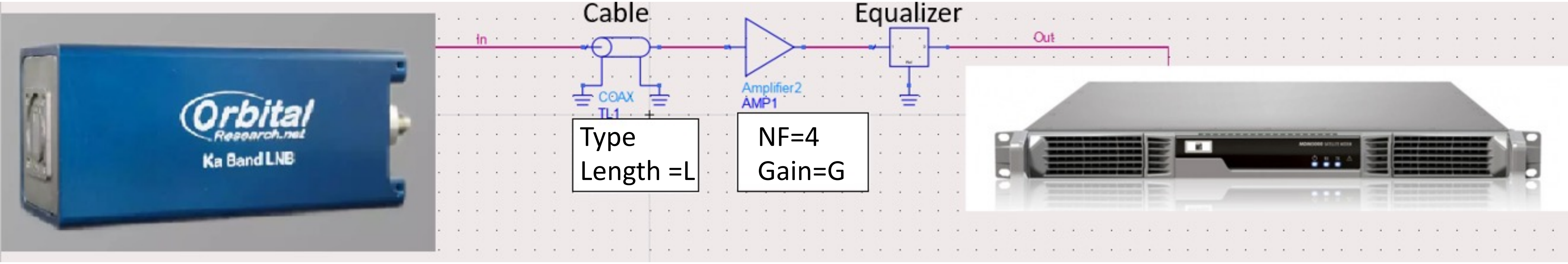


Now that we have an active equalizer, why spend money on a better cable?

Effect of cable loss/slope on system NF and Gain:

Example. Low Noise Downconverter case. LNB NF=1dB, Gain=55dB.

Signal level to modem after cable attenuation and compensation is ~0dBm per tone

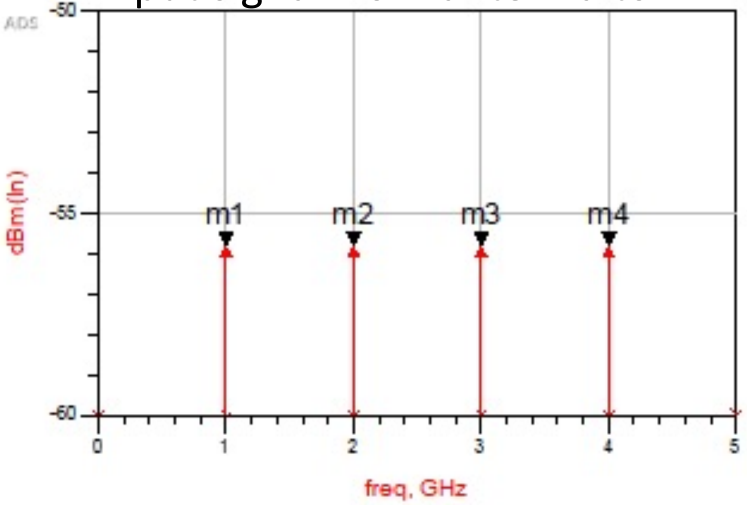


How do we expect the system NF to behave? According to Friis Noise Formula:

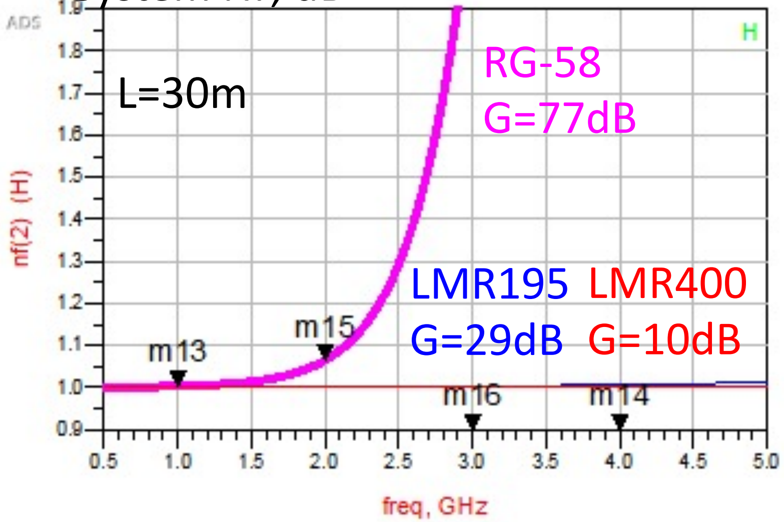
- When cable loss << LNB Gain then NF will not get affected
- When cable loss is compatible with LNB Gain NF will get degraded a little
- When cable loss is > LNB Gain NF will get affected a lot

Since we fully compensate the cable loss with the amplifier gain (i.e. Cable loss ~= G) we show this Gain value on the plots below. To prove that loss is compensated we show the power level to modem for all cases to be approximately the same (~0dBm per tone)

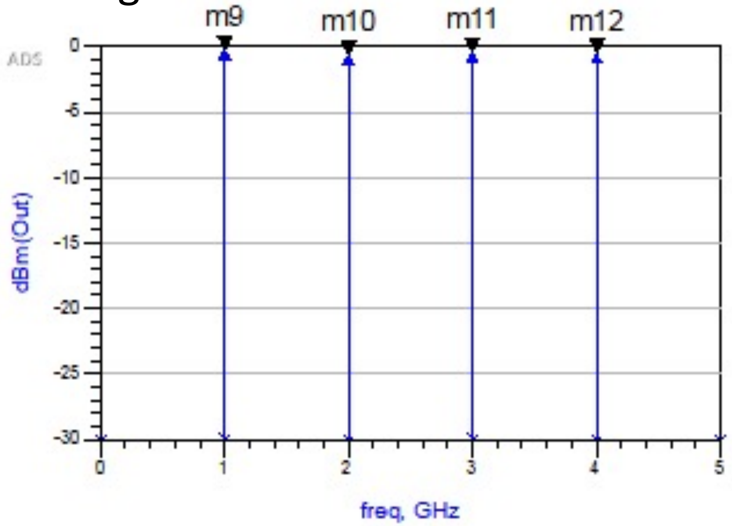
Input signal from antenna to LNB



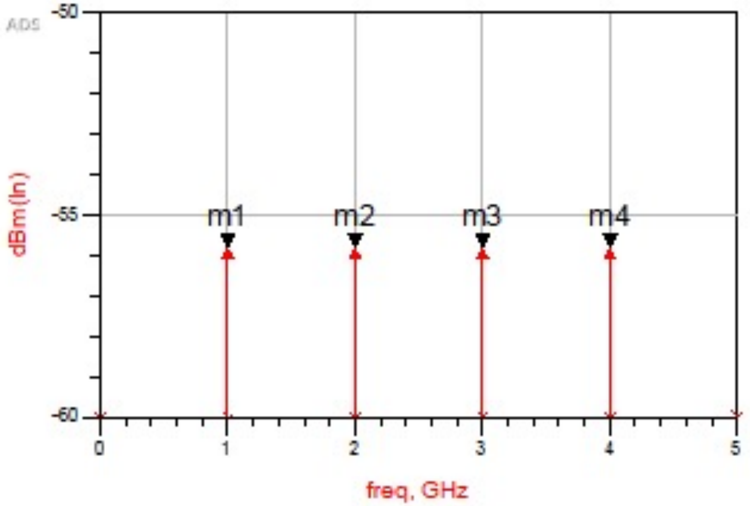
System NF, dB



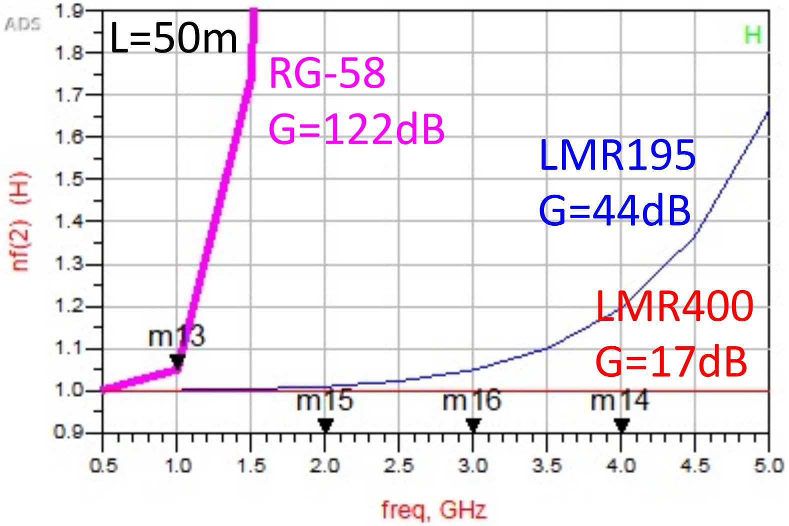
Signal to modem



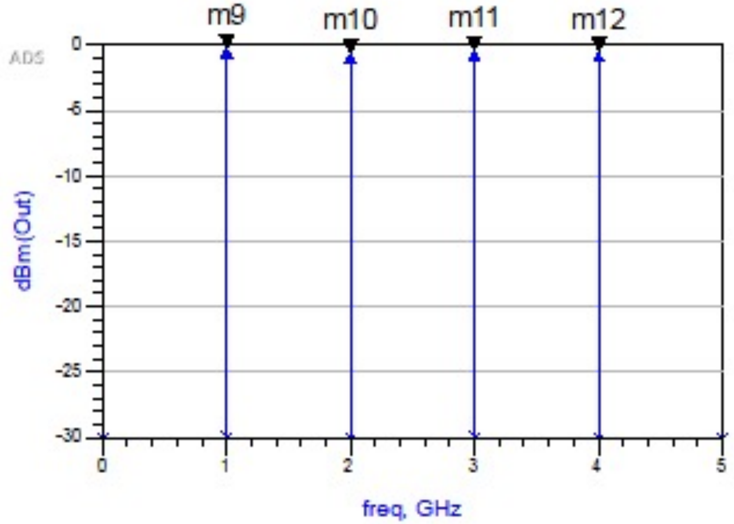
Input signal from antenna to LNB



System NF, dB



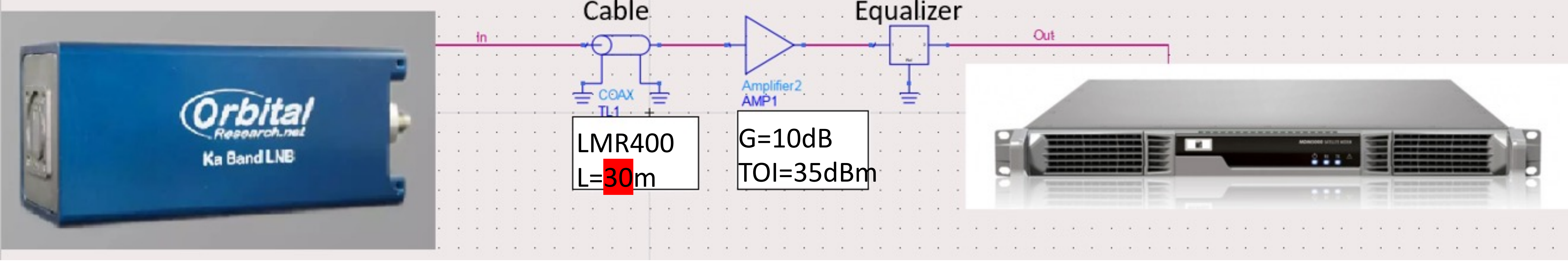
Signal to modem

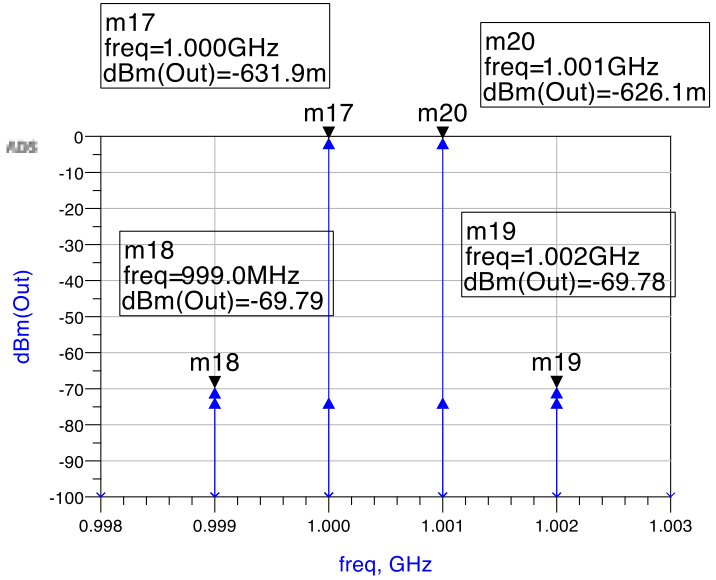


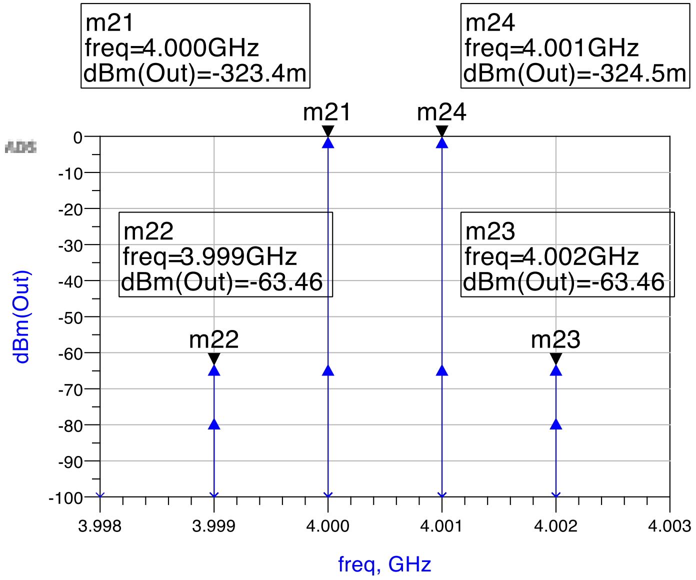
Thicker cables with better RF properties have less effect on system NF
Gain required to compensate the cable loss and slope becomes unmanageable for poorer cables. This is true for both down- and up-converters.
The problem of NF degradation goes away only when the amplifier is at the LNB side i.e. before the cable.

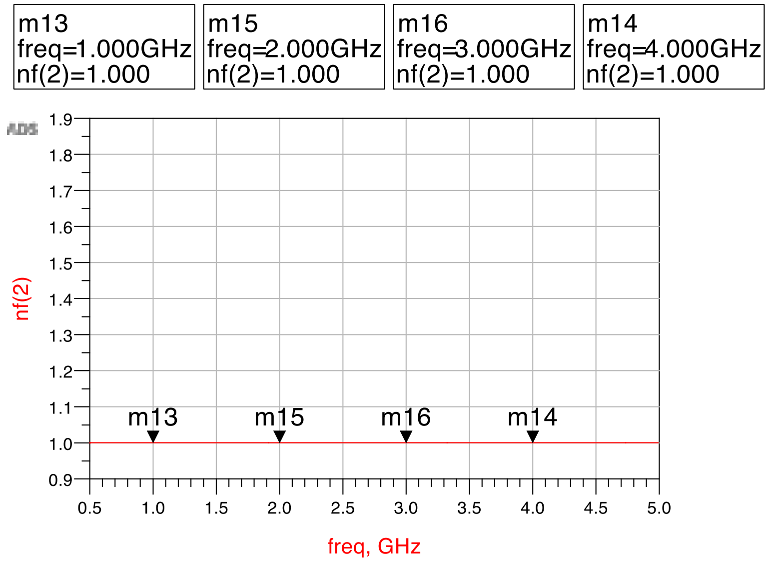
The problem of linearity

- The examples above assumed ideally linear amplifiers
- The real non-linear amplifier placed before the cable in equalizer configuration will have to be able to handle the power of 1W for a equalizer/cable loss of 30dB in order to deliver to modem undistorted signal of 0dBm
- The configuration above can preserve the NF when using good cable but still has a shortfall: even good cables at 30 meters will exhibit 6dB loss at higher frequencies. An equalizer will make all frequencies have 10dB loss (compensation plus intrinsic loss). This means that the amplifier has to have 10dB higher Third Order Intercept point as compared with the LNB output in order to have the same linearity.



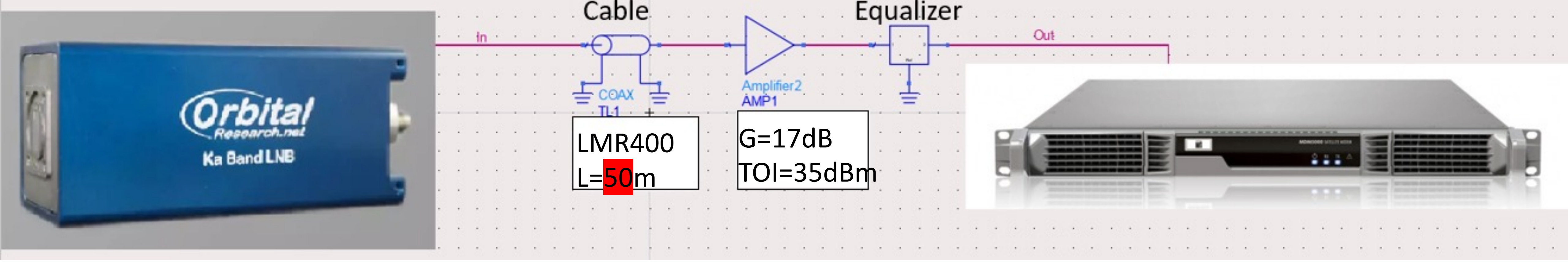


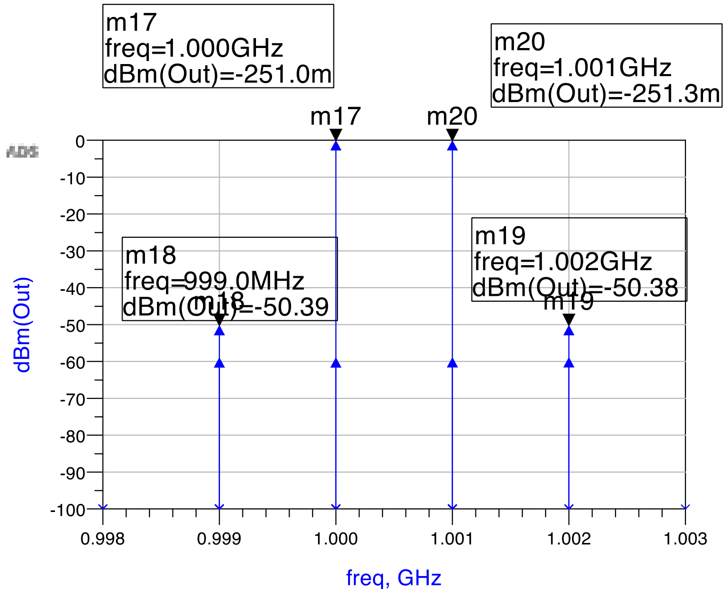


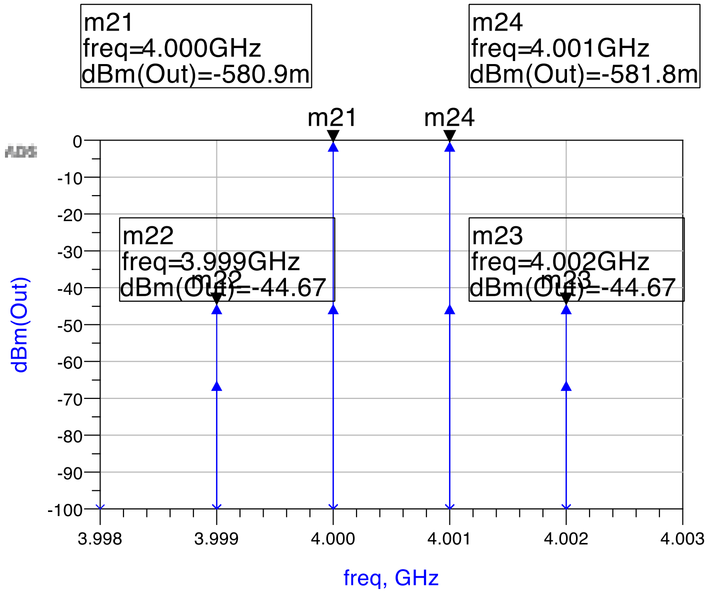


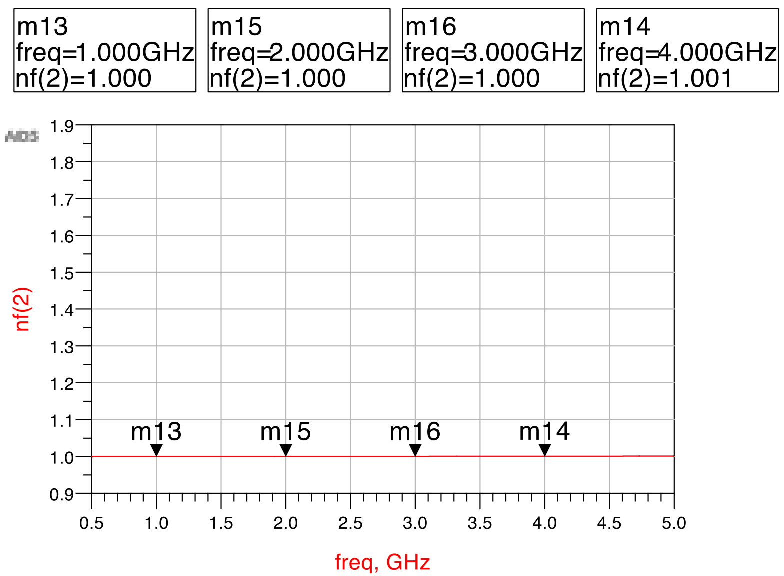
Above: Intermod product at 1GHz, 4GHz (were there is more cable loss) and System NF at all frequencies

Two-tone measurement at 1MHz apart is a standard way to evaluate the intermodulation product and hence the linearity of a device.





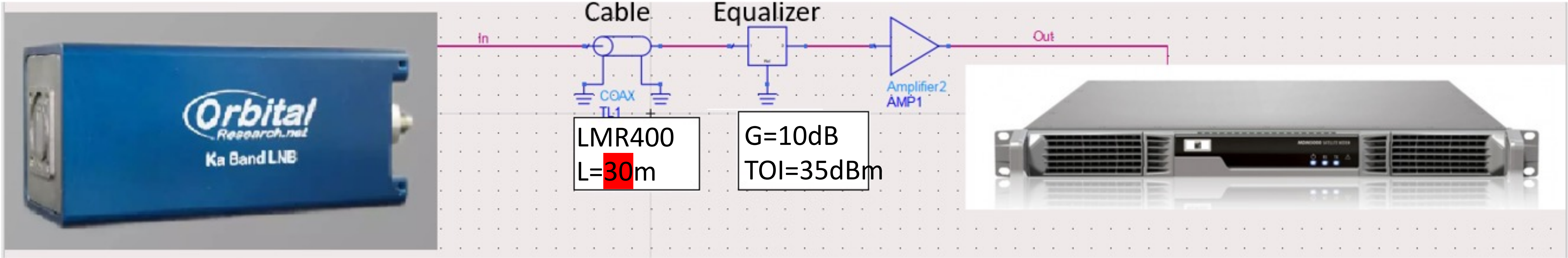


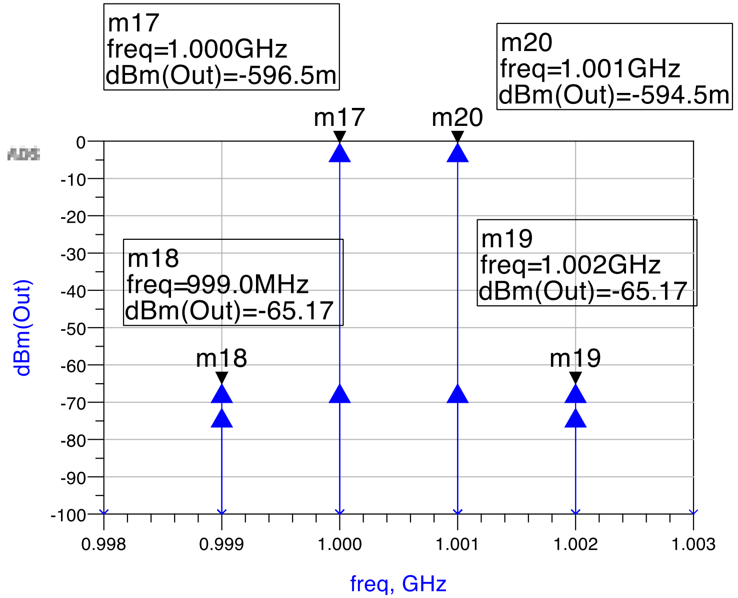


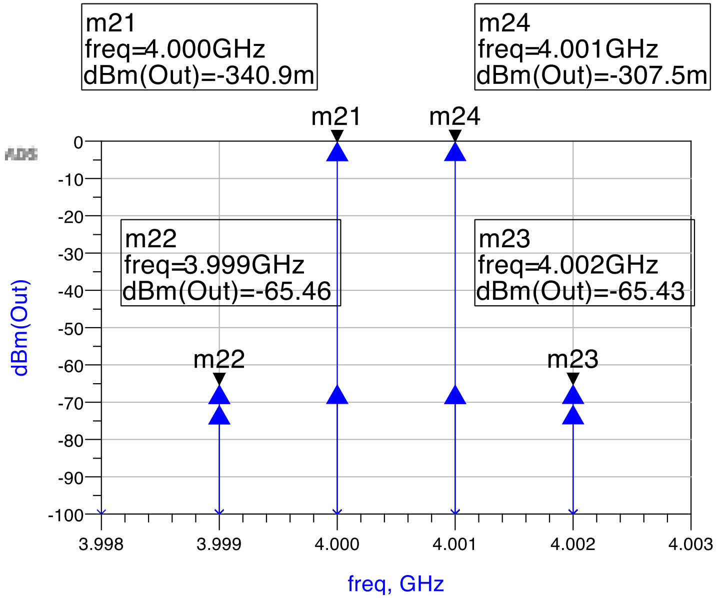
As cable length increases its loss increases too and system needs more equalization (which is a loss too) linearity gets worse. Compare intermod at 1GHz with 4GHz where is even more loss.

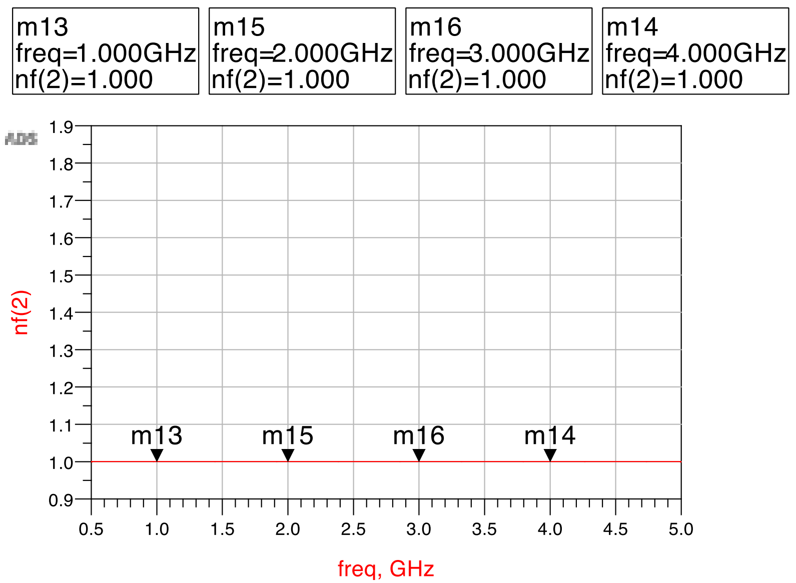
NF so far is not affected because there is not too much loss after the LNB

Let's change the configuration and compare two lengths of LMR400 again

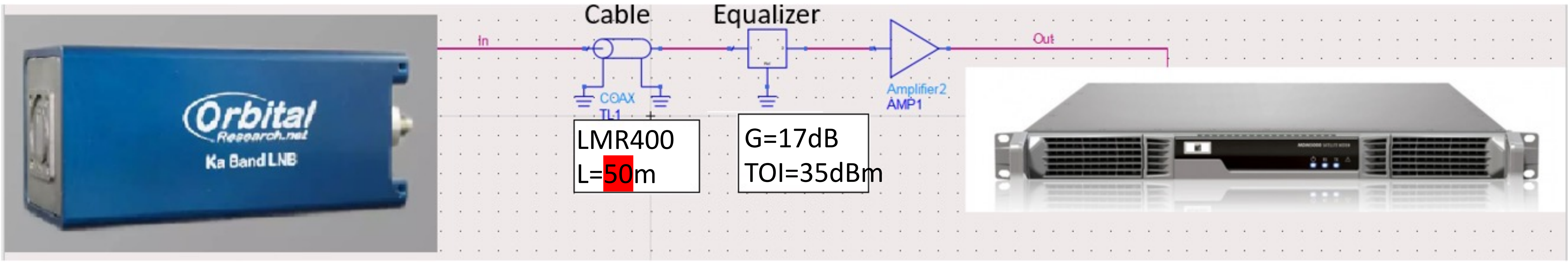


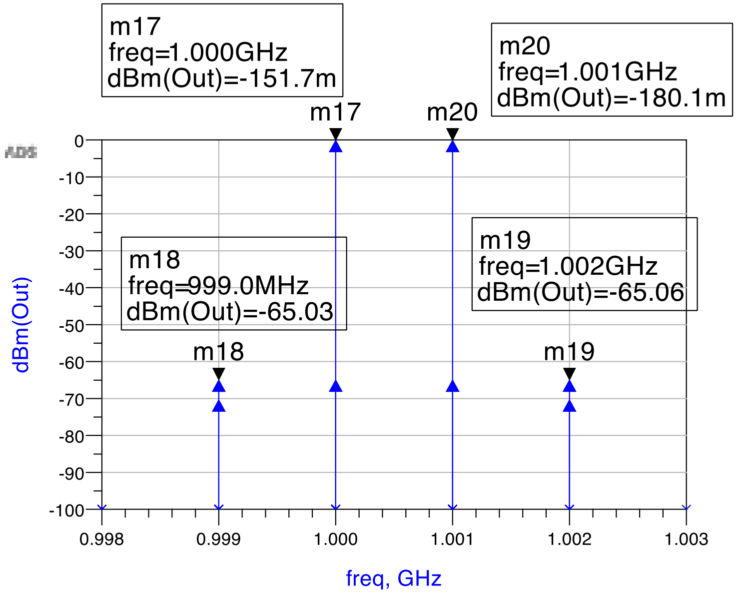


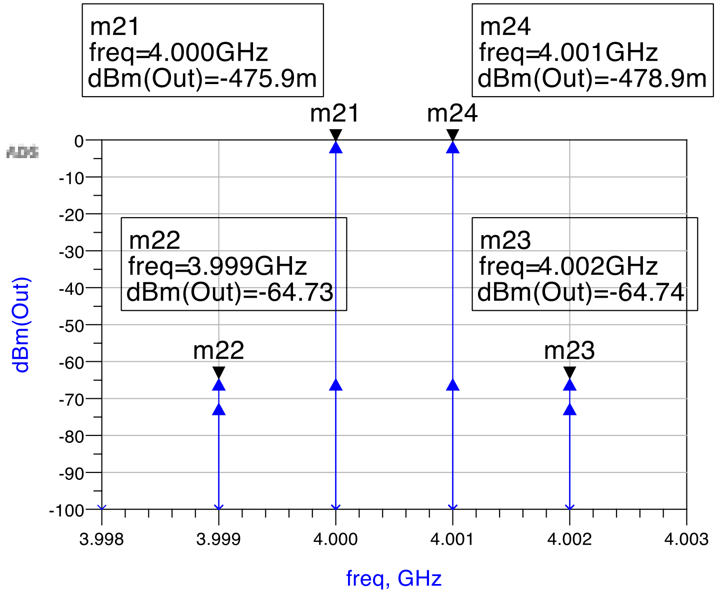


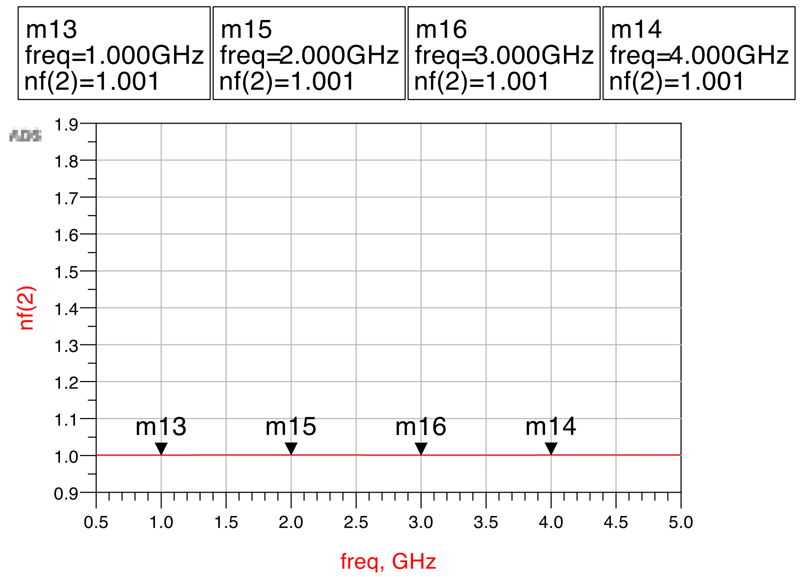


Notice that Intermodulation product becomes more equal at 1GHz and 4GHz and worst case improves from -44dBm to -65dBm.
System NF as a good as in previous configuration



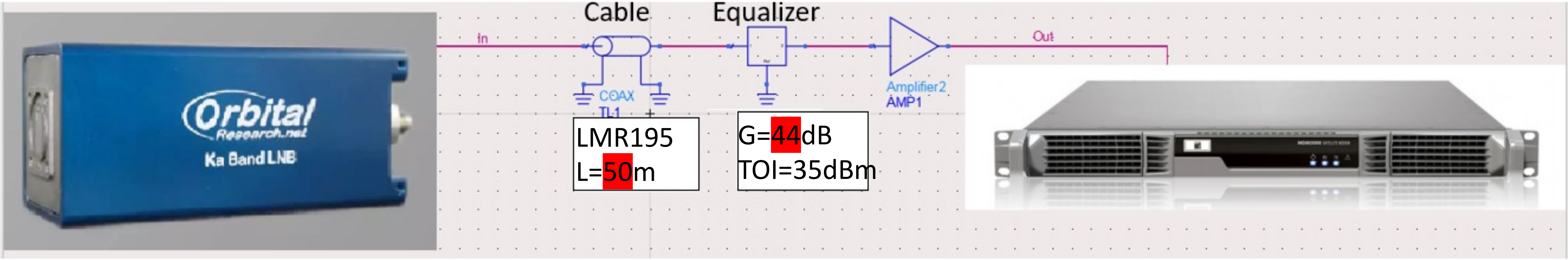


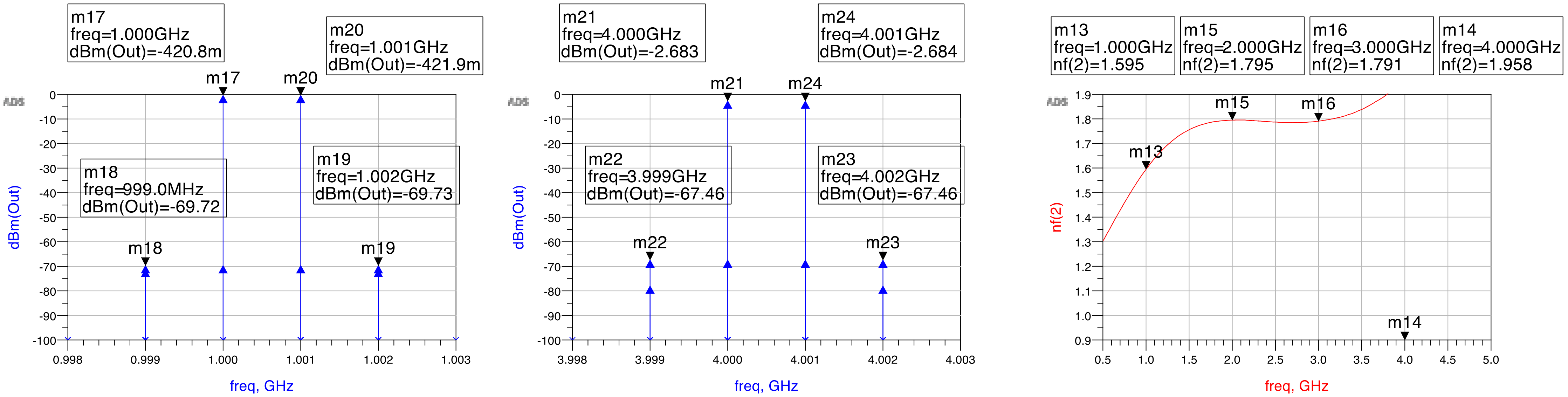




Increasing cable length from 30 to 50 meters does not affect the performance unlike in previous configuration.

Can we get away with 50 meter LMR195 cable?





The answer is NO! the Noise Figure will suffer due to too much loss (we needed 44dB of amplifier gain to compensate for it.

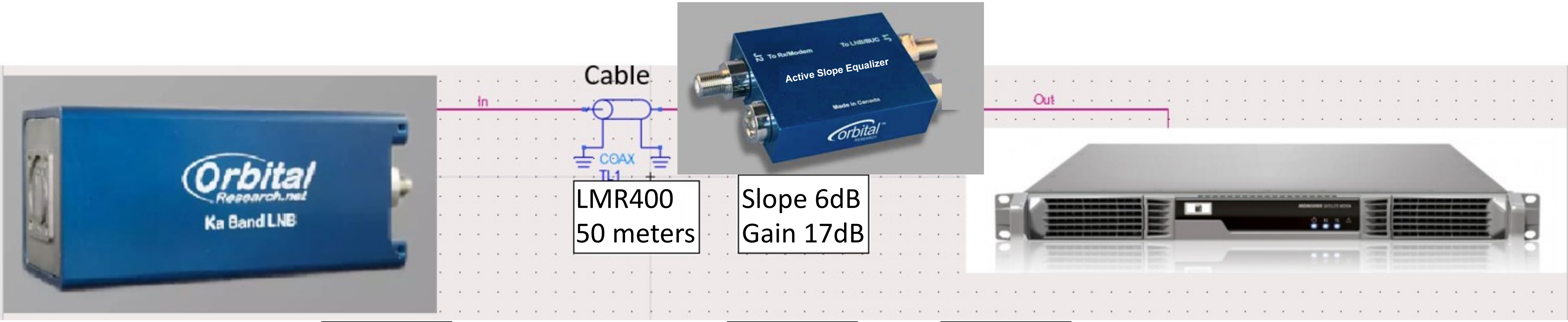
The Intermod is not affected because the signal level into the amp is very low.

Is amplitude/frequency imbalance fatal and why do we need the equalizer?

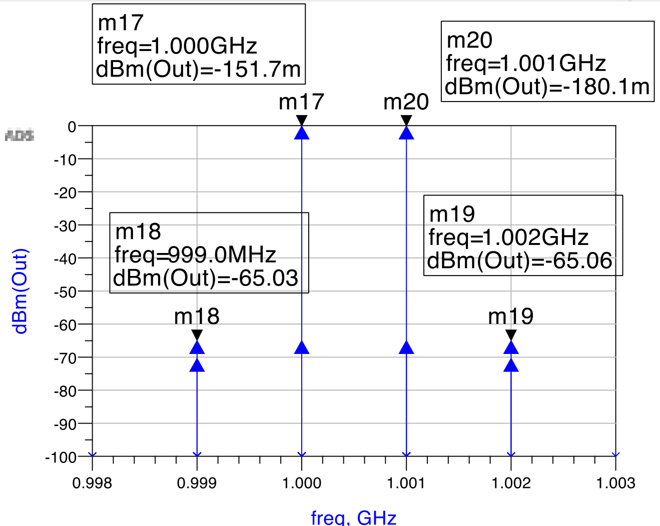
- On short runs of cable the problems with amplitude slope are not severe.
- Modems usually do not require signals at low end of the spectrum to be equal to those at other parts of the spectrum as they can tune to individual carriers, amplify and process the signals.
- Long runs of cable (50, 100 meters or more), power splitters and other attenuating equipment in-line can present the problem. Attenuation can be so high that signal level drops below modem sensitivity level.
- Some software defined radios (SDR) may receive wideband signals from 1GHz to 4GHz and severe slope may present problems for processing.

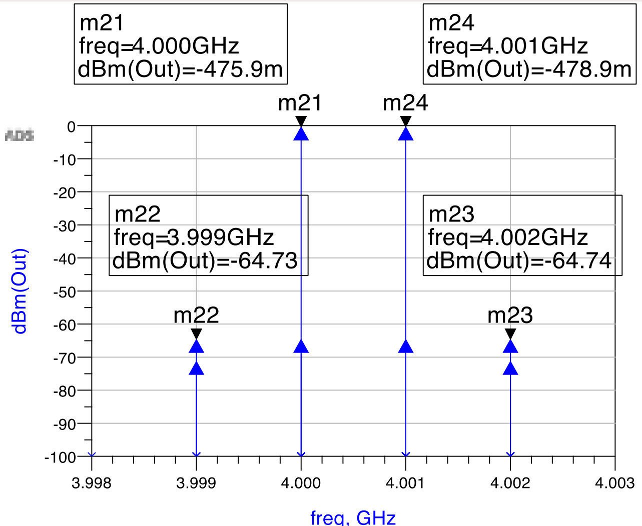
How to deal with very long lengths of cable?

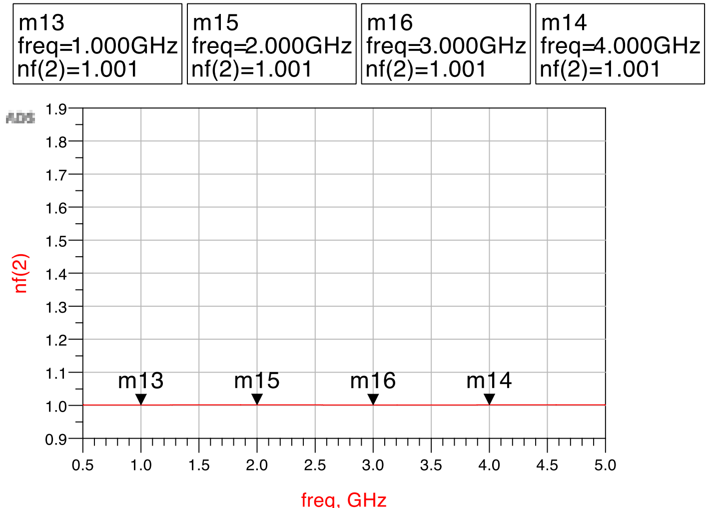
- As shown above extra long stretches of cable (or usage of poor cable) before active equalizer will worsen the system Noise Figure.
- Adding gain/slope will not improve the Noise Figure.



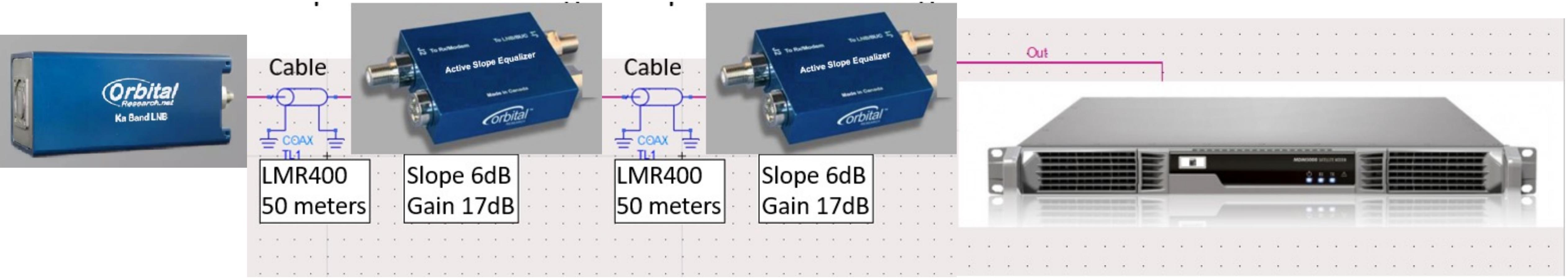
As a rule of thumb
If cable loss in dB
reaches half your
LNB Gain value,
expect NF
degradation



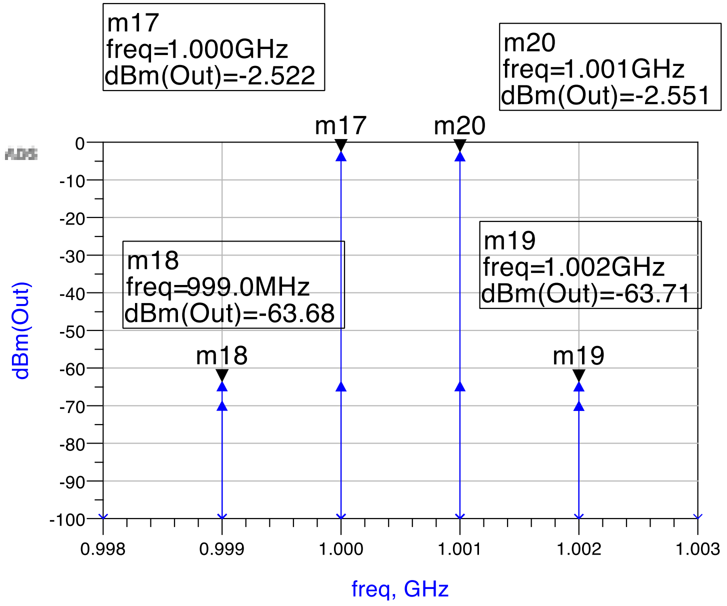


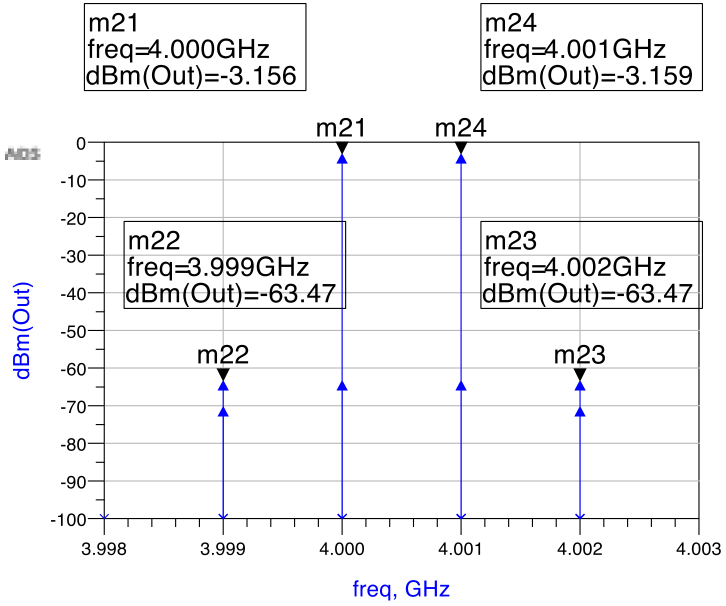


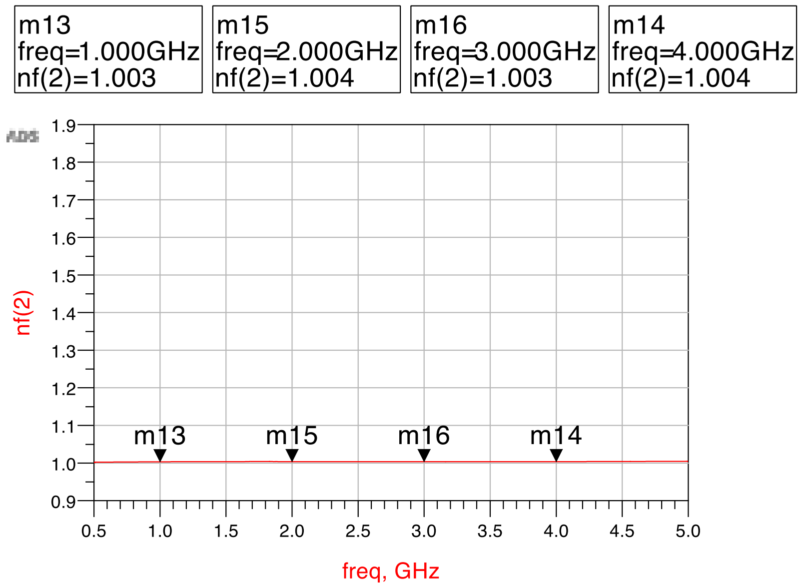
Feasible solution:

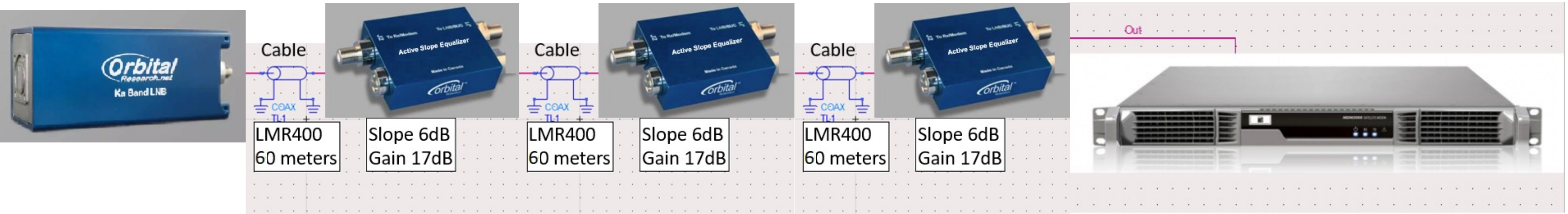


100 meters of LMR400 3 dB less power, no NF degradation and 4dB Intermodulation product degradation

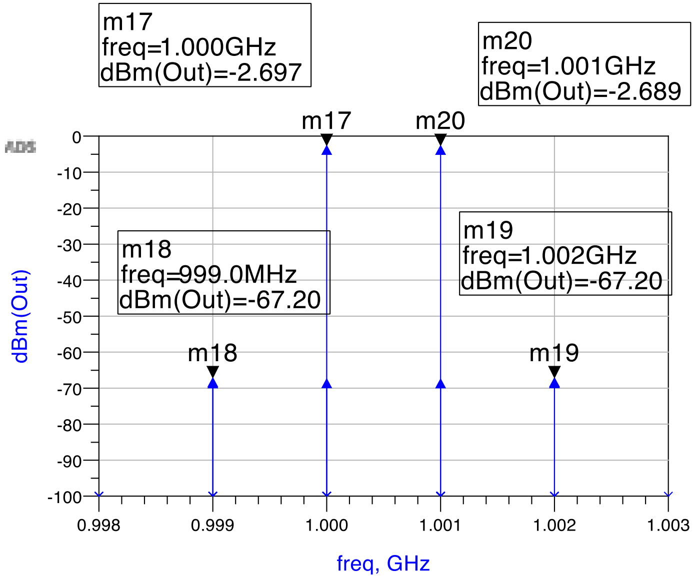


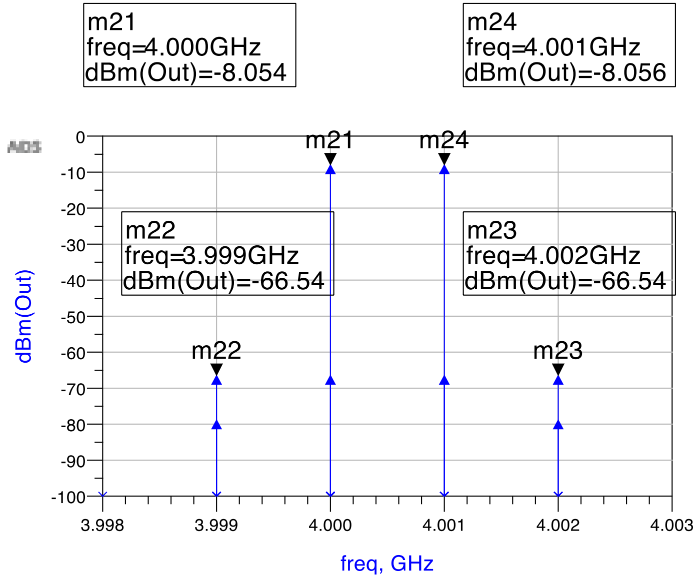


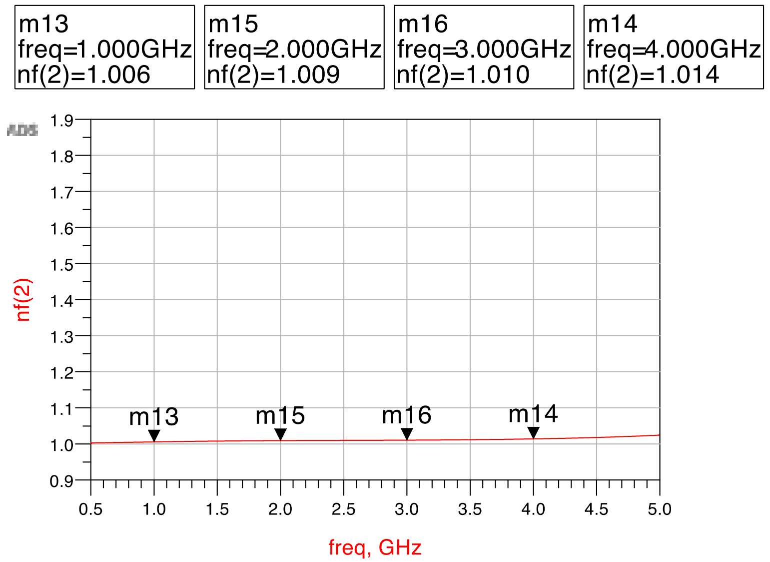




180 meters of LMR400 3 to 8 dB less power, no NF degradation and 6dB Intermodulation product degradation







*Some of the IMD degradation in above two examples come from co-existence of all four carriers in the same signal path

Conclusions

- One cannot get away with poor performance cables. The longer the cable the more pronounced is the difference between good cable and the poor one.
- It is possible to use thin RF cables such as LMR195 on short runs
- It is possible to have an active equalizer with adjustable gain and slope to compensate frequency dependent cable loss and still maintain system Noise figure and OIP3, provided that cable chosen is of good quality.
- It is possible to daisy chain cable length with in-line active equalizers to achieve minimum NF and IMD degradation.
- It is possible to utilize discrete slope settings to accommodate a variety of cable lengths. Adjustable gain is a must.

Reference

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- https://www.microwaves101.com/encyclopedias/coax-loss-due-to-dielectric-conduction
- https://www.timesmicrowave.com/DataSheets/Literature/Interpretation%20of%20electrical%20test%20data.pdf
- https://www.laird.com/products/microwave-absorbers/low-loss-dielectrics/eccostock-pp