

RF & Microwave Engineering 101

Final assignment

*By Oren Hagai, INTERLLIGENT RF & microwave solutions,
Email: Oren.H@int-RF.com*

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RF & Microwave Engineering 101, Final assignment

For submission by 25-SEP-2021

Email scanned homework to: llanit.k@int-RF.com

Your name: _____

Date of submission: _____

Answers summary, you may mark your final answers here:

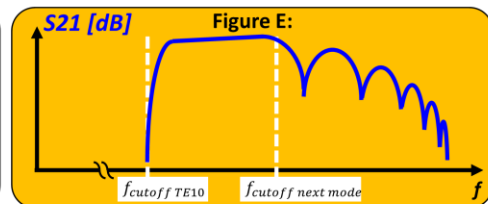
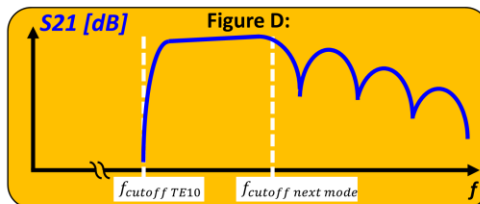
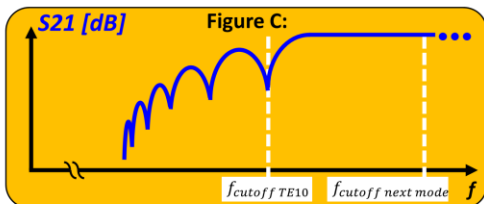
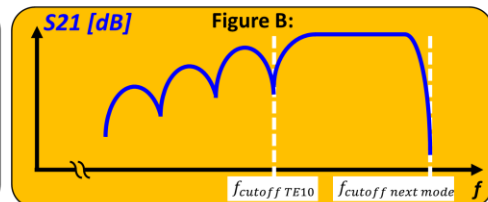
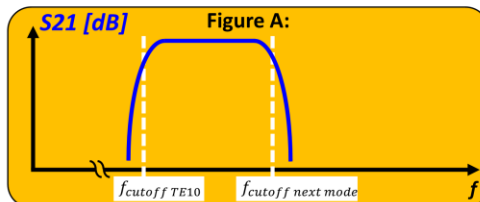
Question number	Subject	Select your choice					Your remarks	Mark
		1	2	3	4	5		
1	The "macro picture" of the S21 response of a waveguide							3%
2A	Free-Space Equivalent-Lengths (FSEL) of the 2 transmission lines							3%
2B	Shape of the time-domain impulse response of the RF channel							4%
2C	Shape of the frequency-domain response of the RF channel							4%
2D	Max. 16QAM bit rate, ISI not exceeding 10% symbol duration							3%
3A	Correct load-device and its components values							3%
3B	Fill-in table						Please fill-in and scan	3%
4A	Calculating the mormalised load parameters							3%
4B	Solving the "1 st half" of the matching problem: Length of TL1							4%
4C	Solving the "2 nd half" of the matching problem: Length of TL2							4%
5A	S21 Polar plot with through-adapter (electrically short)							3%
5B	S21 Polar plot with a cable as the DUT							3%
5C	S11 measurements with a cable as the DUT							3%
6A	Thermal noise power at the antenna's output							3%
6B	System's maximally allowed (worst case) Noise-Figure							3%
6C	RF front-end's output signal power to obtain F/S -2dB							3%
6D	Required system gain for the nominal signal at F/S-2dB							3%
6E	RF-Front-End's output noise power							3%
6F	Choosing RF bandpass filter's type for RF-BPF-1							3%
6G	Choosing type for RF-BPF-2 and frequency plan							3%
6H	Calculating system's (interferer) image-rejection (IRR)							3%
6I	Calculating excessive Noise Figure due to image-noise							3%
6J	Selecting the LNA-Type							3%
6K	Cascaded Gain and NF of the 4 first blocks							3%
6L	Calculating the required Gain of the IF amplifier							3%
6M	Max. allowed SNR degradation for the last sections							3%
6N	Cascaded OIP3 of the first 5 stages							3%
6O	The required system's minimal OIP3							3%
6P	The required IF amplifier's minimal OIP3							3%
6Q	ADC's actual SQNR when receiving the nominal signal							4%
6R	Maximally allowed clock-generators RMS jitter							5%
Total, 31 clauses								100%

Exercise 1: The “macro picture” of the S21 transmission frequency response of a rectangular waveguide.

With respect to a rectangular waveguide, with dimensions $a=2b$, select from the following alternatives the most accurate description of the “macro” picture of the waveguide’s transmission (S21) response over frequency.

It is recommended to look carefully and note the small differences between the figures given below:

With respect to the “macro” picture of the S21 transmission frequency response behavior of a rectangular waveguide, select the most accurate description from the following alternatives:

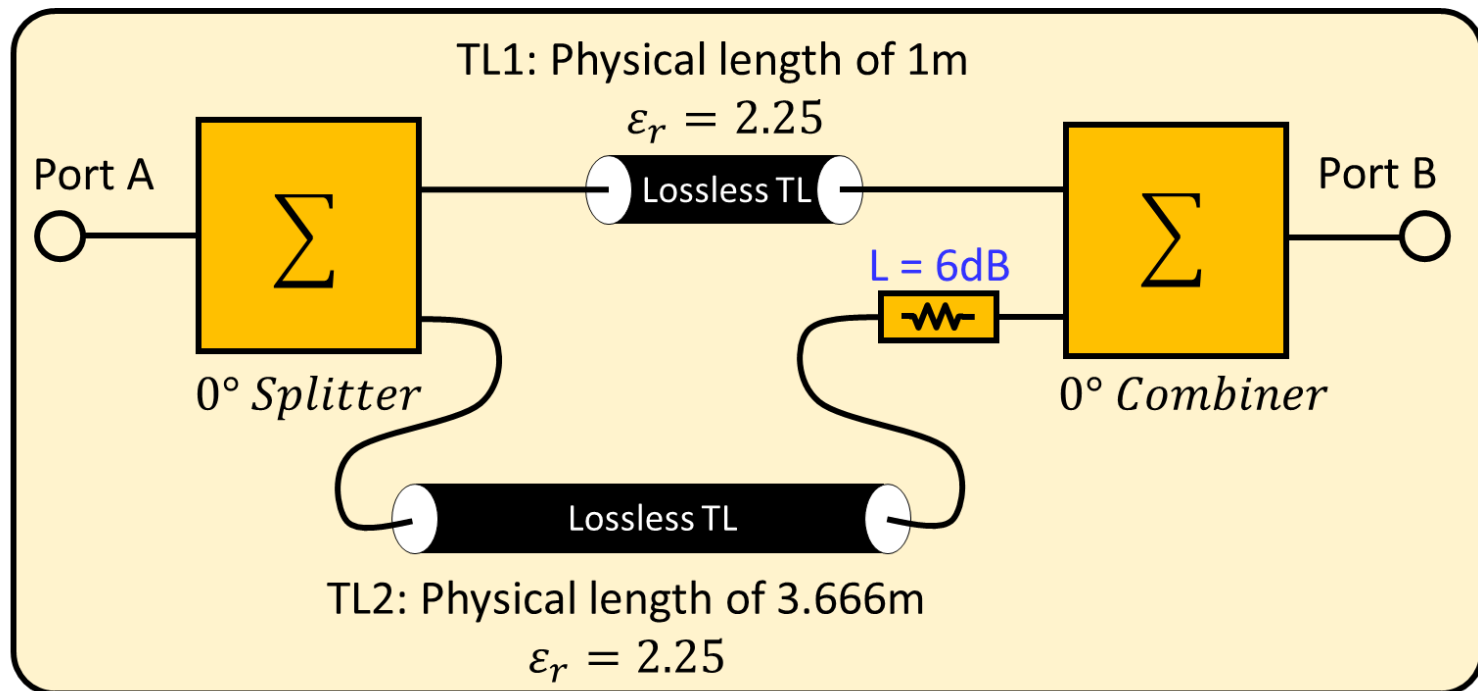


Select the most accurate description and figure, suitable to describe the waveguide’s “macro” (over large frequency spans) S21 frequency response behavior:

- 1-1: The S21 response is a bandpass response, with monotonic, sharp, roll-on and roll-off. The passband is the waveguide’s single-mode frequency band, and it is flat (Fig. A).
- 1-2: The S21 response includes a heavily rippled roll-on (with a fixed “FSR” - free spectral range spacing between ripple peaks), a flat passband and a sharp, monotonic roll-off (Fig. B).
- 1-3: The S21 response is a highpass response, which includes a heavily rippled roll-on (with an increasing with frequency “FSR” – free spectral range spacing between ripple peaks) and then a flat response at all frequencies higher than the TE10 cutoff frequency (Fig. C).
- 1-4: The S21 response includes a sharp, monotonic roll-on, a flat single-mode passband (with a possible small positive slope) and a heavily rippled roll-off in the over-moded frequency range (from the appearance of TE20 and upward in frequency), in which the FSR (free spectral range between ripple peaks) remains fixed as new modes arise at constant frequency offsets between each other (Fig. D).
- 1-5: The S21 response includes a sharp, monotonic roll-on, a flat single-mode passband (with a possible small positive slope) and a heavily rippled roll-off in the over-moded frequency range (from the appearance of TE20 and upward in frequency), in which the FSR (free spectral range between ripple peaks) is decreasing with frequency as new modes arise at decreasing frequency offsets between each other (Fig. E).

Exercise 2: The static multipath channel

A two-path channel (between ports A and B) is implemented by the following system, that includes 2 perfect passive splitters / combiners (0° phase imbalance, 0dB amplitude imbalance and infinite isolation between the two symmetrical splitting / combing ports), a 6dB attenuator and 2 lossless coaxial transmission lines. The transmission lines are of different physical lengths (1m and 3.666m), both with an identical dielectric coefficient of $\epsilon_r = 2.25$. You are requested to ignore the possible reflections between the devices in the system (i.e., to assume good matching between the devices). The electrical lengths of the splitters and the attenuator are negligible.



2A: What are the Free-Space Equivalent-Lengths (FSEL) of the 2 transmission lines?

Clarification / guidance:

The FSEL (Free-Space Equivalent Length) of a non-dispersive medium (such as a transmission line) is the length of its equivalent (in terms of phase accumulation and delay) free-space channel. In other words, the FSEL of a medium is the physical length of a free-space path with the same phase accumulation (and the same associated delay).

2A-1: The Free-Space Equivalent Length of TL1 and TL2 are: 0.444m and 1.36m respectively.

2A-2: The Free-Space Equivalent Length of TL1 and TL2 are: 0.666m and 2.444m respectively.

2A-3: The Free-Space Equivalent Length of TL1 and TL2 are: 1m and 3.666m respectively.

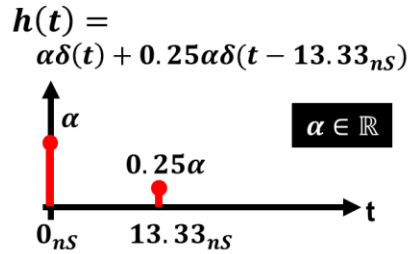
2A-4: The Free-Space Equivalent Length of TL1 and TL2 are: 1.5m and 5.5m respectively.

2A-5: The Free-Space Equivalent Length of TL1 and TL2 are: 2.25m and 8.25m respectively.

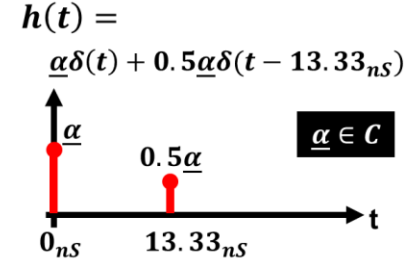
2B: What is the expected shape of the time-domain impulse response of the actual RF (**NOT Baseband representation**) channel between ports A and B? Select the correct figure from the following alternatives:

Alternatives for the RF channel's time-domain impulse response:
 α represents a certain reference amplitude.

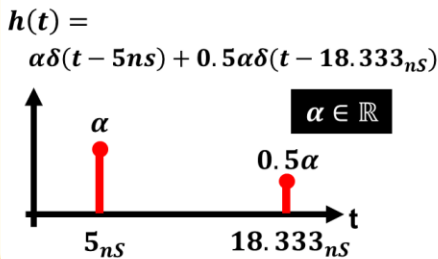
Alternative 2B-1 for the structure of the RF channel's impulse response:



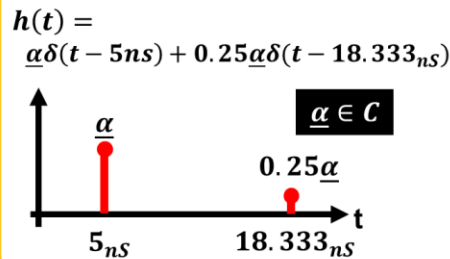
Alternative 2B-2 for the structure of the RF channel's impulse response:



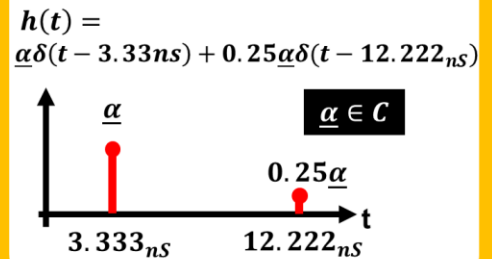
Alternative 2B-3 for the structure of the RF channel's impulse response:



Alternative 2B-4 for the structure of the RF channel's impulse response:



Alternative 2B-5 for the structure of the RF channel's impulse response:



Clarifications / guidance:

1. You are asked about the impulse response of the RF channel, not the equivalent Base-band channel. Consider this difference (between the RF and Baseband responses) with respect to the mathematical representation of the time-domain impulse response (either Real-valued or Complex valued).
2. Remember the time-domain impulse response of the channel, $h(t)$ represents a root-power ratio (a voltage / current or field transfer function), not a power-ratio. For example, in case we transmit an RF voltage $V_{TX(A)}(t)$ into port "A" of the channel, the received RF voltage at port "B" is expressed as the convolution of the time-domain input voltage with the channel's time-domain impulse response:

$$V_{RX(B)}(t) = V_{TX(A)}(t) * h(t) = \int_{-\infty}^{\infty} V_{TX(A)}(\tau) * h(t - \tau) d\tau$$

Hence, you are guided to consider the effect of the 6dB (in terms of power) attenuator, on $h(t)$ (the time-domain impulse response). In specific: How will a 6dB power ratio between the paths effect the **voltage ratios** between the 2 paths?

2B-1: The time-domain impulse response of the RF channel is **real-valued**, in accordance to figure 2B-1.

2B-2: The time-domain impulse response of the RF channel is **complex-valued**, in accordance to figure 2B-2.

2B-3: The impulse response of the RF channel is **real-valued**, in accordance to figure 2B-3.

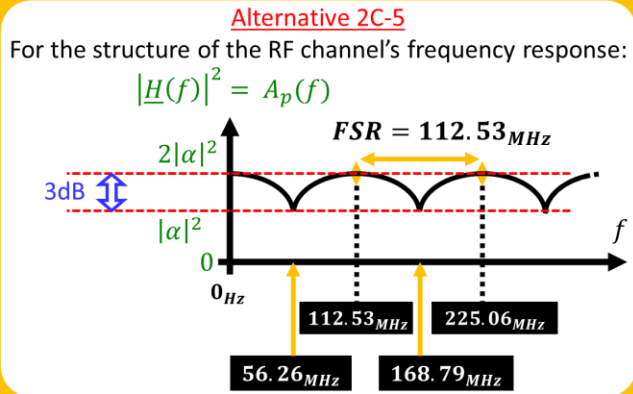
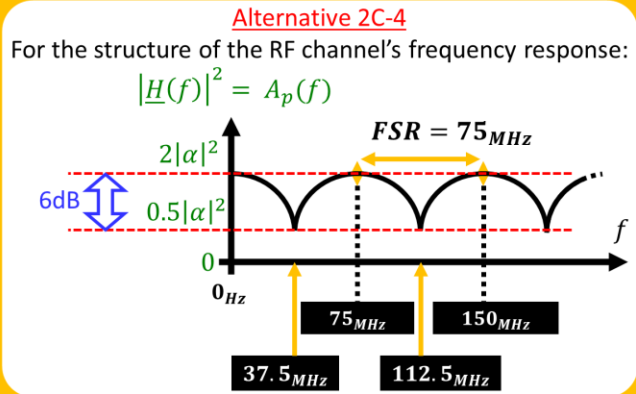
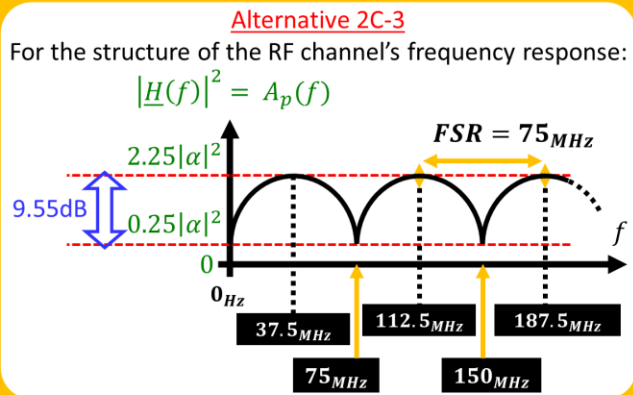
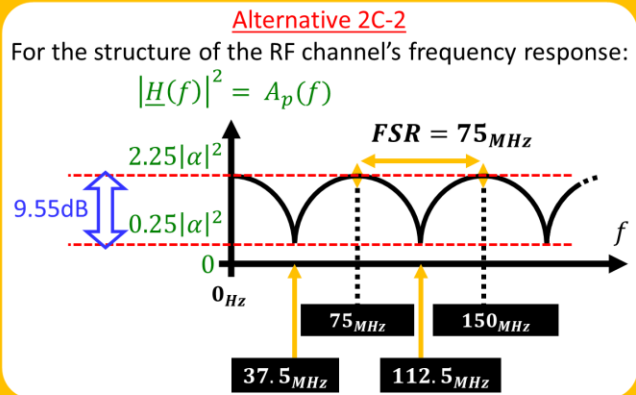
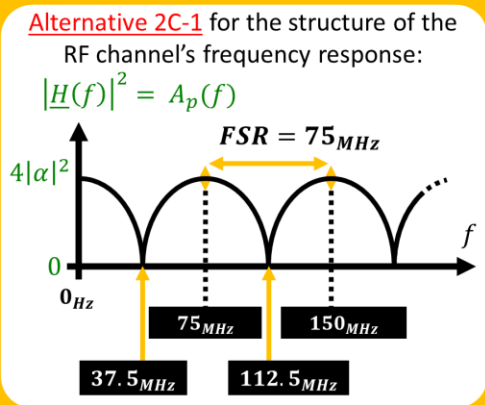
2B-4: The impulse response of the RF channel is **complex-valued**, in accordance to figure 2B-4.

2B-5: The impulse response of the RF channel is **complex-valued**, in accordance to figure 2B-5.

2C: What is the expected structure of the frequency-domain response of the actual RF (NOT Baseband) channel? Select the correct figure from the different alternatives.

Alternatives for the RF channel's frequency-domain response.

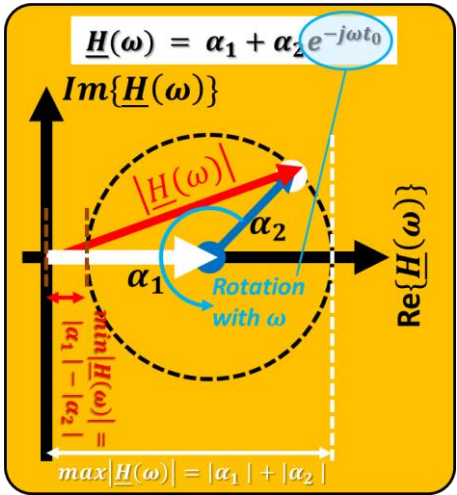
$|H(f)|^2 = A_p(f)$ represents the power amplification factor of the channel.
 α represents a certain reference amplitude.



A small hint for 2-C:

Select your answer:

- 2C-1: The freq. response of the RF channel is in accordance to figure 2C-1.
- 2C-2: The freq. response of the RF channel is in accordance to figure 2C-2.
- 2C-3: The freq. response of the RF channel is in accordance to figure 2C-3.
- 2C-4: The freq. response of the RF channel is in accordance to figure 2C-4.
- 2C-5: The freq. response of the RF channel is in accordance to figure 2C-5.



2D: For the given channel, in case a 16QAM Single-carrier transmitter connected to Port "a", while a suitable receiver is connected to port "B", what is the maximum achievable bit rate (assuming no source coding and no FEC, i.e., the transmitted bits are all information bits) with ISI that will not exceed 10% of a symbol duration?

Clarifications / guidance:

1. For complying with the ISI demand, the symbol duration needs to be 10x the channel's delay spread.
2. Remember that each 16QAM symbol carries $AR = 4$ bits.

2D-1: 75 Mbps: The maximum transmitted bit rate in a single-carrier 16QAM constellation that will guarantee that the ISI shall not exceed 10% of the symbol duration is $R_{info} = 75Mbps$.

2D-2: 300 Mbps: The maximum transmitted bit rate in a single-carrier 16QAM constellation that will guarantee that the ISI shall not exceed 10% of the symbol duration is $R_{info} = 300Mbps$.

2D-3: 7.5 Mbps: The maximum transmitted bit rate in a single-carrier 16QAM constellation that will guarantee that the ISI shall not exceed 10% of the symbol duration is $R_{info} = 7.5Mbps$.

2D-4: 30 Mbps: The maximum transmitted bit rate in a single-carrier 16QAM constellation that will guarantee that the ISI shall not exceed 10% of the symbol duration is $R_{info} = 30Mbps$.

2D-5: 29.63 Mbps: The maximum transmitted bit rate in a single-carrier 16QAM constellation that will guarantee that the ISI shall not exceed 10% of the symbol duration is $R_{info} = 29.63Mbps$.

Exercise 3: Subject: Basic properties of the Smith-chart

The following four S11 "Z" Smith diagrams provide normalised (by 50Ω) impedance VNA measurements, done at a fixed frequency of 100MHz. All "Marker 1" measurements provide identical results, obtained by directly measuring a (single) passive and linear "load device". The "Marker 2" measurements provide 4 different results, obtained by measuring the (same) load device via 4 different passive and linear "input networks".

S11 impedance measurements and measurement description:

Diagram 1: S11, CW at 100MHz

Normalised impedance by $Z_0=50\Omega$:

MKR-1: $0.35 + j0.4$

MKR-2: $0.1 + j0.4$

Diagram 2: S11, CW at 100MHz

Normalised impedance by $Z_0=50\Omega$:

MKR-1: $0.35 + j0.4$

MKR-2: $1.0 + j0.4$

Diagram 3: S11, CW at 100MHz

Normalised impedance by $Z_0=50\Omega$:

MKR-1: $0.35 + j0.4$

MKR-2: $0.35 + j1.0$

Diagram 4: S11, CW at 100MHz

Normalised impedance by $Z_0=50\Omega$:

MKR-1: $0.35 + j0.4$

MKR-2: $0.35 - j0.4$

MKR1 measurement:

Measurement 1

MKR2 measurement:

Measurement 2

Possible load-device configurations:

Possible input-network configurations:

3A: With respect to the "MKR 1" measurement, given the Smith-chart is a "Z" (impedance) chart, normalised to a characteristic impedance of $Z_0 = 50\Omega$, select the correct configuration from the possible load-device alternatives to suite the measured impedance at 100MHz, and calculate its components values:

- 3A-1: The only correct load device configuration is "1", with $R_p = 142.9\Omega$ and $L_p = 198.9\text{nH}$.
- 3A-2: The only correct load device configuration is "2", with $R_p = 142.9\Omega$ and $C_p = 12.73\text{pF}$.
- 3A-3: The only correct load device configuration is "3", with $R_s = 17.5\Omega$ and $C_s = 79.58\text{pF}$.
- 3A-4: There are two suitable configurations for the correct load device. The device may either be "4", with $R_s = 17.5\Omega$ and $L_s = 31.83\text{nH}$, or alternatively "1", with $R_p = 40.36\Omega$ and $L_p = 56.2\text{nH}$.
- 3A-5: The only correct load device configuration is "5", with $L_p = 89.8\text{nH}$ and $C_p = 12.42\text{pF}$.

3B: With respect to the given 4 Smith diagrams, fill-in the following table (not all fields are applicable). In case a field has no solution, fill "N/A" in that field. For the removal of doubt, all resistor values are positive.

The suitable input-network for the MKR-2 measurement:	Diagram 1	Diagram 2	Diagram 3	Diagram 4
Index of the input network:		<i>Example:</i> Input-network 1		
Value and units of the component in the network:		<i>Example:</i> $R_2 = 32.5\Omega$		

Exercise 4: Subject: Single-stub impedance-matching networks

For your convenience, an empty Smith-Chart is provided at the end of this exercise.

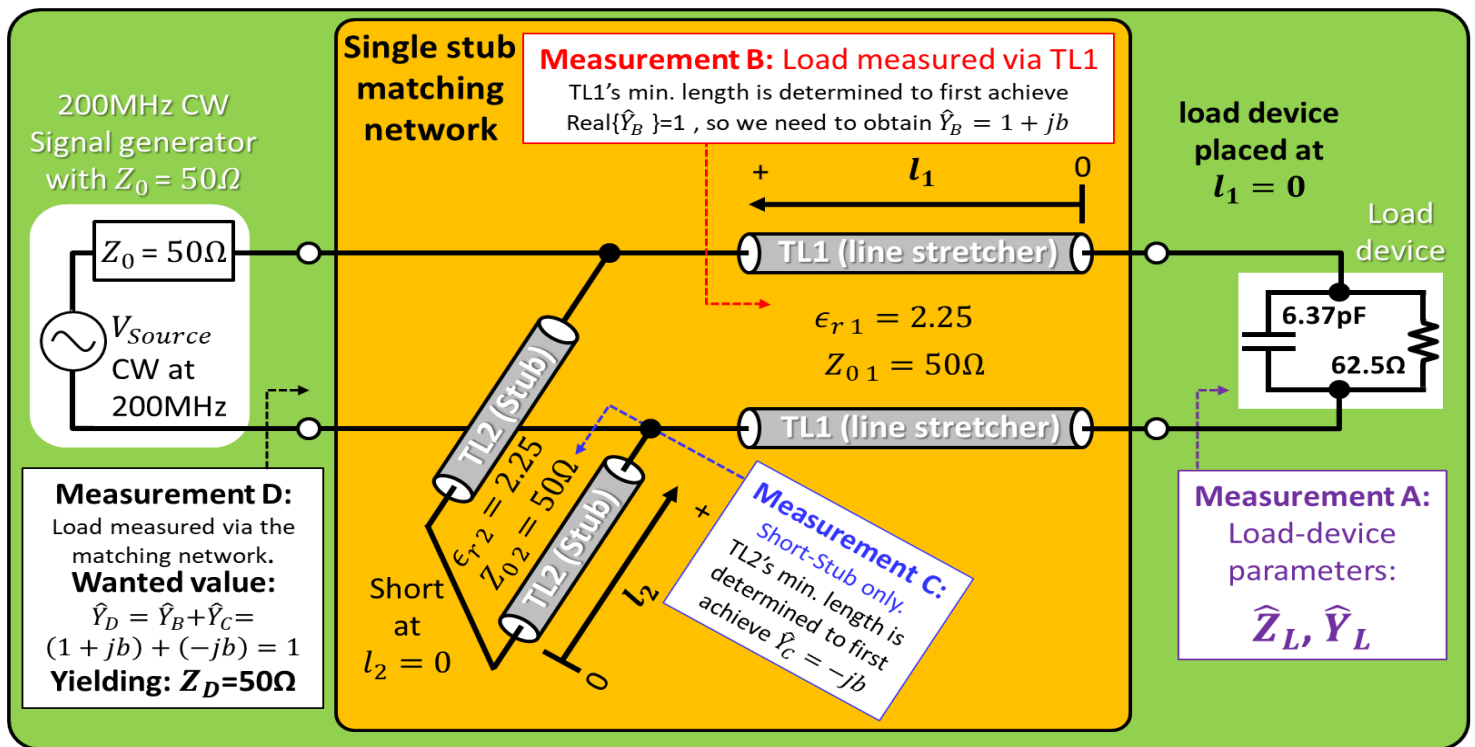
The following system shows a passive load-device (composed of a 62.5Ω resistor in parallel to a 6.37pF capacitor) that connected to a signal source with a characteristic impedance of $Z_0 = 50\Omega$, via a lossless single-stub tuning system. The source provides a CW tone at a fixed frequency of $f = 200MHz$.

The purpose of the single-stub matching network (tuner) is to provide maximum power to the load.

The single-stub matching network (tuner) is made of two lossless coaxial transmission lines:

- **TL1:** A lossless line-stretcher with a characteristic impedance $Z_{01}=50\Omega$, a relative permittivity $\epsilon_{r1}=2.25$ and a length of l_1 . The required length for TL1, is the minimal length that will provide a normalized admittance measurement with a real part of 1 (and some arbitrary susceptance, B): $\hat{Y}_B = 1 + jb$.
- **TL2:** A lossless Shunt Short-Stub (an ideal short circuit is placed at $l_2=0$) with a characteristic impedance $Z_{02}=50\Omega$, a relative permittivity $\epsilon_{r2}=2.25$ and a length of l_2 . The required length for TL2, is the minimal length that will provide a normalized admittance measurement with an imaginary part of (-b), required for obtaining perfect matching at the system's input, reference plane "D".

Four impedance (or admittance) measurement reference planes (marked: A, B, C and D) are defined, according to the following schematic:



4A: Calculating the normalised load parameters: With respect to measurement reference plane "A" (load impedance / admittance measurement), the given frequency and the load components values, what is the load's normalised (by $Z_0=50\Omega$) impedance, $\hat{Z}_L \triangleq \frac{Z_L}{Z_0}$ and its normalised (by $Y_0=0.02\Omega$) admittance, $\hat{Y}_L \triangleq \frac{Y_L}{Y_0}$?

- 4A-1:** The normalised impedance is $\hat{Z}_L = 1 - j0.5$ and the normalised admittance is $\hat{Y}_L = 0.8 + j0.4$.
- 4A-2:** The normalised impedance is $\hat{Z}_L = 1 + j0.5$ and the normalised admittance is $\hat{Y}_L = 0.8 - j0.4$.
- 4A-3:** The normalised impedance is $\hat{Z}_L = 1.25 - j2.5$ and the normalised admittance is $\hat{Y}_L = 0.16 + j0.32$.
- 4A-4:** The normalised impedance is $\hat{Z}_L = 1 - j2$ and the normalised admittance is $\hat{Y}_L = 0.2 + j0.4$.
- 4A-5:** The normalised impedance is $\hat{Z}_L = 1.25 - j0$ and the normalised admittance is $\hat{Y}_L = 0.8 + j0$.

4B: **Solving the "first half" of the matching problem: Determining the required length of TL1.**

As a first step towards solving the matching problem, we will now calculate the minimal required length for the first transmission line (TL1), that acting as a phase-shifter (or "line stretcher"). As we should remember, TL1's minimal length can be obtained using the Smith chart (see next page), while circling clockwise (because TL1 stretches from the load, with positive length toward the generator) around the centre of the diagram (in a fixed $|\Gamma|$ circle) from the \hat{Y}_L point (, to the (first) meeting of the $\text{Real}\{\hat{Y}_B\}=1$ circle.

With respect to the 5 different diagrams **that are provided in the next page**, what is the minimal possible length (in terms of λ_r , i.e., wavelengths within the cable) for TL1?

4B-1: The minimum electrical length for TL1 that is required for obtaining a unity real-part for \hat{Y}_B is $l_1 = 0.0387\lambda_r$, as presented by diagram 1.

4B-2: The minimum electrical length for TL1 that is required for obtaining a unity real-part for \hat{Y}_B is $l_1 = 0.0387\lambda_r$, as presented by diagram 2.

4B-3: The minimum electrical length for TL1 that is required for obtaining a unity real-part for \hat{Y}_B is $l_1 = 0.25\lambda_r$, as presented by diagram 3.

4B-4: The minimum electrical length for TL1 that is required for obtaining a unity real-part for \hat{Y}_B is $l_1 = 0.125\lambda_r$, as presented by diagram 4.

4B-5: The minimum electrical length for TL1 that is required for obtaining a unity real-part for \hat{Y}_B is $l_1 = 0.2113\lambda_r$, as presented by diagram 5.

4C: **Solving the "second half" of the matching problem: Determining the required length of TL2.**

With respect to your previous electrical-length selection for TL1, this selection dictates a certain $\hat{Y}_B = 1 + jb$ that has a unity real-part (conductance), and some (unwanted) imaginary part (susceptance), "b". The essence of the parallel stub, TL2, is to provide an antipodal (to \hat{Y}_B) susceptance, explicitly: $\hat{Y}_{C, \text{wanted}} = 0 - jb$. When this is achieved and the TL2 stub is connected in parallel to the end of TL1 (as shown in the tuner's schematic), the tuner will yield an overall input admittance of $\hat{Y}_{D, \text{wanted}} = \hat{Y}_B + \hat{Y}_C = (1 + jb) + (0 - jb) = 1$, implying perfect input matching.

Given the frequency of operation (200MHz), the admittance \hat{Y}_B dictated by your previous selection of TL1's length, the relative permittivity of TL2 ($\epsilon_{r2}=2.25$) and the fact that TL2 begins (at $l_2 = 0$) by a perfect short-circuit, what is the minimal required **physical-length** for TL2, to obtain perfect input matching?

For your convenience, an empty Smith-Chart is provided at the end of this exercise.

4C-1: The minimum physical length for TL2 for perfect input matching is $PL2 = 17.6\text{cm}$

4C-2: The minimum physical length for TL2 for perfect input matching is $PL2 = 26.4\text{cm}$

4C-3: The minimum physical length for TL2 for perfect input matching is $PL2 = 39.6\text{cm}$

4C-4: The minimum physical length for TL2 for perfect input matching is $PL2 = 32.4\text{cm}$

4C-5: The minimum physical length for TL2 for perfect input matching is $PL2 = 48.6\text{cm}$

Selection for clause 4B: Possible Smith diagrams for the selection of the required electrical length for coaxial transmission line #1:

Diagram 1:

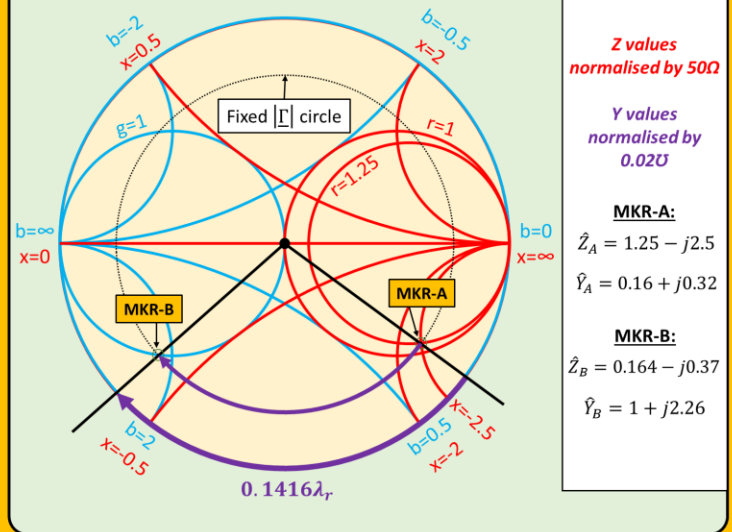


Diagram 2:

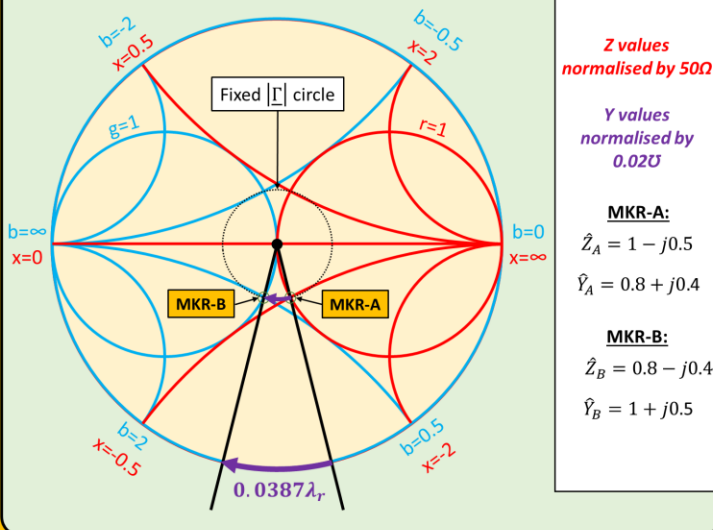


Diagram 3:

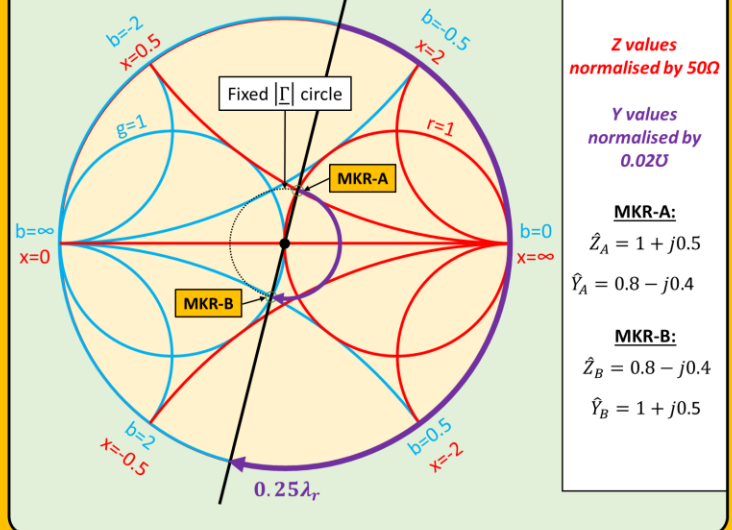


Diagram 4:

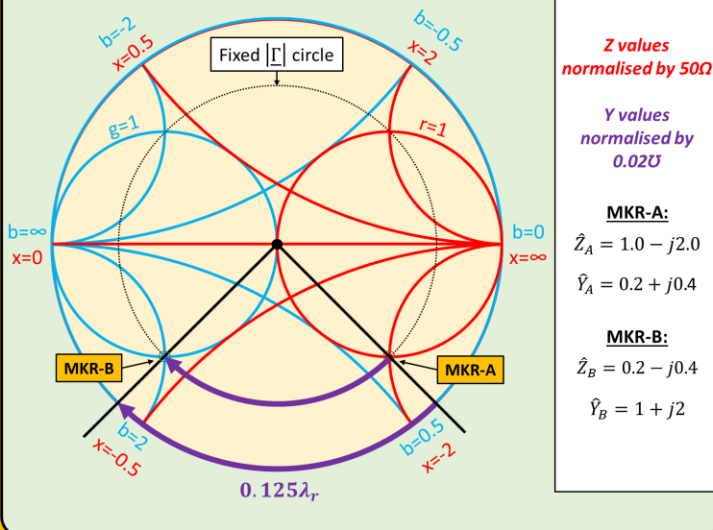
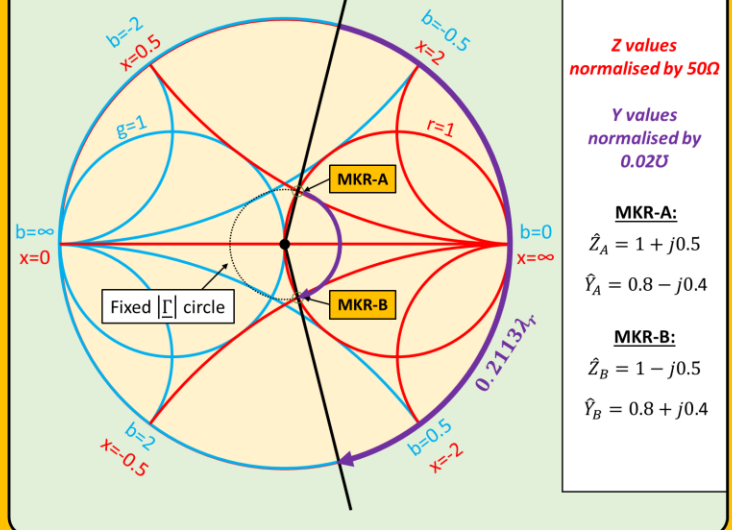
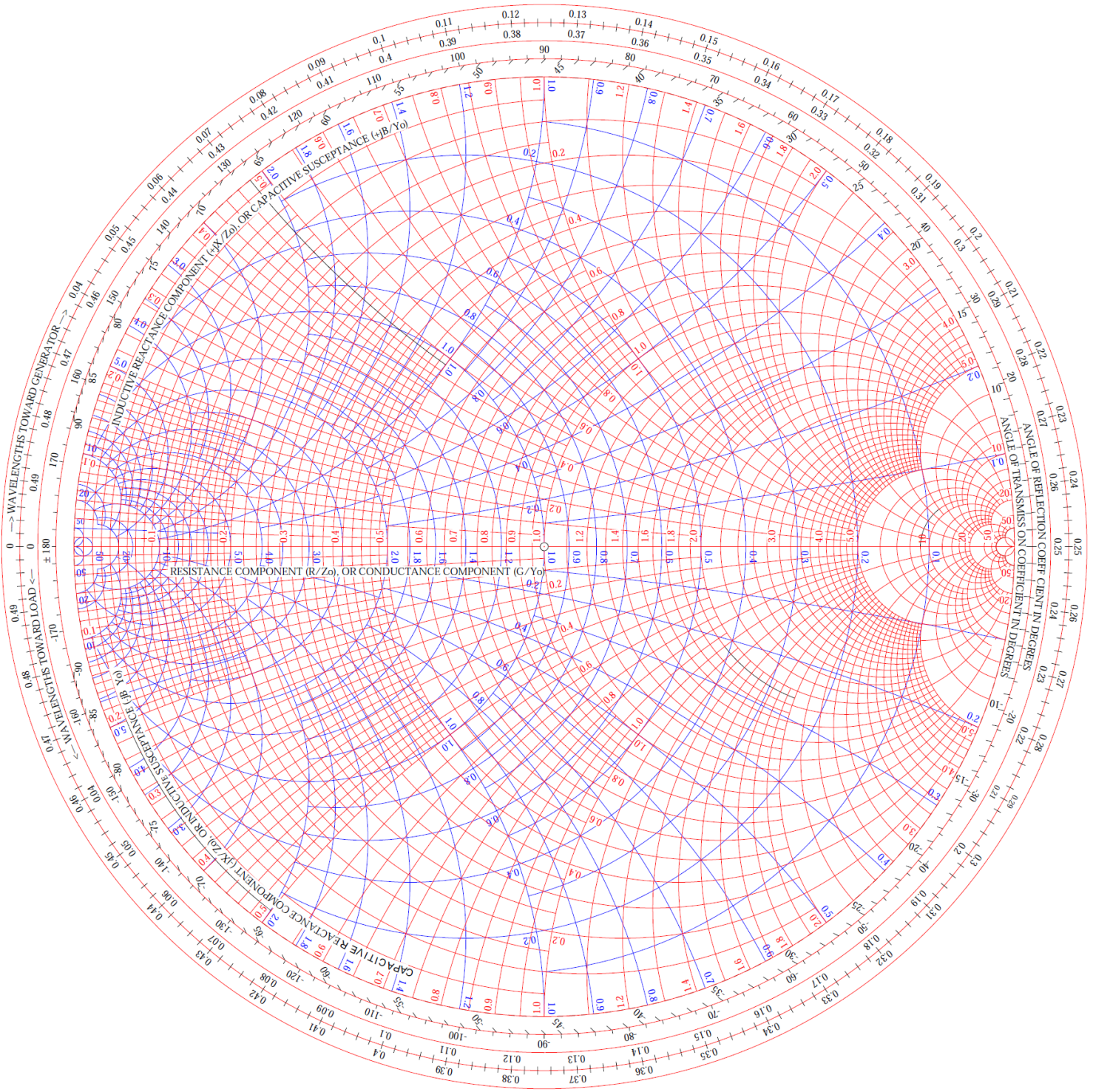


Diagram 5:



Smith Chart for exercise 4:

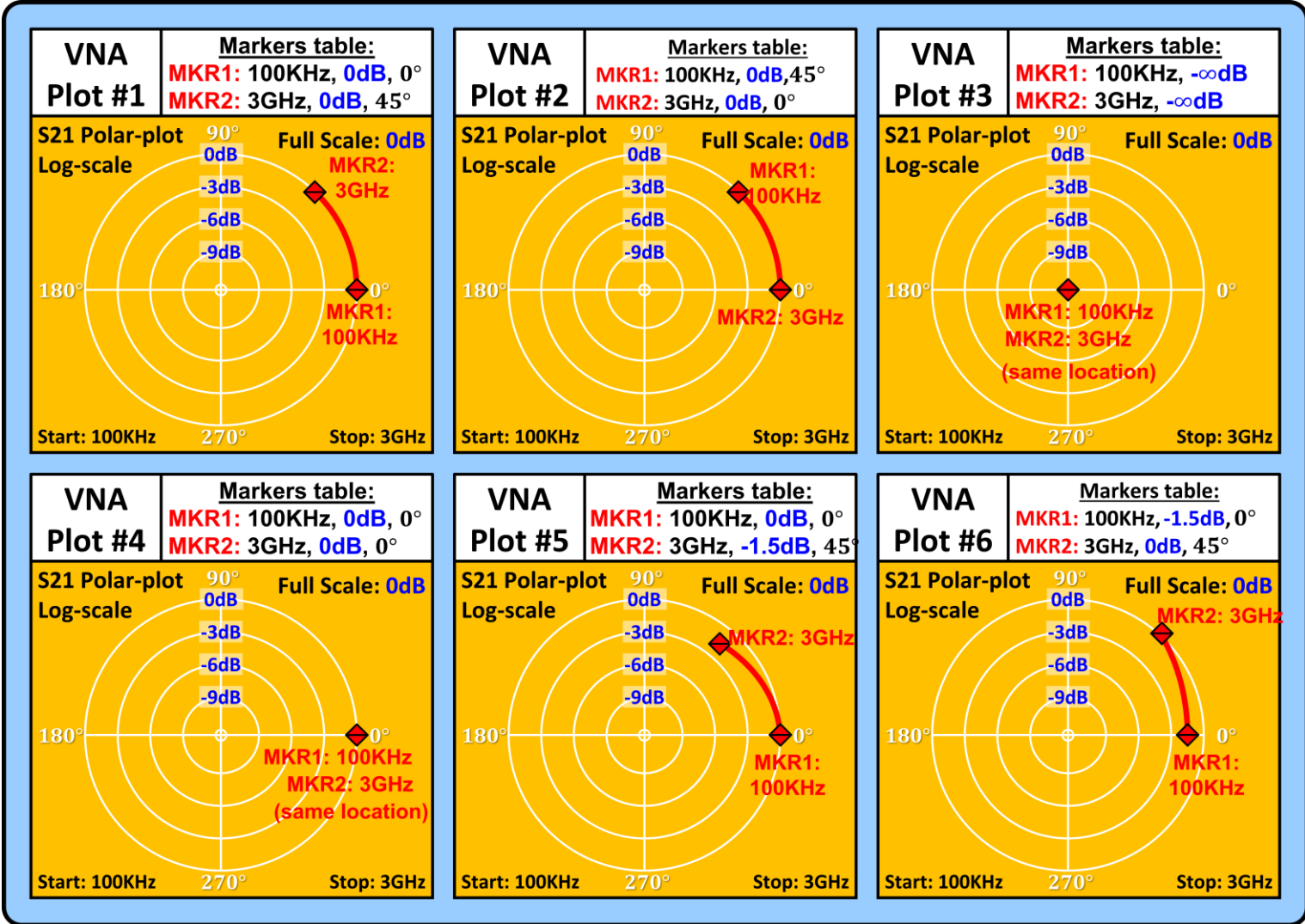


Exercise 5: Subject: VNA measurements

A two-port Vector Network Analyser (VNA) is capable of measuring S-parameters in the frequency range of 100KHz to 3GHz. The user has connected two test-port cables to the 2 VNA ports and performed a full-2-port calibration procedure, in order to include the 2 test port cables within the calibrated VNA measurement. In other words, after the calibration, the phase and amplitude reference planes have shifted to the "DUT" ends (sides) of the 2 test-port cables. **To answer clauses 5A-C refer to the S21 Polar plots given in the next page.**

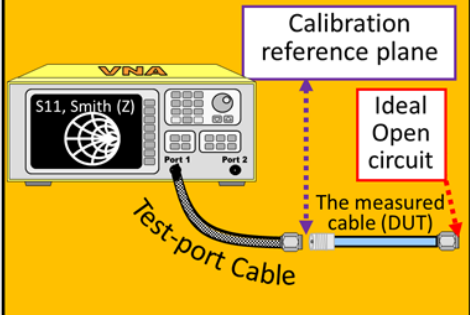
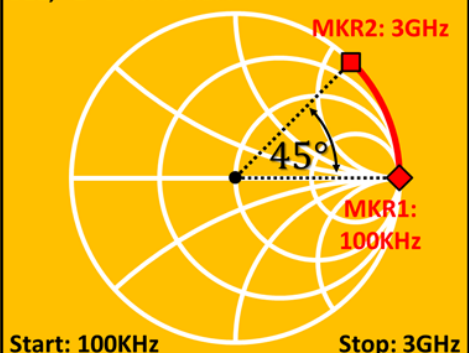
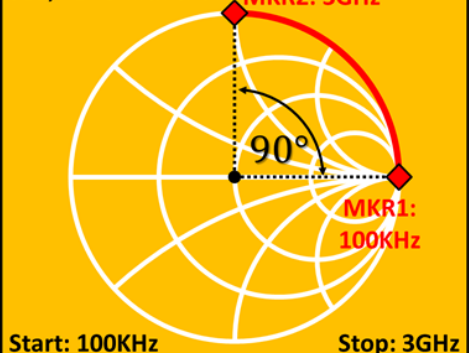
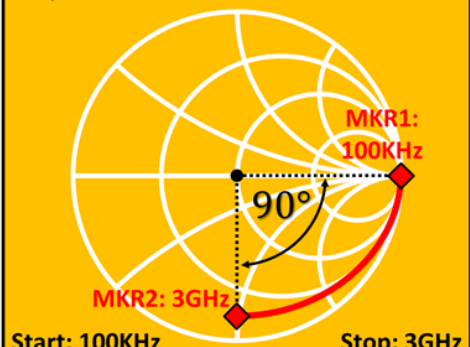
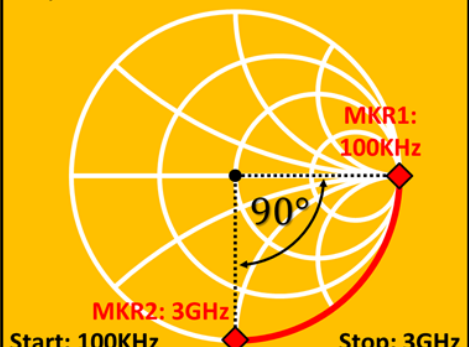

- 5A: After calibrating the VNA including its 2 test-port cables, the user connected an electrically-short "Through" adapter (the adapter's electrical length and its insertion loss can be considered as negligible) between the 2 "DUT" ends of the test-port cables, in order to connect their "DUT" ends together. The user then selected an S21 measurement in Polar-plot format. Which one of the 6 alternative plots presented above shows the expected measurement result, under the above specified conditions, and why?
- 5A-1: The expected result appears in plot #1. The plot shows the calibrated insertion gain of the 2-test port cables (0dB) and their transmission phase accumulation, which linearly increases over frequency.
- 5A-2: The expected result appears in plot #2. The plot shows the calibrated insertion gain of the 2-test port cables (0dB) and their transmission phase accumulation, which linearly decreases over frequency.
- 5A-3: The expected result appears in plot #3. The plot describes a negligible voltage transmission coefficient (Implying good impedance matching between the test cables).
- 5A-4: The expected result appears in plot #4. The plot shows the (negligible) insertion gain and phase accumulation of the through adapter. Since the through adapter has negligible loss and electrical length, this plot implies that the calibration process has been successful.
- 5A-5: The expected result appears in plot #5. The plot shows the (increasing with frequency) insertion loss of the 2 test-port cables (together) and their (also increasing with frequency) insertion phase accumulation.
- 5B: Now, after calibrating the VNA including its 2 test-port cables, the user has connected between the 2 "DUT" ends of the test-port cables, a DUT which is a coaxial cable by itself. The DUT (the measured coaxial cable) has a given **velocity factor of $VF = 2/3$** . The S21 measurement result is given by plot #5. Which of the following paragraphs best describes the interpretation of the measurement (as presented by plot #5)?
- 5B-1: The measurement indicates that both the insertion **gain** and the insertion phase of the measured cable, increase with (increasing) frequency. In particular, the DUT's insertion phase accumulation at $f = 3GHz$ is $\Delta\theta = 45^\circ$ and the DUT's **gain** at that frequency is **1.5dB**.
- 5B-2: The measurement indicates that both the insertion **loss** and the insertion phase of the measured cable, increase with (increasing) frequency. In particular, the DUT's **loss** at $f = 3GHz$ is **1.5dB** and its electrical length at that frequency is $\lambda_r/8$ (one eighth **of the signal's wavelength within the measured cable**). Therefore, we can conclude that the physical length of the measured cable (DUT) is $PL = 0.833cm$.
- 5B-3: The measurement indicates that both the insertion **loss** and the insertion phase of the measured cable, increase with (increasing) frequency. In particular, the DUT's **loss** at $f = 3GHz$ is **1.5dB** and its electrical length at that frequency is $\lambda_0/8$ (one eighth **of the signal's free-space wavelength**). Therefore, we can conclude that the physical length of the measured cable (DUT) is $PL = 1.25cm$.
- 5B-4: The measurement indicates that both the insertion **loss** and the insertion phase of the measured cable, increase with (increasing) frequency. Since S21 measurements present the phase and gain accumulated over a "round trip" along the DUT's length (wave propagation forward and then backwards), the DUT's **loss** at $f = 3GHz$ is **0.75dB** and its electrical length at that frequency is $\lambda_r/16$ (one sixteenth **of the signal's wavelength within the measured cable**). Therefore, we can conclude that the physical length of the measured cable (DUT) is $PL = 0.4166cm$.
- 5B-5: The measurement indicates that both the insertion **loss** and the insertion phase of the measured cable, increase with (increasing) frequency. The electrical length and physical length of the measured cable (DUT) **cannot be determined**, since an unknown integral number of 360° phase accumulation intervals may have been accumulated over the measurement frequency range between 100MHz to 3GHz, while the measurement only provides phase within a single 360° phase interval.

VNA Polar plots for exercise 5:



Exercise 5 is continued in the following page...

5C: Now, the user has selected an S11 measurement and has completed a one-port calibration for port 1 to embed the test-port cable of port 1 in the calibration. In other words, the calibrated measurement's reference plane was set at the "DUT" end of port 1's test cable. As a Device Under Test (DUT), the user connected the same coaxial cable that was measured during the previous clause (for which plot 5 provides its S21 measurement in Polar format). One end of the measured cable (DUT) was connected to the "DUT" end of port 1's test-port cable, while the other end of the measured cable was left open without connection (assume an ideal "open circuit"). Which one of the following VNA plots provides the expected measurement result?

<p>The measurement set-up:</p> 	<p>VNA Plot "A"</p> <p>Markers table: MKR1: 100KHz, RL=0dB, 0° MKR2: 3GHz, RL=0dB, 45°</p>	<p>VNA Plot "B"</p> <p>Markers table: MKR1: 100KHz, RL=0dB, 0° MKR2: 3GHz, RL=0dB, 90°</p>
	<p>S11, "Z" Smith chart</p>  <p>Start: 100KHz Stop: 3GHz</p>	<p>S11, "Z" Smith chart</p>  <p>Start: 100KHz Stop: 3GHz</p>
<p>VNA Plot "C"</p> <p>Markers table: MKR1: 100KHz, RL=0dB, 0° MKR2: 3GHz, RL=-3dB, -90°</p>	<p>VNA Plot "D"</p> <p>Markers table: MKR1: 100KHz, RL=0dB, 0° MKR2: 3GHz, RL=0dB, -90°</p>	<p>VNA Plot "E"</p> <p>Markers table: MKR1: 100KHz, RL=0dB, 0° MKR2: 3GHz, RL=0dB, -45°</p>
<p>S11, "Z" Smith chart</p>  <p>Start: 100KHz Stop: 3GHz</p>	<p>S11, "Z" Smith chart</p>  <p>Start: 100KHz Stop: 3GHz</p>	<p>S11, "Z" Smith chart</p>  <p>Start: 100KHz Stop: 3GHz</p>

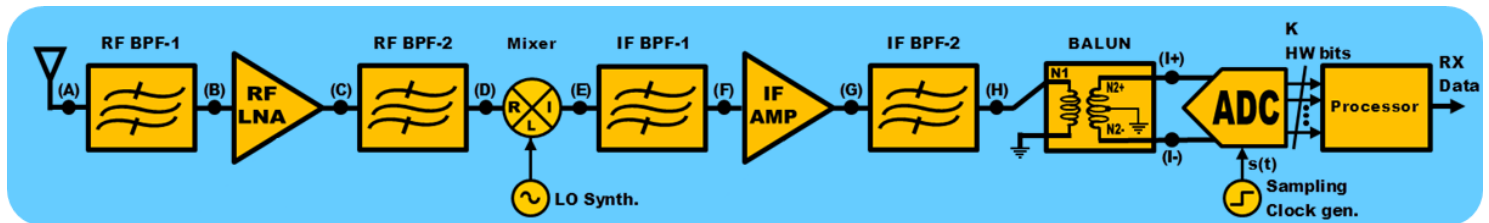
Select the correct result:

- 5C-1: The expected measurement result is given in VNA plot A.
- 5C-2: The expected measurement result is given in VNA plot B.
- 5C-3: The expected measurement result is given in VNA plot C.
- 5C-4: The expected measurement result is given in VNA plot D.
- 5C-5: The expected measurement result is given in VNA plot E.

Exercise 6: Receiver's system design

The exercise covers the subjects of Noise Figure, Linearity, Receiver architecture and ADCs. You will be requested to design the RF front-end chain by selecting the appropriate blocks and calculating the resulting system performance metrics. A minimum RF specifications table is given below, and your design needs to meet the specifications.

In this exercise you are requested to complete the design of a heterodyne RF front end, for a satellite telephony ("Iridium") application with a block diagram as follows:



It is given that the antenna provides an output thermal noise density of $N_A = N_0$ and that the Balun is lossless in terms of power dissipation. All the passives in the chain (4 filters and one Balun) may be considered as totally linear devices.

The receiver's minimum required specifications:

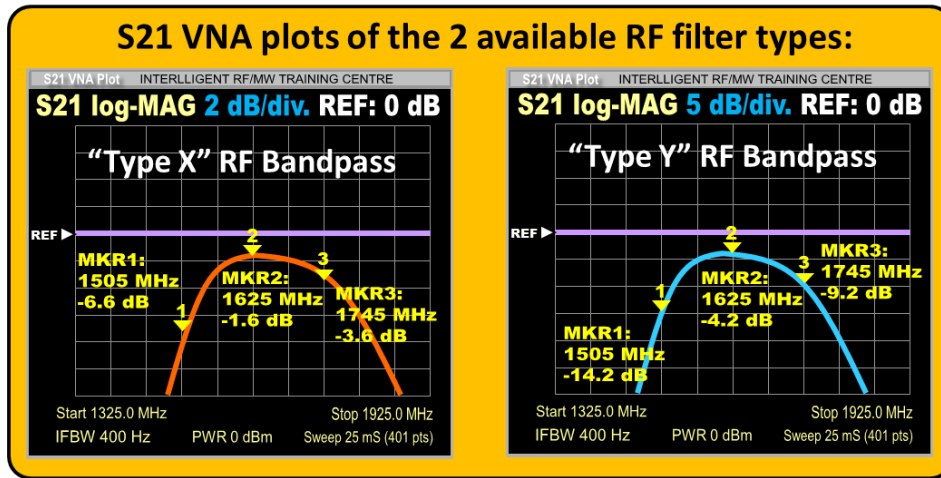
Parameter:	Symbol	value	Units	Remarks
Received centre frequency	f_{RF}	1.625	GHz	The receiver is tuned to this fixed frequency only
Channel bandwidth:	B	41.667	KHz	Noise equivalent BW for SNR calculations
IF out centre frequency	f_{IF}	60	MHz	
Worst case (minimum) system's image interferer rejection:	$IRR_{System, min}$	12	dB	Rejection for received signals at the image frequency compared to the wanted RF frequency, for the system, i.e., overall rejection from point (a) to (H).
Minimum (threshold) output SNR for acceptable BER	$SNR_{out TH (H)}$	17.1	dB	Measured at point (H) for over the channel's bandwidth
System's sensitivity	$P_{Sig in TH (A)}$	-106	dBm	Minimum required received power at point (A) to obtain the given minimum 17.1dB (threshold) output SNR at point H for over the channel's bandwidth.
Expected (Nominal, planned value) received signal power	$P_{Sig in Nominal (A)}$	-70	dBm	This is the expected received signal power according to the planned link-budget. In other words, the link budget is planned with a 36dB Fade margin between this nominal value and the sensitivity level.
ADC backoff from full-scale when receiving the expected (nominal) signal:	$ADC_{Back-Off}$	2	dB	Required ADC backoff from F/S, when receiving the expected (nominal) received signal above. This B/O will be considered for calculating the actual SQNR when receiving the expected (nominal) signal.
ADC's sampling rate	f_{samp}	80	MHz	Can also be measured in Msamp/Sec
Minimal system's output SFDR3	$SFDR3_{out (H)}$	60	dBc	The minimal required system's output SFDR3, calculated according to the given channel's Noise Equivalent bandwidth.
RF path characteristic impedance	Z_0	50	Ω	For the components of the RF front end, between points A to H.

Your available components:

Your design is limited to the following available components only. You are requested to select the most suitable components to meet the specifications.

2 available RF bandpass filter types:

There are 2 available types (models / part numbers) of RF bandpass filters you may use: "Type X" and "Type Y". You are requested to choose the correct combination of the "Type X" / "Type Y" filter types to play the roles of the 2 filters "RF BPF 1" and "RF BPF 2", that will allow the system to meet its required specifications. To meet the specifications, you may need to select just a single filter type (i.e., using 2 identical units of a given type) for playing the roles of the 2 RF filters ("RF BPF 1" and "RF BPF 2"), or to decide on a combination of the 2 filter types ("X and Y") to implement these blocks, while deciding on their placement order (which type to play the role of each RF filter). You may assume the filters are perfectly matched in their passband and that they are also totally linear. The S21 VNA responses of the 2 available filter types are given below:



2 available RF LNA types:

There are two available types (models / part numbers) of RF LNA amplifiers that you may use: "Type W" and "Type Z". You are requested to choose a single "correct" type to play the role of the LNA in order to meet the specifications. Here are the basic specifications of the 2 available LNA types:

Parameter	"Type W" RF amplifier	"Type Z" RF amplifier	Remarks
Small signal gain	$G_W = 24$ dB	$G_Z = 27$ dB	Flat over frequency
NF	$NF_W = 1.3$ dB	$NF_Z = 3.3$ dB	Flat over frequency
OIP3	$OIP3_W = +18.7$ dBm	$OIP3_Z = +34$ dBm	Flat over frequency

The available Mixer:

The available mixer has the following RF specifications:

- Conversion loss (RF to IF, flat over frequency): $CL_{Mixer} = 8$ [dB]; This can be used also as the device's SSB NF.
- Input IP3 (RF port to IF port): $IIP3_{Mixer} = +27$ [dBm]

Available IF filters:

You may use any kind of IF bandpass filter. The only limitation you need to consider is an insertion loss (per each "functional block" of filter) of $IL_{IF Filter} = 0.5$ [dB]. The IF filters can be considered as totally linear devices.

ADC and Balun:

- The Balun can be seen as a lossless transformer (i.e., without power losses) which is also totally linear.
- The ADC is of **FLASH** technology, with $K=8$ hardware bits and an implementation constant of $C = 1.78$ bits.
- The ADC's input resistance (measured between the points I+ and I-) is $R_{in ADC} = 1,200\Omega$.
- The ADC's **peak-to-peak** full-scale input voltage (measured between the points I+ and I-) is $V_{FS} = 2V_{p-p}$
- The ADC's sampling rate is $f_{Samp} = 80_{Ms/Sec}$

You may find it convenient to fill-in the details of your findings during this exercise in the following table (optional):

Stage:	<u>Stage 1:</u> RF-BPF1	<u>Stage 2:</u> LNA	<u>Stage 3:</u> RF-BPF2	<u>Stage 4:</u> Mixer	<u>Stage 5:</u> IF-BPF1	<u>Stage 6:</u> IF-AMP	<u>Stage 7:</u> IF-BPF2
Location in schematic:	(A)→(B)	(B)→(C)	(C)→(D)	(D)→(E)	(E)→(F)	(F)→(G)	(G)→(H)
SSB NF:	___ [dB]	___ [dB]	___ [dB]	8 dB	___ [dB]	___ [dB]	___ [dB]
Stage Gain:	___ [dB]	___ [dB]	___ [dB]	-8 dB	-0.5 dB	___ [dB]	-0.5 dB
Stage OIP3:	∞ dBm	___ [dBm]	∞ dBm	___ [dBm]	∞ dBm	___ [dBm]	∞ dBm
Stage's Image rejection ratio:	___ [dB]	N/A	___ [dB]	N/A	N/A	N/A	N/A
Selected type:	X / Y	W / Z	X / Y	N/A	N/A	N/A	N/A
Remarks:							

6A: Calculating the thermal noise power at the antenna's output:

Considering the given thermal noise density at the receiving antenna's output, $N_A = N_0$ and the given channel's bandwidth, $B = 41.667\text{KHz}$, calculate the thermal noise power that is accumulated over the channel bandwidth, provided into the RF chain by the receiving antenna, $P_{Noise\ 0\ (A)}$.

Round your result to the closest 0.1dB value.

6A-1: The thermal noise power at the antenna's output at the given bandwidth is: $P_{Noise\ 0\ (A)} = -100.2\text{dBm}$

6A-2: The thermal noise power at the antenna's output at the given bandwidth is: $P_{Noise\ 0\ (A)} = -160.2\text{dBm}$

6A-3: The thermal noise power at the antenna's output at the given bandwidth is: $P_{Noise\ 0\ (A)} = -141.6\text{dBm}$

6A-4: The thermal noise power at the antenna's output at the given bandwidth is: $P_{Noise\ 0\ (A)} = -157.8\text{dBm}$

6A-5: The thermal noise power at the antenna's output at the given bandwidth is: $P_{Noise\ 0\ (A)} = -127.8\text{dBm}$

6B: Calculating the system's maximally allowed (worst case) Noise-Figure that meets the specifications:

With respect to the required sensitivity level specification ($P_{Sig\ in\ TH\ (A)} = -106\text{dBm}$), that is specified for obtaining the threshold-level output SNR (of $SNR_{out\ TH\ (H)} = 17.1\text{dB}$) over the channel's bandwidth ($B = 41.667\text{KHz}$), what is the maximum allowed system's Noise Figure?

Round your result to the closest 0.1dB value.

6B-1: The maximum acceptable system's Noise Figure is: $NF_{System, max. (A) \rightarrow (H)} = 4.7\text{dB}$

6B-2: The maximum acceptable system's Noise Figure is: $NF_{System, max. (A) \rightarrow (H)} = 2.8\text{dB}$

6B-3: The maximum acceptable system's Noise Figure is: $NF_{System, max. (A) \rightarrow (H)} = 3.2\text{dB}$

6B-4: The maximum acceptable system's Noise Figure is: $NF_{System, max. (A) \rightarrow (H)} = 5.2\text{dB}$

6B-5: The maximum acceptable system's Noise Figure is: $NF_{System, max. (A) \rightarrow (H)} = 7.7\text{dB}$

6C: Calculating the RF front-end's output signal power to obtain "F/S -2dB" ADC acquisition:

In this clause, you are requested to calculate the RF output power that is required to be delivered by the RF front-end into the ADC's input, to obtain a "Full Scale minus 2dB Back-off" acquisition.

For the purposes of this clause, you are requested to treat the IF signal as a sinewave (CW signal).

Given the ADC's input resistance ($R_{in\ ADC} = 1,200\Omega$) and Full-Scale input's voltage ($V_{FS} = 2V_{p-p}$), what is the RF output power required at the RF-front-end's output, to allow for an ADC acquisition at Full-Scale minus a 2dB back-off?

Hints: (1) Remember that our Balun is lossless in terms of power.

(2) This clause requires only basic electricity / basic circuit theory knowledge:

Calculate the average power that a sinewave with a $2V_{p-p}$ amplitude will generate on a $1.2K\Omega$ resistor, and reduce 2dB.

6C-1: The front end's required output power, for maintaining a F/S-2dB ADC acquisition is: $P_{Out(H)} = -0.8dBm$.

6C-2: The front end's required output power, for maintaining a F/S-2dB ADC acquisition is: $P_{Out(H)} = -1.8dBm$.

6C-3: The front end's required output power, for maintaining a F/S-2dB ADC acquisition is: $P_{Out(H)} = -2.8dBm$.

6C-4: The front end's required output power, for maintaining a F/S-2dB ADC acquisition is: $P_{Out(H)} = -3.8dBm$.

6C-5: The front end's required output power, for maintaining a F/S-2dB ADC acquisition is: $P_{Out(H)} = -5.8dBm$.

6D: Calculating the required total system gain for a F/S-2dB acquisition of the "expected-to-be received" signal (the given "nominal" received signal power as expected by the system's link-budget):

With respect to the given nominal (expected) received signal level, $P_{Sig\ in\ Nominal(A)} = -70dBm$ according to the planned link-budget, and to your previously calculated front end's required output power, for maintaining a F/S-2dB ADC acquisition, $P_{Out(H)}$, calculate the required overall required system (small signal) gain.

6D-1: The required RF front end's overall gain, for maintaining a F/S-2dB ADC acquisition when receiving a $-70dBm$ signal level is: $G_{System(A)\rightarrow(H)} = 35.2dB$.

6D-2: The required RF front end's overall gain, for maintaining a F/S-2dB ADC acquisition when receiving a $-70dBm$ signal level is: $G_{System(A)\rightarrow(H)} = 64.2dB$.

6D-3: The required RF front end's overall gain, for maintaining a F/S-2dB ADC acquisition when receiving a $-70dBm$ signal level is: $G_{System(A)\rightarrow(H)} = 66.8dB$.

6D-4: The required RF front end's overall gain, for maintaining a F/S-2dB ADC acquisition when receiving a $-70dBm$ signal level is: $G_{System(A)\rightarrow(H)} = 70.2dB$.

6D-5: The required RF front end's overall gain, for maintaining a F/S-2dB ADC acquisition when receiving a $-70dBm$ signal level is: $G_{System(A)\rightarrow(H)} = 71.2dB$.

6E: Calculating the RF-Front-End's output noise power (integrated over the given channel bandwidth):

Calculate the RF front-end's output noise power, considering:

- The Noise equivalent bandwidth is the given channels bandwidth, $B = 41.667\text{KHz}$.
- The antenna's output noise density, was given as $N_{in(A)} = N_0$
- The RF front end has an overall gain that equals the previously calculated required gain, $G_{System(A) \rightarrow (H)}$
- The RF front end has an overall Noise-Figure that equals the previously calculated maximum acceptable system's Noise Figure, $NF_{System, max. (A) \rightarrow (H)}$

Under the above conditions, what is the RF-Front-End system's output noise power?

6E-1: Under the given conditions, the system's output noise power is $P_{Noise(H)} = -48\text{dBm}$.

6E-2: Under the given conditions, the system's output noise power is $P_{Noise(H)} = -51.2\text{dBm}$.

6E-3: Under the given conditions, the system's output noise power is $P_{Noise(H)} = -57.4\text{dBm}$.

6E-4: Under the given conditions, the system's output noise power is $P_{Noise(H)} = -58.9\text{dBm}$.

6E-5: Under the given conditions, the system's output noise power is $P_{Noise(H)} = -67\text{dBm}$.

6F: Choosing the suitable RF bandpass filter's type for playing the role of RF-BPF-1:

With respect to the maximum acceptable system NF you previously calculated, $NF_{System, max. (A) \rightarrow (H)}$, and to the 2 given types ("Type X" and "Type Y") of the available RF filters, mark the paragraph with your selection of the first (i.e. RF BPF 1) RF filter's type that will satisfy the system's Noise Figure (and sensitivity) specifications:

6F-1: The only RF Filter type selection suitable for the 1st RF BPF in the chain, that will enable compliance with the system's sensitivity (and Noise Figure) specification is **the "Type X" filter**.

6F-2: The only RF Filter type selection suitable for the 1st RF BPF in the chain, that will enable compliance with the system's sensitivity (and Noise Figure) specification is **the "Type Y" filter**.

6F-3: It is possible to select **any one of the 2 available RF filter types (either "Type X" or "Type Y")** to play the role of RF-BPF-1 and comply with the system's sensitivity (and Noise Figure) specification.

6F-4: It is possible to select **any one of the 2 available RF filter types (either "Type X" or "Type Y")** to play the role of RF-BPF-1 and comply with the system's sensitivity (and Noise Figure) specification, as long as the selected LNA type is the "W" type.

6F-5: It is possible to select **any one of the 2 available RF filter types (either "Type X" or "Type Y")** to play the role of RF-BPF-1 and comply with the system's sensitivity (and Noise Figure) specification, as long as the selected LNA type is the "Z" type.

6G: Choosing the suitable RF bandpass filter's type for playing the role of RF-BPF-2 and the receiver's frequency plan (yielding the system's image frequency):

With respect to the system's minimum required image (interferer) rejection ratio (IRR) specification, $IRR_{System, min} = 12\text{dB}$, and to the 2 given types ("Type X" and "Type Y") of available RF filters, choose the suitable 2nd RF filter's type and the converter's frequency plan, to satisfy the system's IRR requirements:

6G-1: The only RF Filter type suitable as the 2nd RF BPF in the chain in terms of compliance with the required IRR is **the "Type X" filter**. The IRR spec will be met only for the tuning equation: $f_{IF} = f_{RF} - f_{LO}$.

6G-2: The only RF Filter type suitable as the 2nd RF BPF in the chain in terms of compliance with the required IRR is **the "Type Y" filter**. The IRR spec will be met only for the tuning equation: $f_{IF} = f_{RF} - f_{LO}$.

6G-3: It is possible to select **any one of the 2 available RF filter types (either "Type X" or "Type Y")** to play the role of RF-BPF-2 and comply with the system's IRR specification.

6G-4: The only RF Filter type suitable as the 2nd RF BPF in the chain in terms of compliance with the required IRR is **the "Type X" filter**. The IRR spec will be met only for the tuning equation: $f_{IF} = f_{LO} - f_{RF}$.

6G-5: The only RF Filter type suitable as the 2nd RF BPF in the chain in terms of compliance with the required IRR is **the "Type Y" filter**. The IRR spec will be met only for the tuning equation: $f_{IF} = f_{LO} - f_{RF}$.

6H: Calculating the actual system's (interferer) image-rejection-ratio (IRR):

Based on your previous selections for RF-BPF-1, RF-BPF-2 and the tuning equation that will allow meeting the required minimal system's image-rejection ratio, what is the **actual** result for the system's IRR?

- 6H-1:** The actual calculated result for the system's image (interferer) rejection ratio, based on the chosen RF filter types and frequency plan is: $IRR_{System, actual} = 12.8dB$.
- 6H-2:** The actual calculated result for the system's image (interferer) rejection ratio, based on the chosen RF filter types and frequency plan is: $IRR_{System, actual} = 20.8dB$.
- 6H-3:** The actual calculated result for the system's image (interferer) rejection ratio, based on the chosen RF filter types and frequency plan is: $IRR_{System, actual} = 15dB$.
- 6H-4:** The actual calculated result for the system's image (interferer) rejection ratio, based on the chosen RF filter types and frequency plan is: $IRR_{System, actual} = 13.2dB$.
- 6H-5:** The actual calculated result for the system's image (interferer) rejection ratio, based on the chosen RF filter types and frequency plan is: $IRR_{System, actual} = 20dB$.

6I: Calculating the system's excessive Noise Figure due to image-noise conversion, ΔNF_{DSB} :

As studied in the course, a real-IF converter system's Noise Figure is given by:

$$NF_{System} \text{ (also called the "DSB" NF)} = NF_{SSB} + \Delta NF_{DSB}$$

Where:

- NF_{SSB} is the single-sideband Noise Figure (without any image-noise-conversion effects, that can be calculated according to the Friis cascaded noise factor formula, while considering the mixer as a simple attenuator with $L=CL$).
- ΔNF_{DSB} is the excessive Noise Figure due to image-noise conversion into the IF path by the mixer.

With respect to your previous selections for the RF filters and frequency plan (tuning equation), what is the system's excessive Noise Figure due to image-noise conversion?

- 6I-1:** The system's excessive Noise Figure due to image noise conversion is: $\Delta NF_{DSB} = 0.1dB$.
- 6I-2:** The system's excessive Noise Figure due to image noise conversion is: $\Delta NF_{DSB} = 0.4dB$.
- 6I-3:** The system's excessive Noise Figure due to image noise conversion is: $\Delta NF_{DSB} = 0.8dB$.
- 6I-4:** The system's excessive Noise Figure due to image noise conversion is: $\Delta NF_{DSB} = 1.2dB$.
- 6I-5:** The system's excessive Noise Figure due to image noise conversion is: $\Delta NF_{DSB} = 2.1dB$.

6J: Selecting the LNA-Type to meet the system's maximum allowed NF specification and calculating the cascaded NF of the 3 first blocks (RF BPF 1, LNA and RF BPF 2):

With respect to your previous selection for the filter types for implementing RF BPF 1 and RF BPF2 and to the maximum acceptable system's Noise-Figure that you calculated before, choose the appropriate LNA type (select between the 2 given LNA types, "Z" or "W") that will allow your system to meet the NF (sensitivity) specifications. Based on your LNA selection and your previous selections for the 2 RF filters, what will be the cascaded NF for the first 3 stages together (between points "A" to "D")?

Hint: Remember that there is no frequency conversion within the 3 first stages. Hence there is no need to include a ΔNF_{DSB} term. The cascaded NF of the 3 first stages is entirely an SSB noise figure, that can easily be calculated at the RF signal's frequency (while considering the 2 filters as attenuators, each with an attenuation according to its S21 response at the RF frequency, according to the given S21 plots of the filters).

- 6J-1:** The selected LNA type will be "Z" and the resulting NF of the 3 first stages is: $NF_{A \rightarrow D} = 3.3dB$.
- 6J-2:** The selected LNA type will be "Z" and the resulting NF of the 3 first stages is: $NF_{A \rightarrow D} = 7.5dB$.
- 6j-3:** The selected LNA type will be "Z" and the resulting NF of the 3 first stages is: $NF_{A \rightarrow D} = 4.9dB$.
- 6J-4:** The selected LNA type will be "W" and the resulting NF of the 3 first stages is: $NF_{A \rightarrow D} = 5.5dB$.
- 6J-5:** The selected LNA type will be "W" and the resulting NF of the 3 first stages is: $NF_{A \rightarrow D} = 2.9dB$.

6K: Calculating the cascaded Gain and NF of the 4 first blocks (RF BPF 1, LNA and RF BPF 2 and mixer):

In the previous clause, you completed your selections for the first 3 stages and calculated their cascaded NF. Now, you are requested to extend your Noise Figure calculation to include the 4th stage (the mixer) in the NF and Gain calculation as well.

As the mixer is a frequency translating device, you will need to include the ΔNF_{DSB} term, hence the overall NF of the 4 first stages will be given by: $NF_{A \rightarrow D} = NF_{SSB A \rightarrow D} + \Delta NF_{DSB}$, Where $NF_{SSB A \rightarrow D}$ simply considers the mixer as an attenuator with $L = CL$, and ΔNF_{DSB} is the excessive Noise Figure due to image-noise conversion into the IF path by the mixer. In other words, for the requested NF, first calculate the SSB NF of the four blocks, and then add the (previously calculated) ΔNF_{DSB} .

Based on your previous selections for the first 3 stages and their specifications, and mixer's given conversion loss (8dB), calculate the overall Gain and Noise Figure (**for the wanted received signal**) from point (A) to (E).

- 6K-1: With respect to the first 4 stages, the gain is $G_{A \rightarrow E} = 10.2dB$ and the Noise Figure is $NF_{A \rightarrow E} = 3.1dB$.
- 6K-2: With respect to the first 4 stages, the gain is $G_{A \rightarrow E} = 10.2dB$ and the Noise Figure is $NF_{A \rightarrow E} = 3.5dB$
- 6K-3: With respect to the first 4 stages, the gain is $G_{A \rightarrow E} = 12.8dB$ and the Noise Figure is $NF_{A \rightarrow E} = 3.5dB$
- 6K-4: With respect to the first 4 stages, the gain is $G_{A \rightarrow E} = 10.6dB$ and the Noise Figure is $NF_{A \rightarrow E} = 2.9dB$
- 6K-5: With respect to the first 4 stages, the gain is $G_{A \rightarrow E} = 13.2dB$ and the Noise Figure is $NF_{A \rightarrow E} = 3.3dB$.

6L: Calculating the required Gain of the IF amplifier:

By now, you are familiar with all the relevant specifications of the first 4 stages of your receiver. Also, in section 6D you have already calculated the required total system (receiver) gain, $G_{System (A) \rightarrow (H)}$, for a F/S-2dB acquisition of the "expected-to-be received" signal.

Calculate the required gain for the IF amplifier, based upon:

- Your knowledge of the required total receiver gain (as already calculated in clause 6D)
- Your knowledge of the gain of the first 4 stages (that was calculated in the previous clause, 6K)
- Consider each of the two IF filters to have a pass-band insertion loss of 0.5dB
- Consider the Balun as a lossless device

- 6L-1: The required IF-amplifier's gain is: $G_{IF-AMP (F \rightarrow G)} = 66dB$.
- 6L-2: The required IF-amplifier's gain is: $G_{IF-AMP (F \rightarrow G)} = 54.2dB$.
- 6L-3: The required IF-amplifier's gain is: $G_{IF-AMP (F \rightarrow G)} = 40.2dB$.
- 6L-4: The required IF-amplifier's gain is: $G_{IF-AMP (F \rightarrow G)} = 55dB$.
- 6L-5: The required IF-amplifier's gain is: $G_{IF-AMP (F \rightarrow G)} = 58.2dB$.

6M: Calculating the maximally allowed SNR degradation for the system's last sections (between points "E" to "H") and the resulting maximum allowed Noise-Figure for the IF amplifier:

Based upon your previous results for the maximally-allowed overall receiver Noise-Figure, and for the Noise-figure of the first 4 sections only, calculate:

- $\Delta SNR_{max, E \rightarrow H}$: The maximum allowed SNR degradation of the "remaining" sections (the whole receiver excluding its first 4 sections), between points "E" to "H", while still conforming with the maximal system's NF.
- $NF_{IF Amp max}$: Based on your above result for the maximum allowed SNR degradation for the last sections (between points "E" to "H"), and by using the correction factors table in its "over-gain" application, what is the resulting maximum allowed Noise-Figure for the IF amplifier?

Hint for calculating the maximum allowed IF amplifier's NF: Assume that a sufficiently large (greater than 15dB) over-gain is obtained on IF-BPF-2 by the previous stages, so the SNR degradation across the 2nd IF filter can be considered as negligible. Therefore, you may treat the $\Delta SNR_{max, E \rightarrow H}$ (the maximum allowed SNR degradation of the "remaining" sections) as obtained only across the first IF filter (which has a known IL of 0.5dB) and the IF amplifier.

6M-1: The maximally allowed SNR degradation is $\Delta SNR_{max, E \rightarrow H} = 1.2dB$ and the maximally allowed Noise Figure for the IF amplifier is $NF_{IF Amp max} = 0.7dB$.

6M-2: The maximally allowed SNR degradation is $\Delta SNR_{max, E \rightarrow H} = 1.6dB$ and the maximally allowed Noise Figure for the IF amplifier is $NF_{IF Amp max} = 1.1dB$.

6M-3: The maximally allowed SNR degradation is $\Delta SNR_{max, E \rightarrow H} = 1.2dB$ and the maximally allowed Noise Figure for the IF amplifier is $NF_{IF Amp max} = 8.2dB$.

6M-4: The maximally allowed SNR degradation is $\Delta SNR_{max, E \rightarrow H} = 1.6dB$ and the maximally allowed Noise Figure for the IF amplifier is $NF_{IF Amp max} = 8.2dB$.

6M-5: The maximally allowed SNR degradation is $\Delta SNR_{max, E \rightarrow H} = 1.4dB$ and the maximally allowed Noise Figure for the IF amplifier is $NF_{IF Amp max} = 10.8dB$.

6N: Calculating $OIP3_{A \rightarrow F}$, the cascaded OIP3 of the first 5 stages (RF BPF1, LNA, RF BPF 2, mixer and 1st IF BPF):

You are now familiar with all the relevant specifications of the first 5 stages of your receiver, from the antenna's input (point "A") to the first IF filter's output (point "F"). Based upon the specifications of these 5 stages, calculate their cascaded OIP3. Round your result to the closest 0.1dB.

Hints:

1. The RF filters may be treated as totally linear "attenuators", with attenuation specified either as 0.5dB (in the case of the IF filter) or (in the case of the RF filters) according to the given S21 plots (measured at the RF frequency – i.e., at the frequency of the wanted signal).
2. Be careful when dealing with the mixer's OIP3: Most passive mixers (as well as "our" mixer) include an IIP3 specification, rather than OIP3 (so, what is the relationship required to translate this spec into OIP3 terms?).
3. It can be useful to use the "simplification trick" we studied, for calculating the cascaded OIP3 of a 2-stage "cluster" that consists of a cascade of an active device followed by a passive (linear) attenuator.
4. Eventually, even if you do employ the simplification "trick" above, you will still need to calculate the cascaded OIP3 of at least 2 (equivalent) stages. You may use the correction-factors based method for calculating cascaded OIP3.
5. It is highly recommended to verify your $OIP3_{A \rightarrow F}$ result by simulating the RF chain using a tool such as "[Avaqo Appcad](#)". Open "Appcad" and choose "Signals / Systems" → "Noise Calc" to simulate.

6N-1: The cascaded OIP3 of the first 5 stages is: $OIP3_{A \rightarrow F} = 5.8dBm$.

6N-2: The cascaded OIP3 of the first 5 stages is: $OIP3_{A \rightarrow F} = 6.3dBm$.

6N-3: The cascaded OIP3 of the first 5 stages is: $OIP3_{A \rightarrow F} = 6.0dBm$.

6N-4: The cascaded OIP3 of the first 5 stages is: $OIP3_{A \rightarrow F} = 7.1dBm$.

6N-5: The cascaded OIP3 of the first 5 stages is: $OIP3_{A \rightarrow F} = 12.7dBm$.

6O: Calculating the required system's minimal OIP3, to meet the minimum SFDR-3 specification (of 60dBc):
 During your previous calculations (in clause 6E) you have calculated the RF-Front-End's output noise power (integrated over the given channel bandwidth, $P_{Noise(H)}$). Based on this result, and on the given **minimum system's SFDR-3 specification**, calculate the **minimum required system's OIP3**.

Hint: Use the SFDR3 definition that defines SFDR3 in terms of the OIP3 and the system's output noise power.

6O-1: The systems minimally required OIP3 is: $OIP3_{System, minimal, A \rightarrow H} = 31.1dBm$.

6O-2: The systems minimally required OIP3 is: $OIP3_{System, minimal, A \rightarrow H} = 23.0dBm$

6O-3: The systems minimally required OIP3 is: $OIP3_{System, minimal, A \rightarrow H} = 37.1dBm$

6O-4: The systems minimally required OIP3 is: $OIP3_{System, minimal, A \rightarrow H} = 41.1dBm$

6O-5: The systems minimally required OIP3 is: $OIP3_{System, minimal, A \rightarrow H} = 33.1dBm$

6P: Calculating the required IF amplifier's minimal OIP3, to meet the minimum SFDR-3 specification:

At this stage, you are already familiar with the OIP3 specifications of all the components in the receiver, other than the OIP3 of the IF amplifier.

In specific:

- In clause 6N, you calculated $OIP3_{A \rightarrow F}$, the cascaded OIP3 of the first 5 stages.
- In the previous clause (clause 6O), you calculated the minimum required system-level OIP3, namely $OIP3_{System, minimal, A \rightarrow H}$.

Based on the above previously done calculations, find the minimum required OIP3 specification for the IF amplifier, in order to allow the receiver to comply with the SFDR-3 specification.

Hints:

1. *Simplify this problem into a simple 2-stage OIP3 cascade calculation (done using the correction method), containing:*
 - *A first (equivalent) stage consisting of the first 5 stages, with an OIP3 as calculated in clause 6N.*
 - *A second (equivalent) stage consisting of the IF amplifier followed by the 2nd IF filter (using the cascaded OIP3 "simplification trick" we studied for such "active device followed by attenuator" clusters).*
2. *Don't forget to "de-embed" the 2nd IF filter from your result, to provide the OIP3 of the IF-amplifier alone (i.e., not to include the 2nd IF filter in the requested result).*
3. *Verify your results using a simulation (such as by using the "[Avago Appcad](#)" SW).*

6P-1: The IF amplifier's minimally required OIP3 is: $OIP3_{IF amp} = 30.5dBm$.

6P-2: The IF amplifier's minimally required OIP3 is: $OIP3_{IF amp} = 31.1dBm$

6P-3: The IF amplifier's minimally required OIP3 is: $OIP3_{IF amp} = 31.6dBm$

6P-4: The IF amplifier's minimally required OIP3 is: $OIP3_{IF amp} = 32.7dBm$

6P-5: The IF amplifier's minimally required OIP3 is: $OIP3_{IF amp} = 36.5dBm$

6Q: Calculating the ADC's actual SQNR when receiving the "expected" (nominal) signal, for a F/S-2dB acquisition:

In this clause, you are requested to calculate the signal-to-quantisation noise ratio (SQNR) at the ADC's output, under the following guidelines:

- The requested SQNR is NOT the Full-Scale (maximum) SQNR since a 2dB backoff is required. Hence, use the $SQNR_{MAX=F/S}$ expression and subtract 2dB to account for the required backoff: Hence ,you will need to use:

$$SQNR_{F/S-2dB} = (K - C) \cdot 6.02 + WPR + OSR - 2dB$$

- Please make sure to multiply (K-C) by exactly 6.02 (not just by 6), to reduce rounding errors.
- For obtaining the signal's WPR (waveform power ratio), treat the IF signal as a CW (sinewave) waveform. To reduce rounding errors, please use the exact sinewave WPR value, with a 0.01dB accuracy.
- For calculating the processing gain due to over-sampling (also called averaging), **OSR**, calculate the ratio between the bandwidth of a Nyquist Zone (remember: the given ADC's sampling rate is 80Ms/S) and of the given bandwidth of the signal (41.667KHz):

$$OSR = 10Log \left(\frac{Nyquist\ Zone\ BW}{Signal\ BW} \right)$$

To reduce rounding errors, please use the exact log-form result of this ratio, with a 0.01dB accuracy.

- Remember the ADC's specifications:**
 - Flash ADC
 - Sampling frequency (rate): 80Ms/S
 - Number of HW bits: K=8 bit
 - Implementation constant (the number of bits required to be subtracted from K in order to express imperfections in the quantiser): C=1.78 bits.

6Q-1: The SQNR obtained at F/S-2dB is (rounded to the closest 0.1dB): $SQNR_{F/S-2dB} = 66dB$

6Q-2: The SQNR obtained at F/S-2dB is (rounded to the closest 0.1dB): $SQNR_{F/S-2dB} = 67dB$

6Q-3: The SQNR obtained at F/S-2dB is (rounded to the closest 0.1dB): $SQNR_{F/S-2dB} = 68dB$

6Q-4: The SQNR obtained at F/S-2dB is (rounded to the closest 0.1dB): $SQNR_{F/S-2dB} = 70dB$

6Q-5: The SQNR obtained at F/S-2dB is (rounded to the closest 0.1dB): $SQNR_{F/S-2dB} = 82dB$

6R: Calculating the maximally allowed clock-generators RMS jitter:

In this clause, you are requested to calculate the worst-case (maximal allowed) RMS Jitter value for the ADC's sampling clock, to allow the ADC to yield an output SNR (limited due to jitter and quantisation only) that still fully supports the RF chain's SFDR3 specification (of 60dBc).

Guidelines and step-by-step instructions:

- For the "expected" $F/S-2dB$ analogue input signal into the ADC, the ADC needs to be able to provide an output SNR of 60dB (with limitations due to quantisation and jitter only).
- This required value of 60dB output SNR therefore can be expressed by:

$$SNR_{Max, ADC} = 60dB = \underbrace{SQNR_{F/S-2dB}}_{\text{You found in 6Q}} \parallel \underbrace{SJNR}_{\text{Need to find}}$$

- The SQNR for the $F/S-2dB$ acquisition, $SQNR_{F/S-2dB}$, was already calculated in the previous clause.
- Therefore, you can simply extract the SJNR, either by a linear calculation, or by using the correction factors table. In other words, you need to calculate the SJNR, that together (in parallel) with the $SQNR_{F/S-2dB}$ that you already found, yields the requested $SNR_{tot}=60dB$.
- After calculating the SJNR, extract the sampling clock's jitter, $\tau_{Jitter RMS}$ from the SJNR formula:

$$SJNR_{[dB]} = 104_{[dB]} - 20Log_{10}\left(\frac{f_{Analogue}}{1 MHz}\right) - 20Log_{10}\left(\frac{\tau_{Jitter RMS}}{1 pS}\right)$$

While using the above SJNR formula, consider the analogue signal's frequency as 60MHz: $f_{Analogue} = 60MHz$ (as the central IF frequency).

- In order to select the correct answer from the provided alternatives, you MAY need to translate your RMS jitter result from its time [pS] units representation into angular units (such as mDeg or mRad). For such calculations, consider (again) the analogue signal's frequency to be exactly 60MHz (the centre IF frequency).

Mark the correct result with respect to the maximum allowed ADC's clock jitter:

- 6R-1: The maximally allowed RMS clock jitter (given in time units) is: $\tau_{Jitter RMS} = 5.54pS$
- 6R-2: The maximally allowed RMS clock jitter (given in angular units) is: $\tau_{Jitter RMS} = 2.78mRad$
- 6R-3: The maximally allowed RMS clock jitter (given in angular units) is: $\tau_{Jitter RMS} = 8.24 mDeg$
- 6R-4: The maximally allowed RMS clock jitter (given in time units) is: $\tau_{Jitter RMS} = 1.82pS$
- 6R-5: The maximally allowed RMS clock jitter (given in angular units) is: $\tau_{Jitter RMS} = 0.8875mRad$

Good luck!