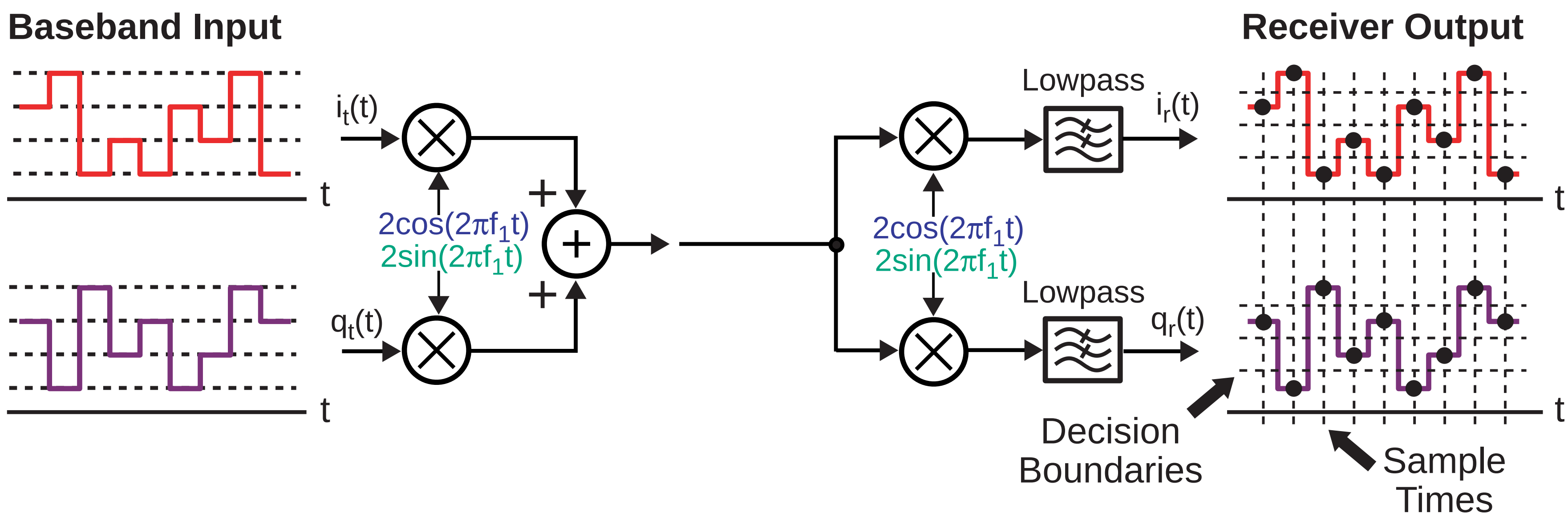
High Speed Communication Circuits and Systems
Lecture 20
Performance Measures of Wireless Communication

Michael H. Perrott

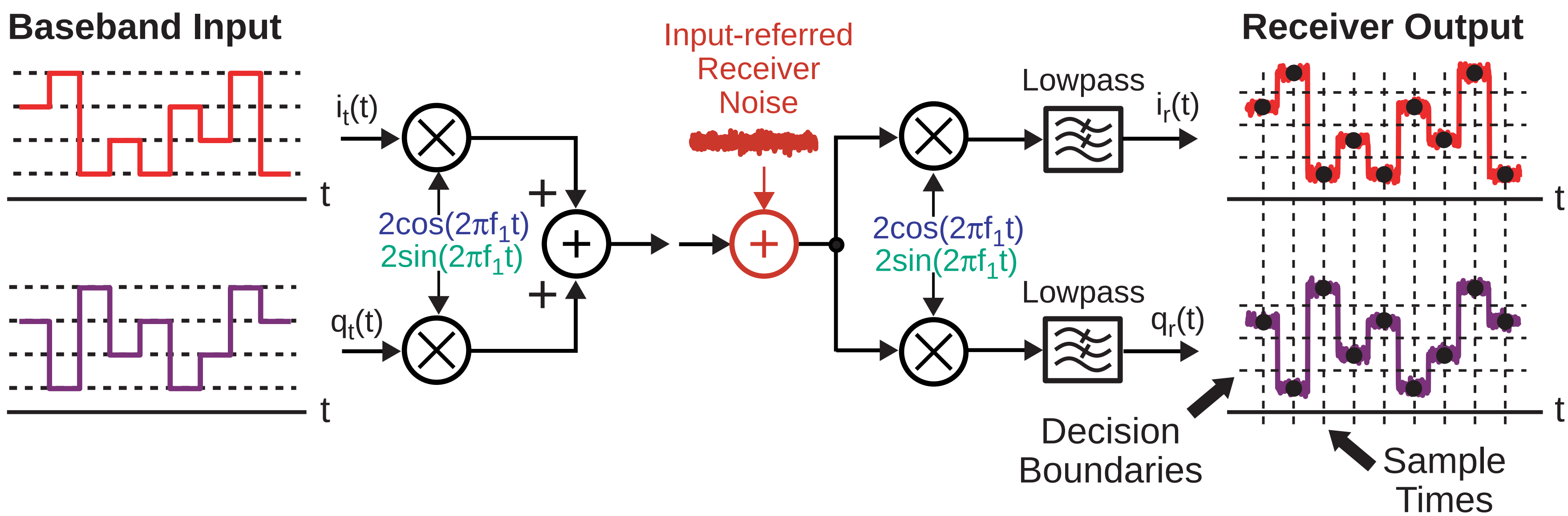
April 21, 2004

Recall Digital Modulation for Wireless Link



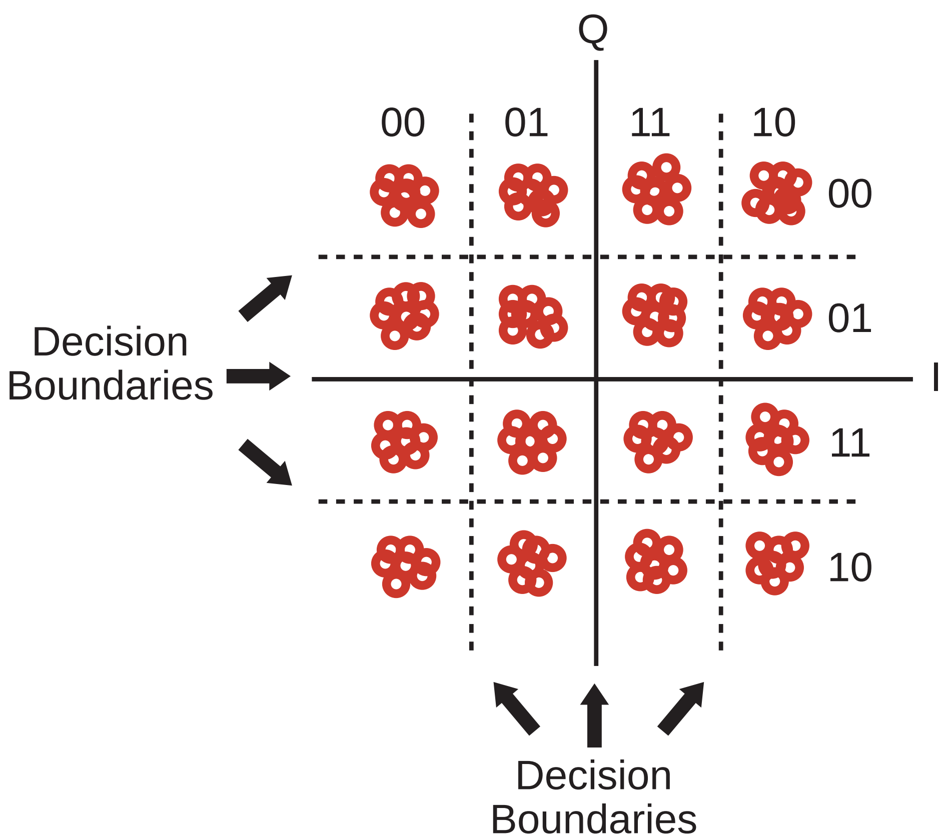
- Send discrete-leveled values on I and Q channels
- Performance issues
  - Spectral efficiency (transmitter)
  - Bit error rate performance (receiver)
- Nonidealities
  - Intersymbol interference
  - Noise
  - Interferers

Impact of Receiver Noise



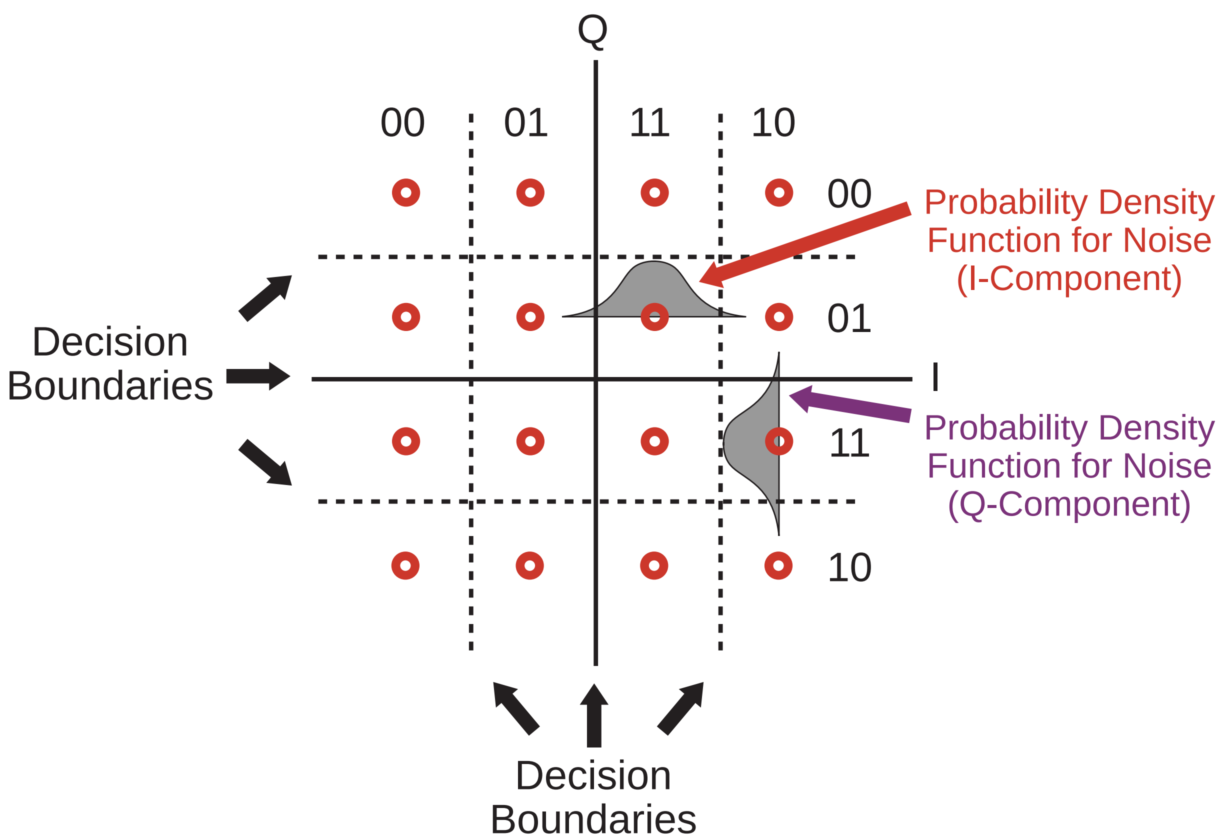
- **Performance impact**
  - **SNR is reduced, leading to possible bit errors**
- **Methods of increasing SNR**
  - **Decrease bandwidth of receiver lowpass**
    - SNR is traded off for intersymbol interference
  - **Increase input power into receiver**
    - Increase transmit power and/or shorten its distance from receiver

View SNR Issue with Constellation Diagram



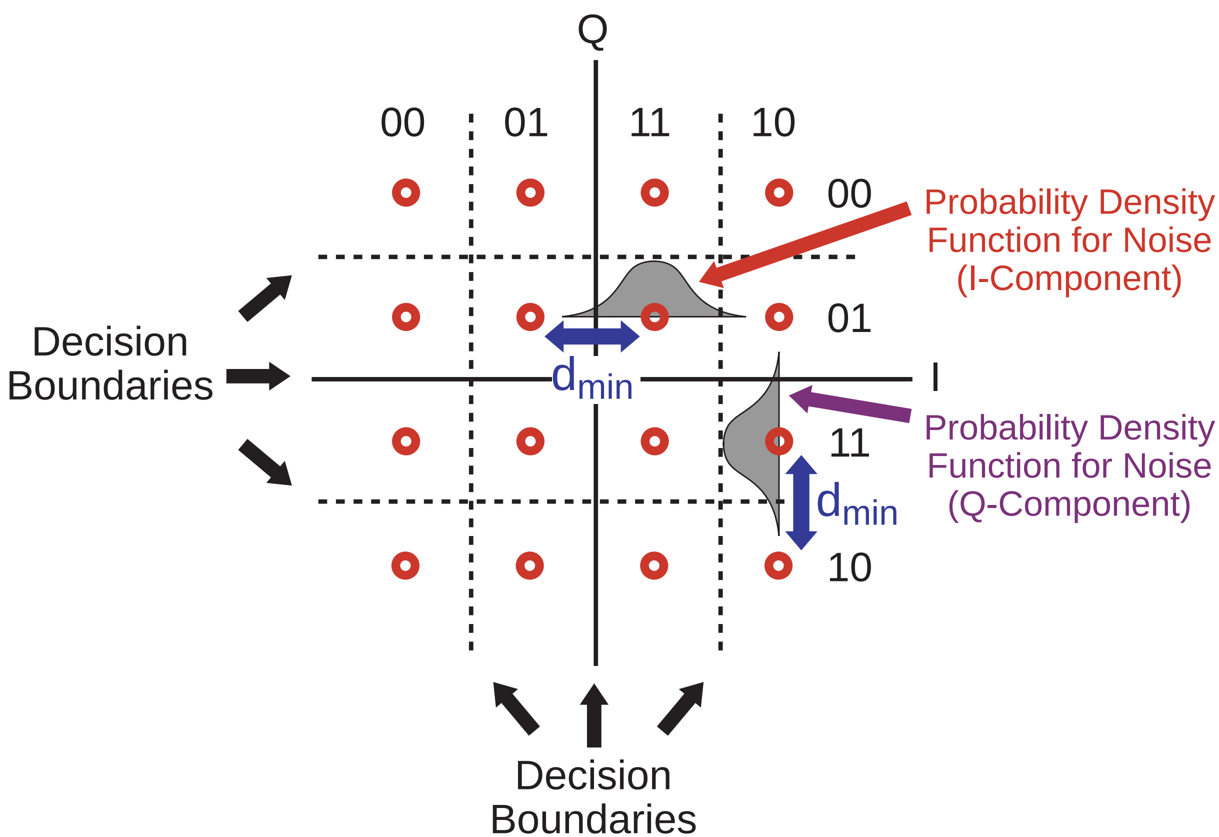
- Noise causes sampled I/Q values to vary about their nominal values
- Bit errors are created when sampled I/Q values cross decision boundaries

Mathematical Analysis of SNR versus Bit Error Rate (BER)



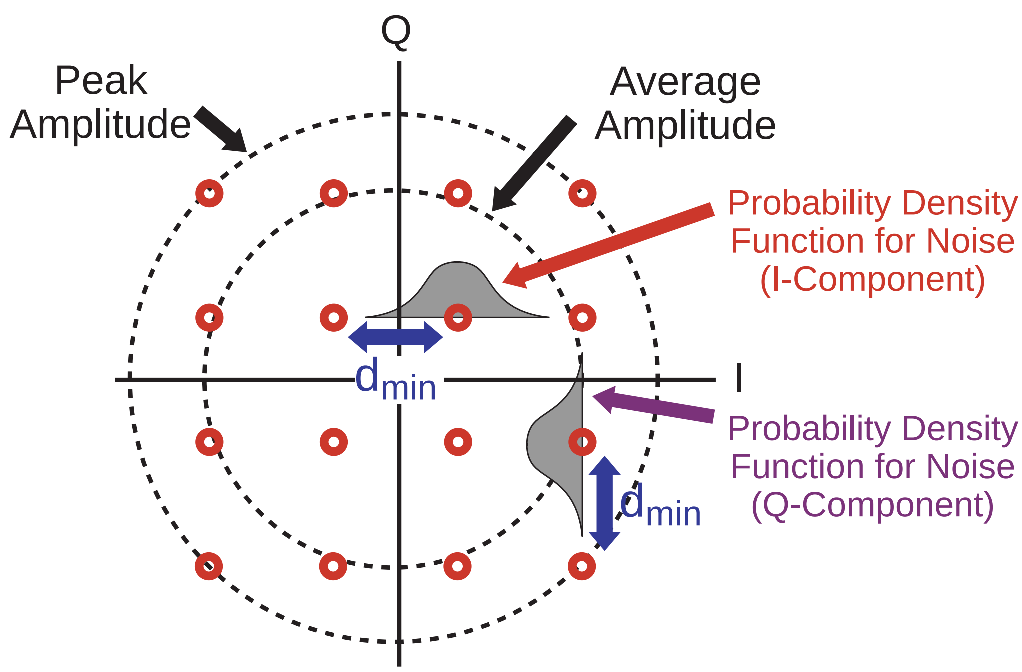
- **Model noise impacting I and Q channels according to a probability density function (PDF)**
  - **Gaussian shape is often assumed**
- **Receiver bit error rate can be computed by calculating probability of tail regions of PDF curves**

Key Parameters for SNR/BER Analysis



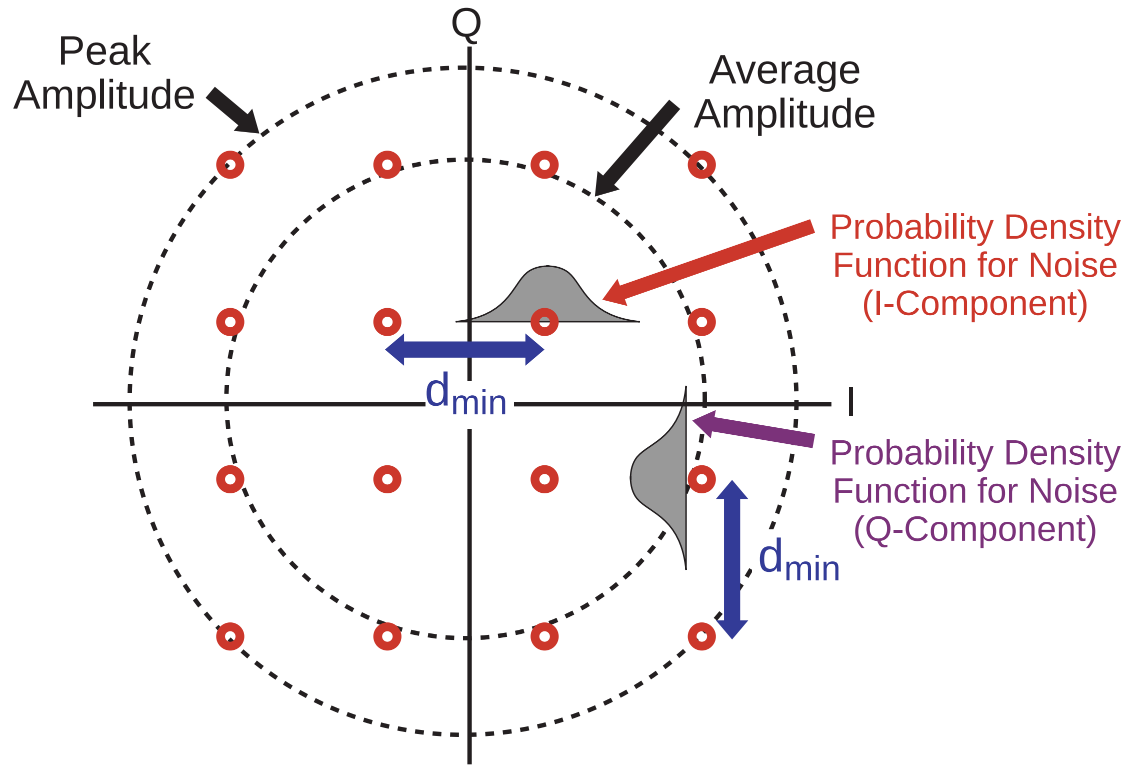
- **Bit error rate (BER) is a function of**
  - **Variance of noise**
  - **Distance between constellation points (d_{min})**
- **Larger d_{min} with a fixed noise variance leads to higher SNR and a lower bit error rate**

Relationship Between Amplitude and Constellation



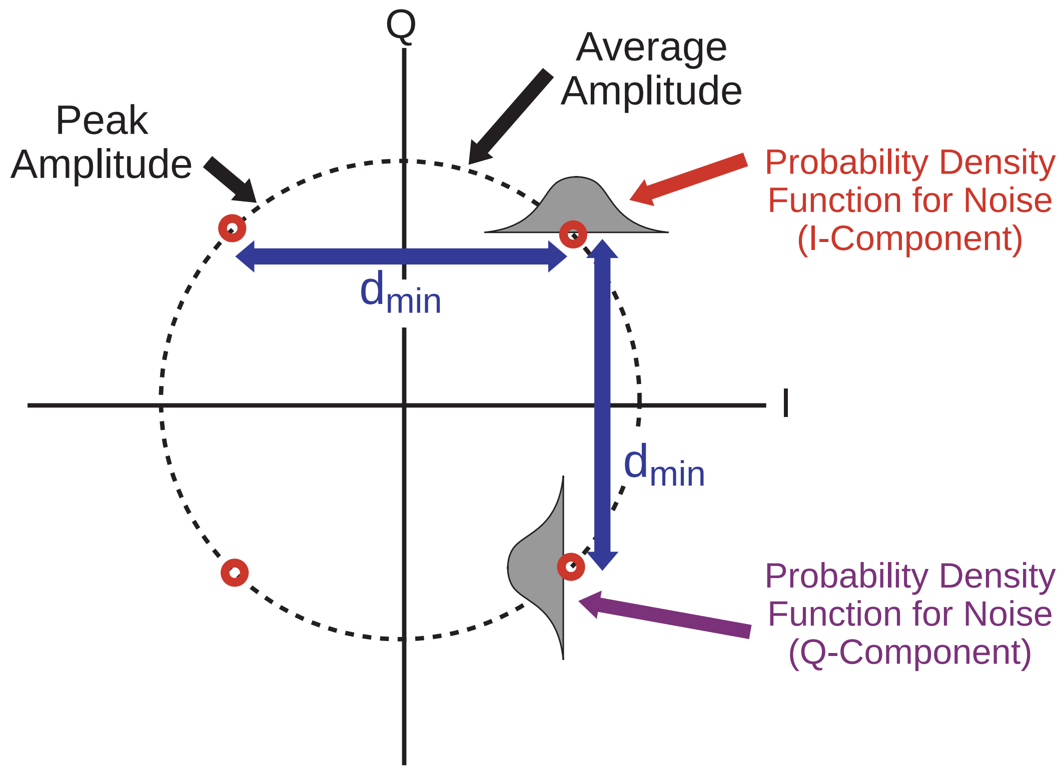
- **Distance of I/Q constellation point from origin corresponds to instantaneous amplitude of input signal at that sample time**
- **Amplitude is measured at receiver and a function of**
  - **Transmit power**
  - **Distance between transmitter and receiver (and channel)**

Impact of Increased Signal Power At Receiver



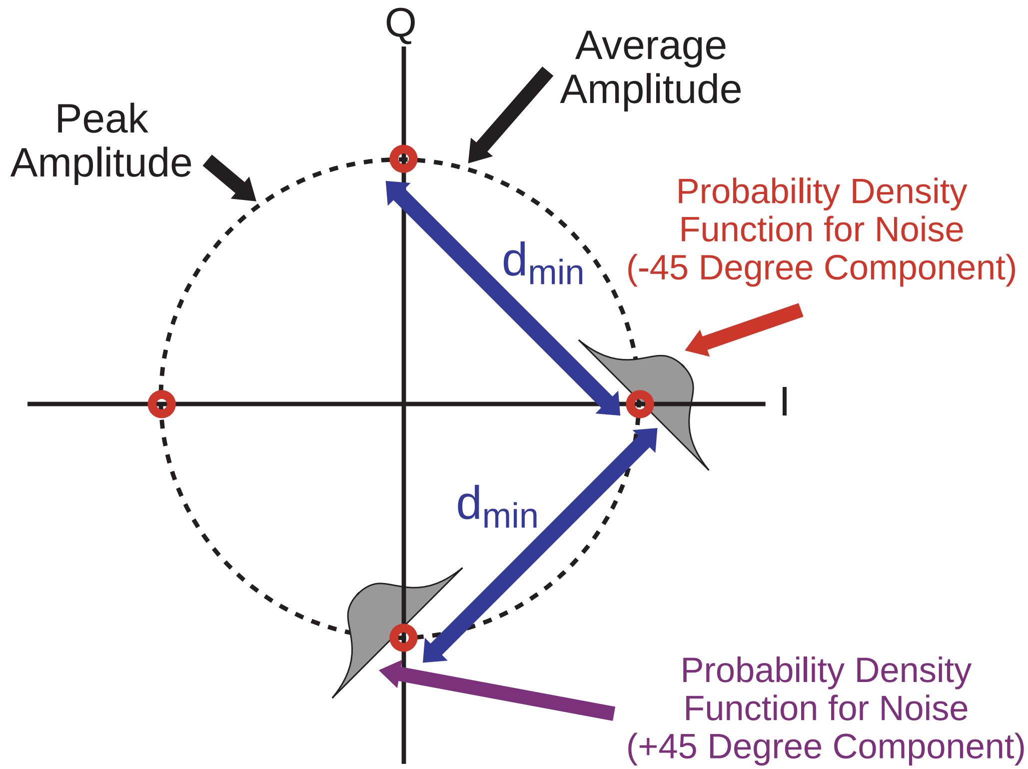
- **Separation between constellation points, d_{min}, increases as received power increases**
- **Noise variance remains roughly constant as input signal power is increased**
  - **Noise variance primarily determined by receiver circuits**
- **Bit error rate improves with increased signal power!**

Impact of Modulation Scheme on SNR/BER



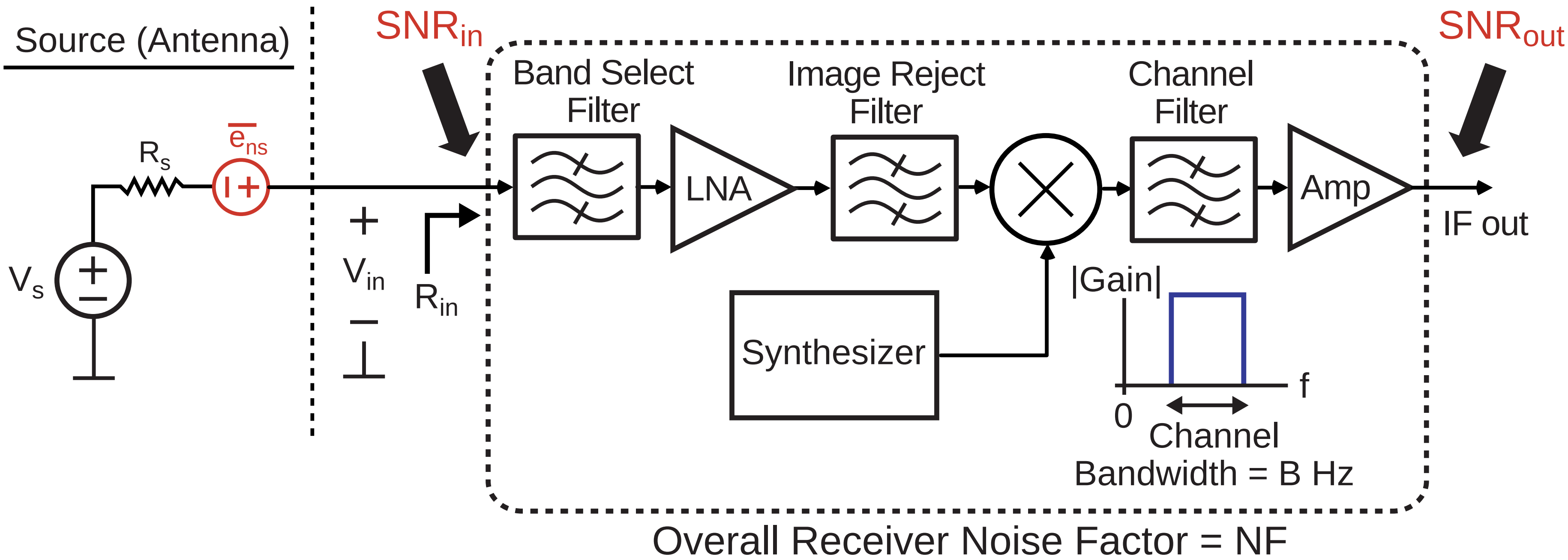
- **Lowering the number of constellation points increases d_{min} for a fixed input signal amplitude**
  - **SNR is increased (given a fixed noise variance)**
  - **Bit error is reduced**
- **Actual situation is more complicated when coding is used**

Alternate View of Previous Constellation



- **Common modulation method is to transmit independent binary signals on I and Q channels**
- **The above constellation has the same d_{min} as the one on the previous slide**
  - **Obtains the same SNR/BER performance given that the noise on I/Q channels is symmetric**

Impact of Noise Factor on Input-Referred SNR



$$NF = \frac{SNR_{in}}{SNR_{out}}$$

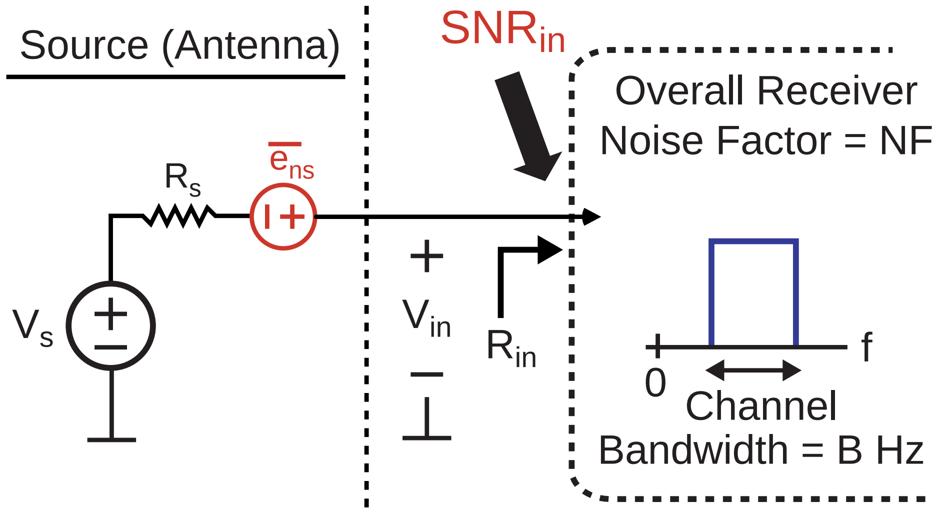
- **To achieve acceptable bit error rates (BER)**

$$SNR_{out} \geq SNR_{out,min}$$

- **Refer SNR requirement to input**

$$\boxed{SNR_{in} = NF \cdot SNR_{out} \geq NF \cdot SNR_{out,min}}$$

Minimum Input Power to Achieve Acceptable SNR



$$\boxed{SNR_{in,min} = NF \cdot SNR_{out,min}}$$

(1)

- **Calculation of input SNR in terms of input power**

$$SNR_{in} = \frac{v_{in}^2/R_{in}}{\alpha^2\overline{e_{nRs}^2}/R_{in}} = \boxed{\frac{P_{in}}{\alpha^2\overline{e_{nRs}^2}/R_{in}},} \text{ where } \alpha = \frac{R_{in}}{R_s + R_{in}}$$

(2)

- **Combine (1) and (2)**

$$\boxed{P_{in,min} = \alpha^2\overline{e_{nRs}^2}/R_{in} \cdot NF \cdot SNR_{out,min}}$$

Simplified Expression for Minimum Input Power

$$P_{in,min} = \alpha^2 \overline{e_{nRs}^2} / R_{in} \cdot NF \cdot SNR_{out,min}$$

- **Assume that the receiver input impedance is matched to the source (i.e., antenna, etc.)**

$$\Rightarrow \quad \alpha = \frac{R_{in}}{R_s + R_{in}} \Big|_{R_{in}=R_s} = \frac{1}{2}$$

$$\Rightarrow \quad \alpha^2 \overline{e_{nRs}^2} / R_{in} \Big|_{R_{in}=R_s} = \left(\frac{1}{2}\right)^2 \frac{4kTR_s\Delta f}{R_{in}} \Big|_{R_{in}=R_s} = kT\Delta f$$

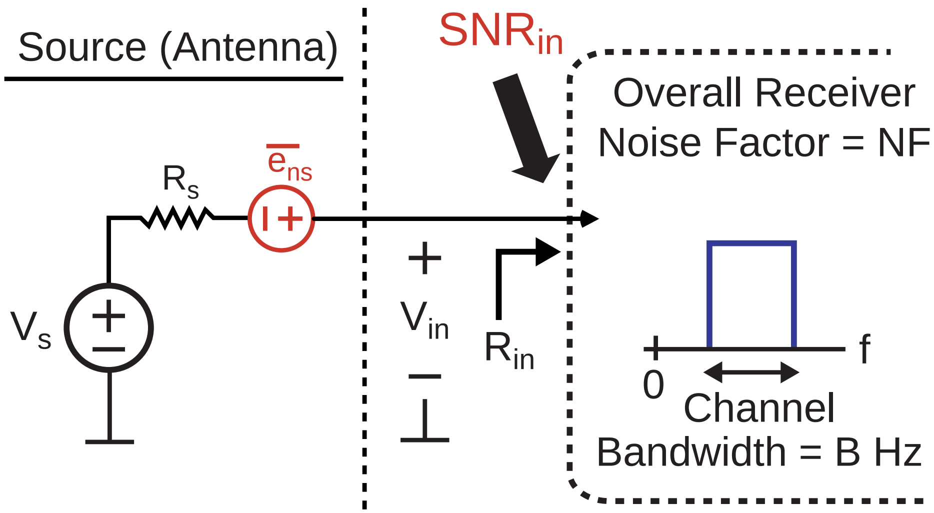
- **Resulting expression**

$$\boxed{P_{in,min} = kT\Delta f \cdot NF \cdot SNR_{out,min}}$$

  - **At room temperature:**

$$kT = -174 \text{ dBm/Hz}$$

Receiver Sensitivity



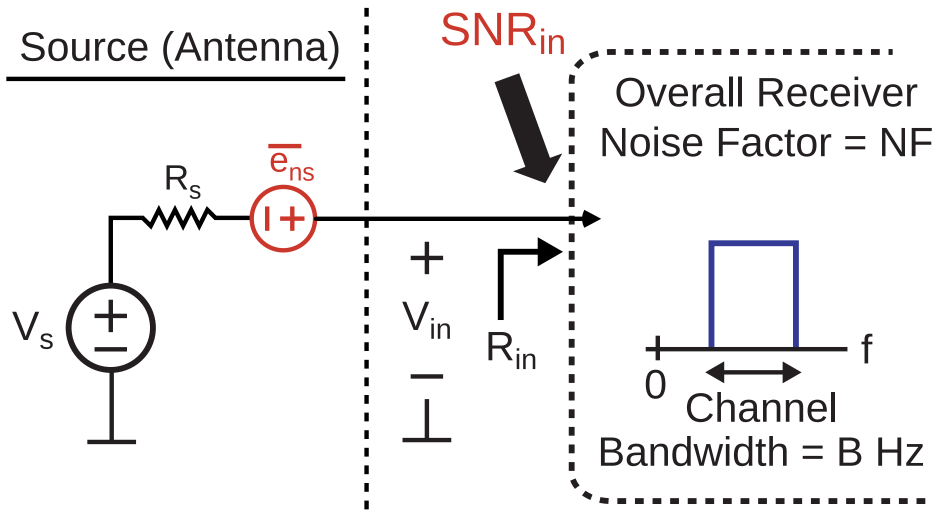
$$\boxed{P_{in,min} = kT\Delta f \cdot NF \cdot SNR_{out,min}}$$

- **Sensitivity of receiver is defined as minimum input power that achieves acceptable SNR (in units of dBm)**

$$dBm(P_{in,min}) = 10\log(kT\Delta f \cdot NF \cdot SNR_{out,min})$$

$$\boxed{= -174 + 10\log(B) + dB(NF) + dB(SNR_{out,min})}$$

Example Calculation for Receiver Sensitivity

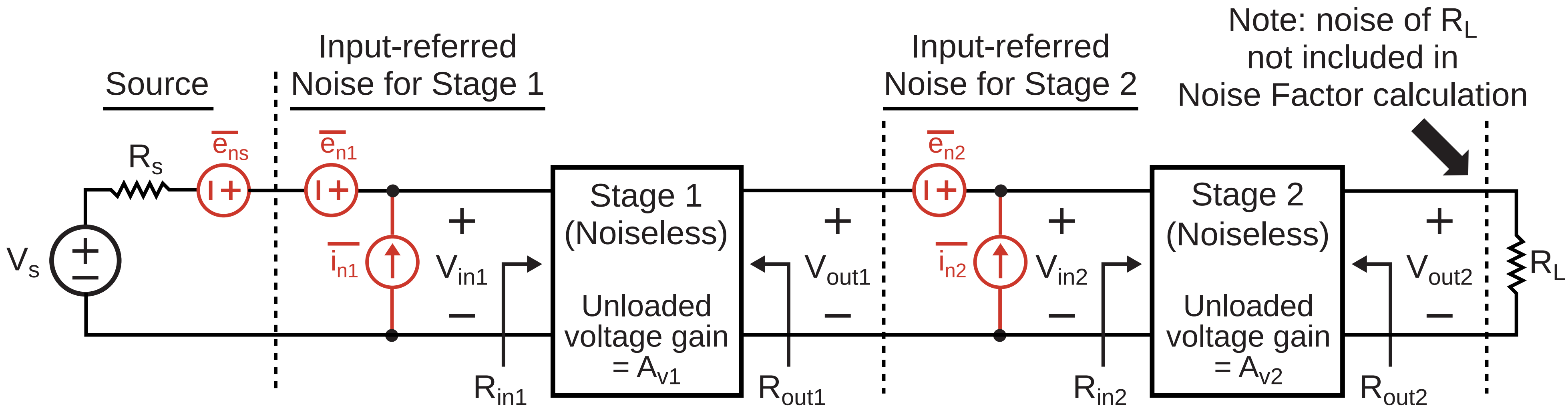


$$\boxed{dBm(P_{in,min}) = -174 + 10\log(B) + dB(NF) + dB(SNR_{out,min})}$$

- **Suppose that a receiver has a noise figure of 8 dB, channel bandwidth is 1 MHz, and the minimum SNR at the receiver output is 12 dB to achieve a BER of 1e-3**
  - **Receiver sensitivity (for BER of 1e-3) is**

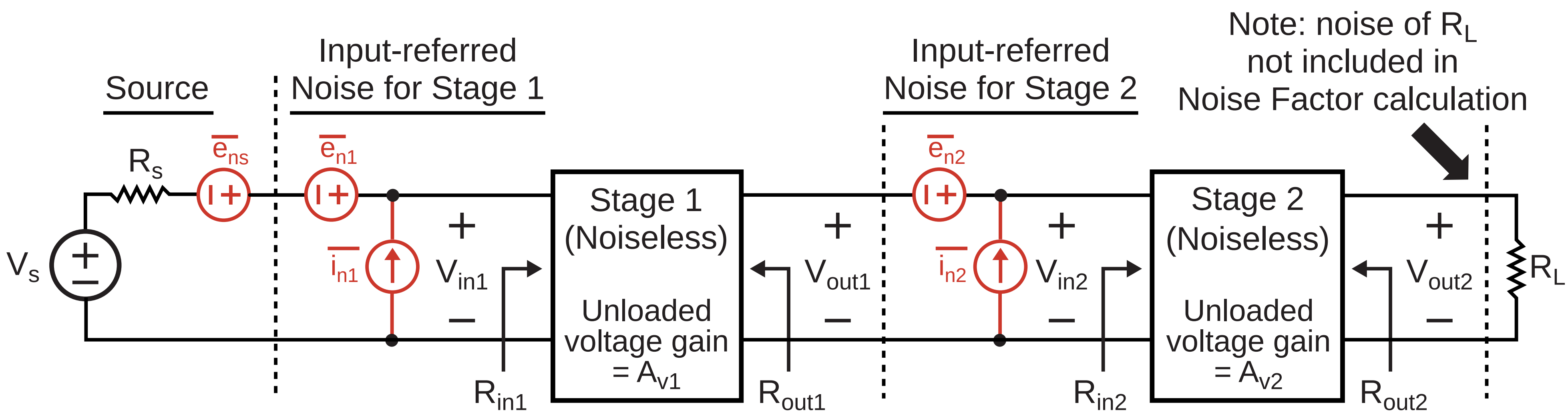
$$\boxed{dBm(P_{in,min}) = -174 + 60 + 8 + 12 = -94\ dBm}$$

Calculation of Noise Figure of Cascaded Stages

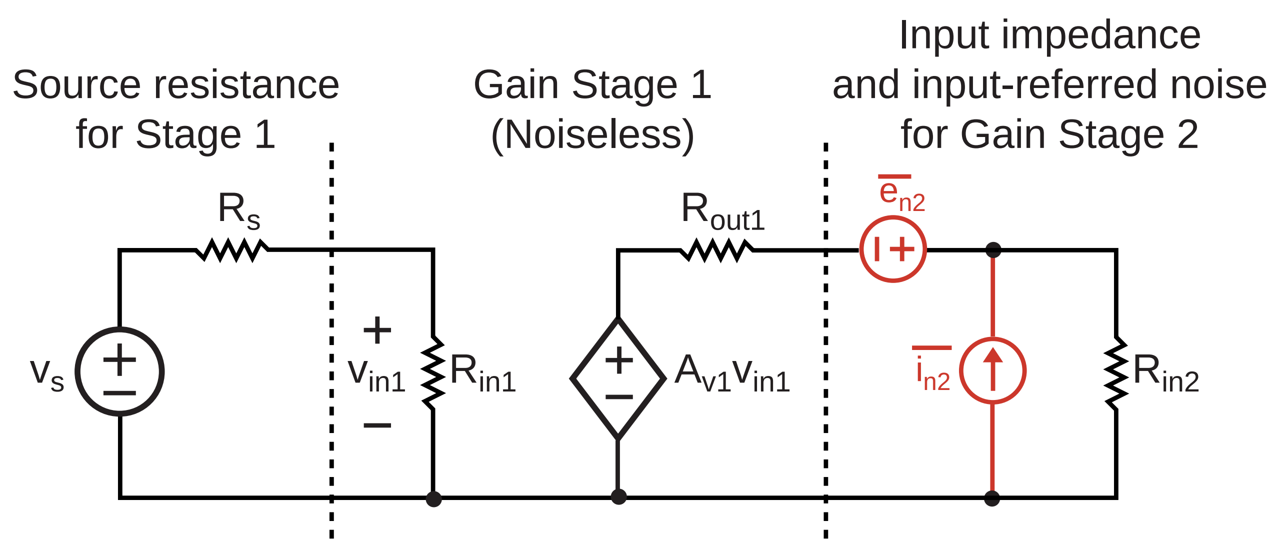


- **Want to calculate overall noise figure of above system**
- **Assumptions**
  - **Input refer the noise sources of each stage**
  - **Model amplification (or attenuation) of each stage as a noiseless voltage controlled voltage source with an unloaded gain equal to A_v**
  - **Ignore noise of final load resistor (or could input refer to previous stage)**

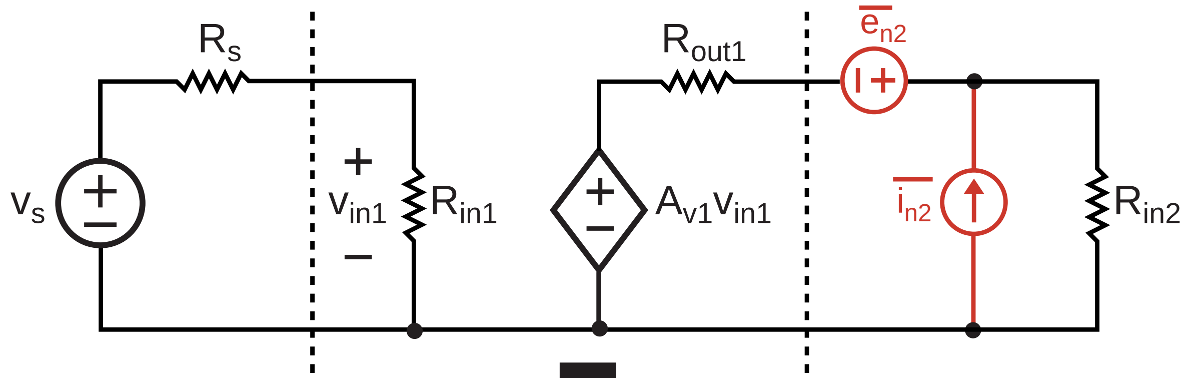
Method: Refer All Noise to Input of First Stage

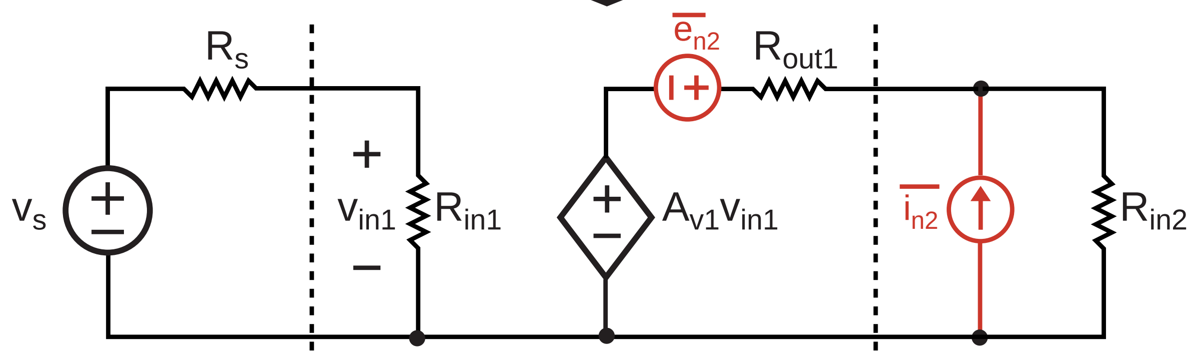


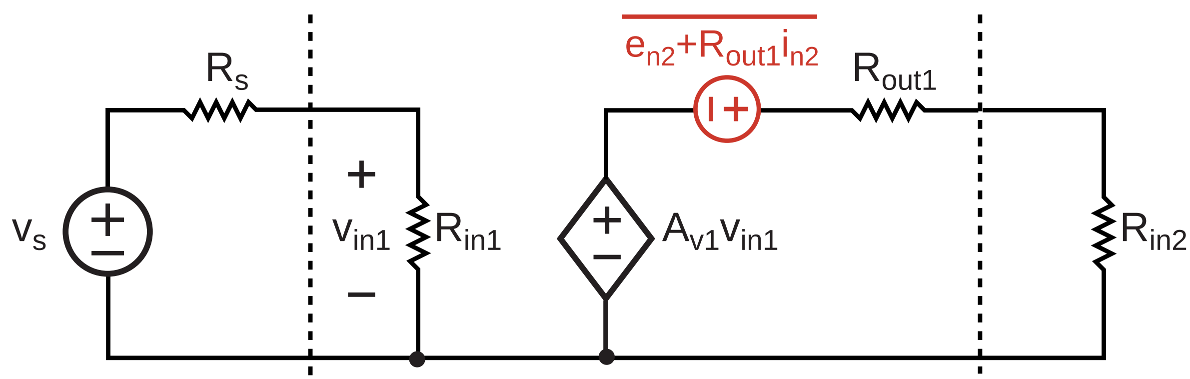
- **Model for referring stage 2 noise to input of stage 1**



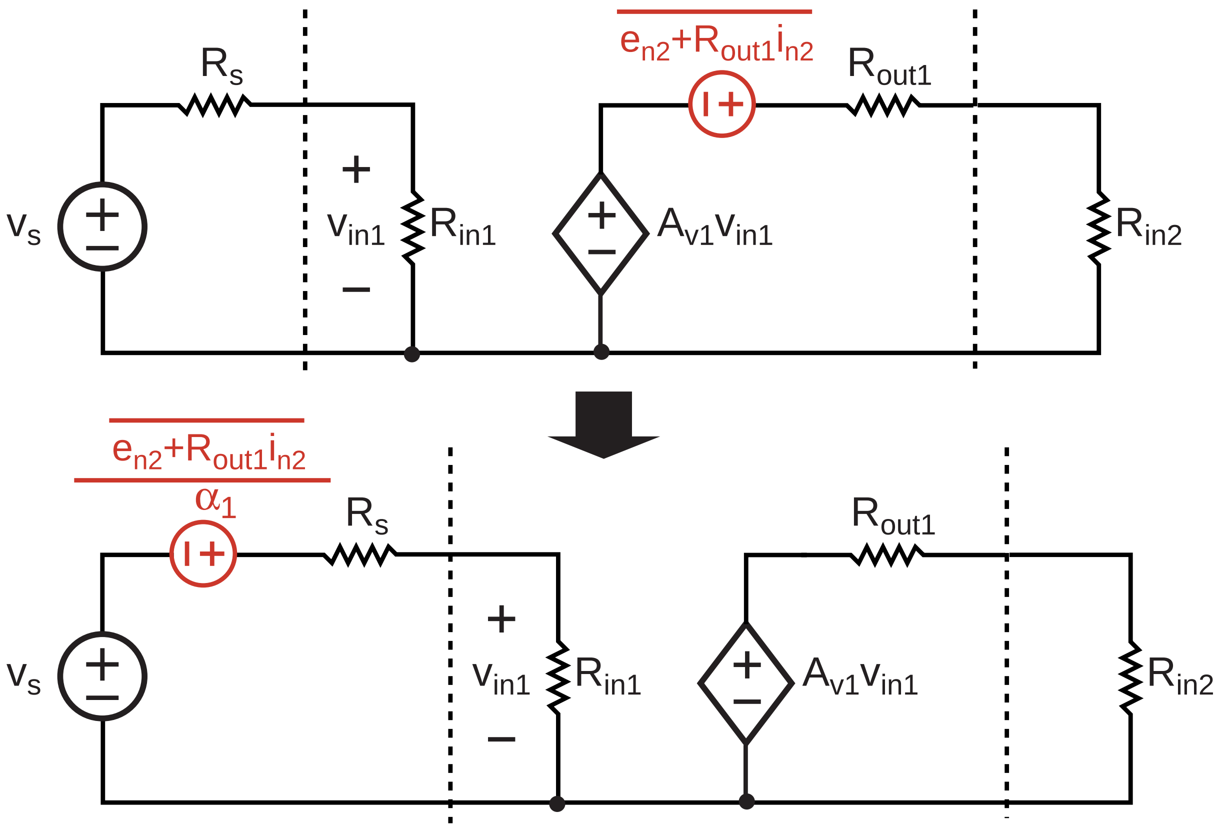
Step 1: Create an Equivalent Noise Voltage Source







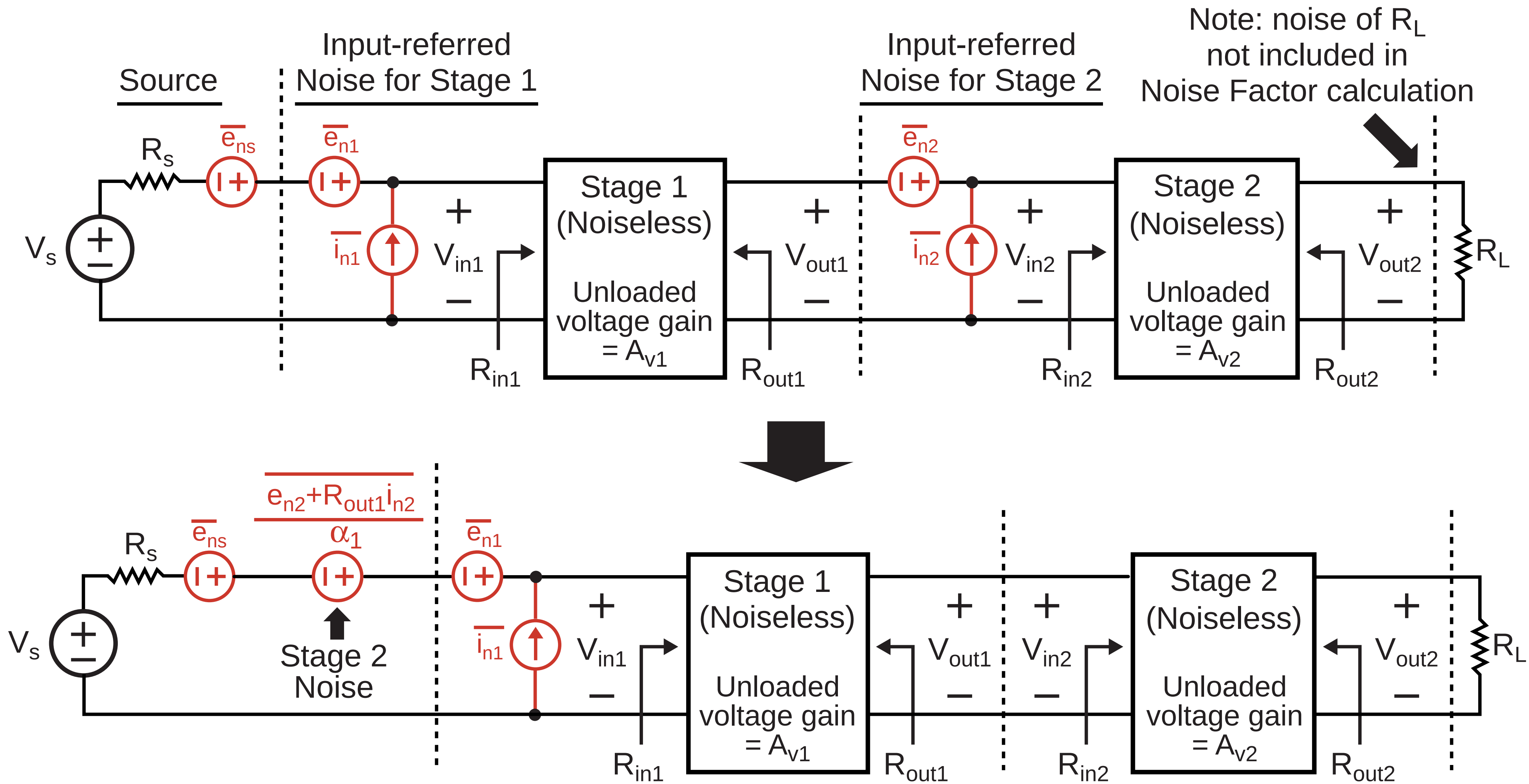
Step 2: Input Refer Voltage Noise Source



- **Scaling factor α_1 is a function of unloaded gain, A_v, and input voltage divider**

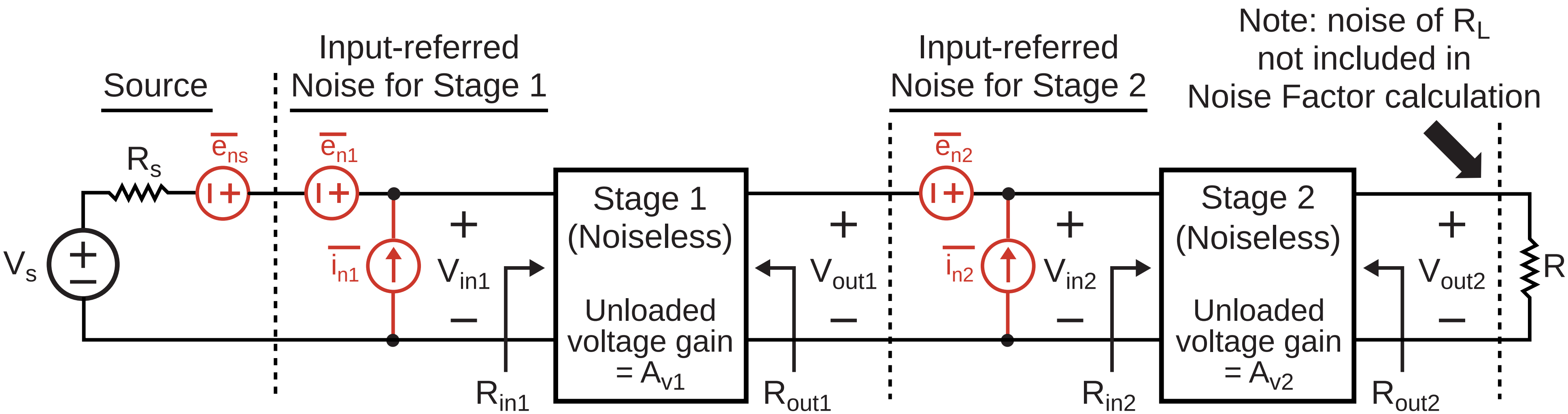
$$\alpha_1 = \frac{R_{in}}{R_s + R_{in}} A_v$$

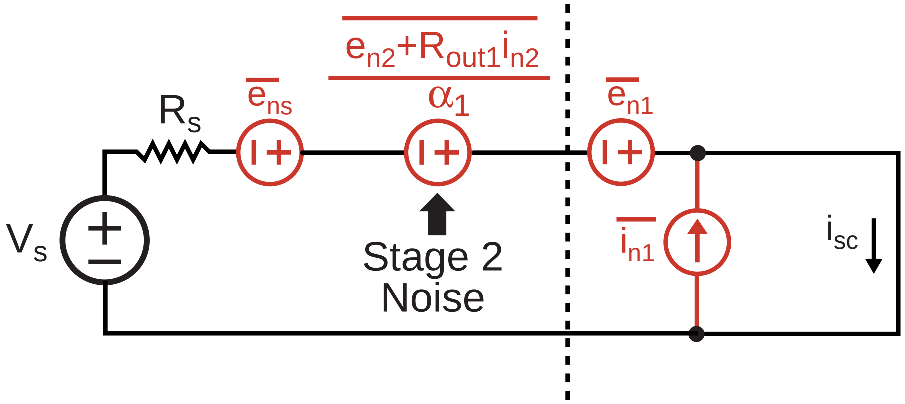
Input Referral of Noise to First Stage



- **Where** $\alpha_1 = \frac{R_{in}}{R_s + R_{in}} A_{v1}$

Noise Factor Calculation





$$\Rightarrow \quad \mathrm{NF} = \frac{\left(\overline{e_{ns}^2} + \overline{(e_{n2} + R_{out1} i_{n2})^2}/\alpha_1^2 + \overline{(e_{n1} + R_s i_{n1})^2}\right)/R_s^2}{\overline{e_{ns}^2}/R_s^2}$$

Alternate Noise Factor Expression

$$\mathrm{NF} = \frac{\left(\overline{e_{ns}^2} + \overline{(e_{n2} + R_{out1} i_{n2})^2}/\alpha_1^2 + \overline{(e_{n1} + R_s i_{n1})^2}\right)/R_s^2}{\overline{e_{ns}^2}/R_s^2}$$

$$= \frac{\overline{e_{ns}^2} + \overline{(e_{n1} + R_s i_{n1})^2} + \overline{(e_{n2} + R_{out1} i_{n2})^2}/\alpha_1^2}{\overline{e_{ns}^2}}$$

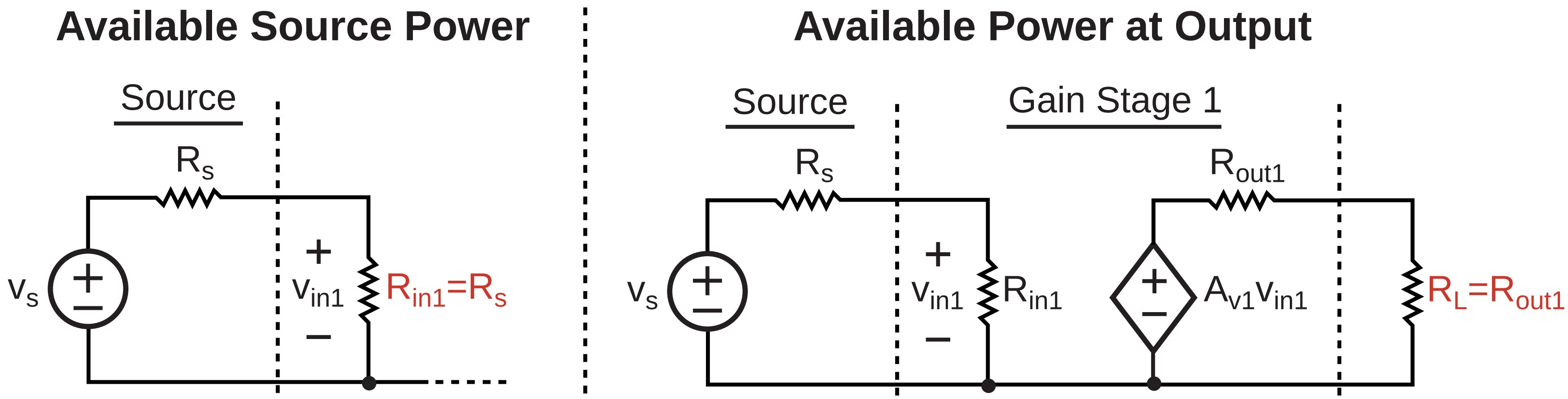
$$= 1 + \frac{\overline{(e_{n1} + R_s i_{n1})^2}}{\overline{e_{ns}^2}} + \frac{1}{\alpha_1^2}\frac{\overline{(e_{n2} + R_{out1} i_{n2})^2}}{\overline{e_{ns}^2}}$$

$$= 1 + \frac{\overline{(e_{n1} + R_s i_{n1})^2}}{4kTR_s} + \frac{1}{\alpha_1^2}\frac{R_{out1}}{R_s}\frac{\overline{(e_{n2} + R_{out1} i_{n2})^2}}{4kTR_{out1}}$$

$$= 1 + (\mathrm{NF}_1 - 1) + \frac{1}{\alpha_1^2}\frac{R_{out1}}{R_s}(\mathrm{NF}_2 - 1)$$

$$\boxed{= 1 + (\mathrm{NF}_1 - 1) + \frac{(\mathrm{NF}_2 - 1)}{A_{p1}}, \qquad A_{p1} = \alpha_1^2 \frac{R_s}{R_{out1}}}$$

Define "Available Power Gain"



- **Available power gain for stage 1 defined as**

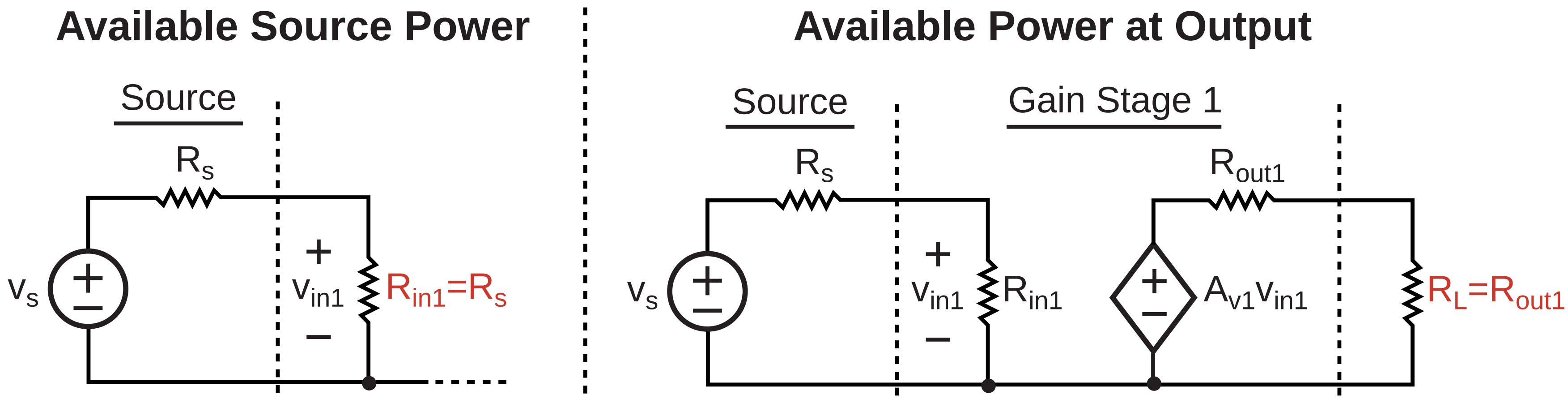
$$A_{p1} = \frac{\text{Available power at output (matched load)}}{\text{Available source power (matched load)}}$$

  - **Available power at output**

$$\left(v_s\frac{R_{in1}}{R_s+R_{in1}}A_{v1}\frac{R_{out1}}{R_{out1}+R_{out1}}\right)^2/R_{out1} = \frac{v_s^2\alpha_1^2}{4R_{out1}}$$

  - **Available source power** $\left(v_s\frac{R_s}{R_s+R_s}\right)^2/R_s = \frac{v_s^2}{4R_s}$

Available Power Gain Versus Loaded Voltage Gain



- **Available power gain for stage 1**

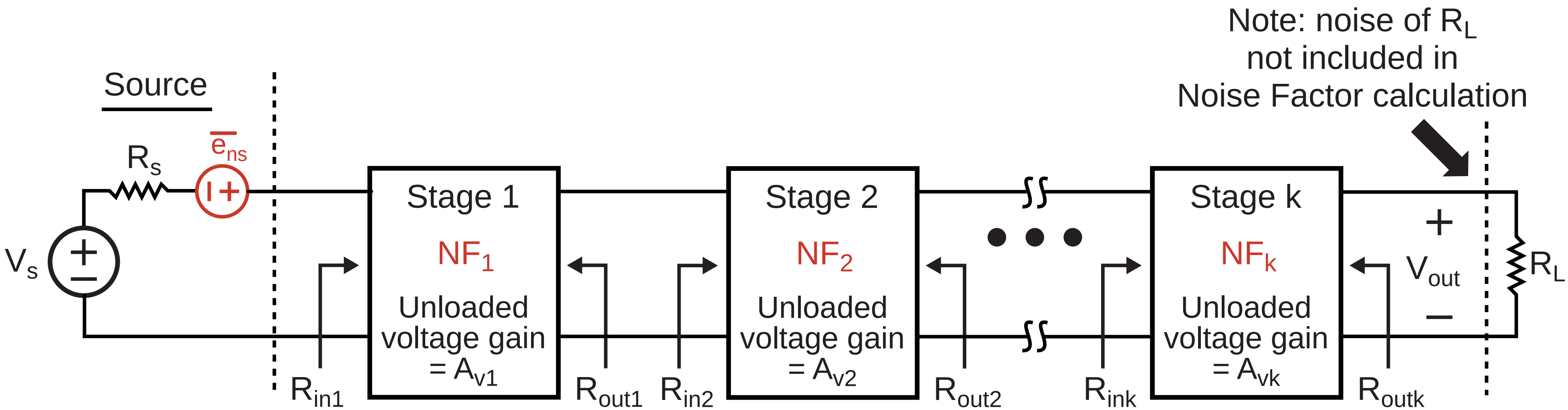
$$A_{p1} = \frac{v_s^2 \alpha_1^2}{4R_{out1}} \frac{4R_s}{v_s^2} = \alpha_1^2 \frac{R_s}{R_{out1}} \quad \text{where} \quad \alpha_1 = \frac{R_{in1}}{R_s + R_{in1}} A_{v1}$$

- **If $R_{in1} = R_{out1} = R_s$**

$$\alpha_1 = \frac{1}{2} A_{v1} \quad \Rightarrow \quad \boxed{A_{p1} = \frac{1}{4} A_{v1}^2 = A_{v1\_l}^2}$$

  - **Where A_{v1_l} is defined as the “loaded gain” of stage 1**

Final Expressions for Cascaded Noise Factor Calculation



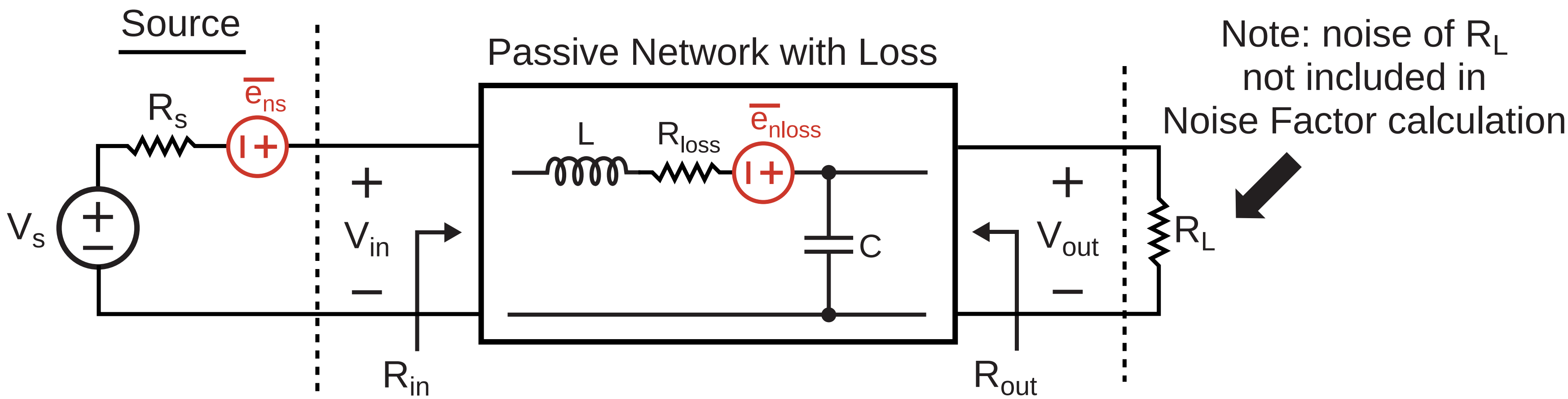
- **Overall Noise Factor (general expression)**

$$NF = 1 + (\mathrm{NF}_1 - 1) + \frac{(\mathrm{NF}_2 - 1)}{A_{p1}} + \cdots + \frac{(\mathrm{NF}_k - 1)}{A_{p1} \cdots A_{pk}}$$

- **Overall Noise Factor when all input and output impedances equal R_s:**

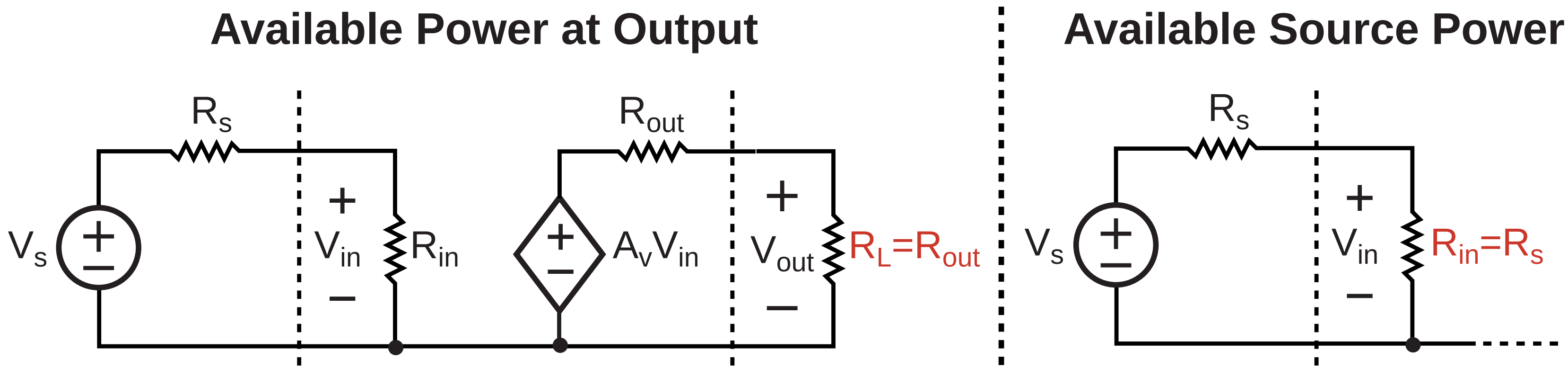
$$NF = 1 + (\mathrm{NF}_1 - 1) + \frac{(\mathrm{NF}_2 - 1)}{A_{v1\_l}^2} + \cdots + \frac{(\mathrm{NF}_k - 1)}{A_{v1\_l}^2 \cdots A_{vk\_l}^2}$$

Calculation of Noise Factor for Lossy Passive Networks



- **RF systems often employ passive filters for band select and channel select operations**
  - **Achieve high dynamic range and excellent selectivity**
- **Practical filters have loss**
  - **Can model as resistance in equivalent RLC network**
  - **Such resistance adds thermal noise, thereby lowering noise factor of receiver**
- **We would like to calculate noise factor contribution of lossy passive networks in a straightforward manner**
  - **See pages 46-48 of Razavi book**

Define "Available Power Gain" For Passive Networks



- **Available power at output**

$$V_s^2\left(\frac{R_{in}}{R_s+R_{in}}\right)^2 A_v^2\left(\frac{R_{out}}{R_{out}+R_{out}}\right)^2 / R_{out}$$

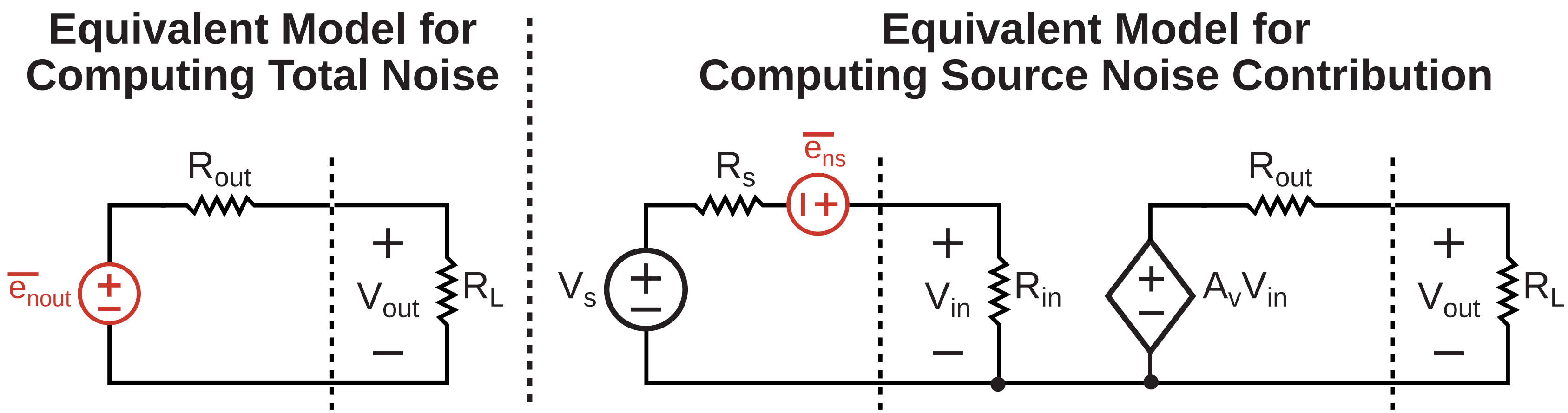
$$= \frac{V_s^2}{4R_{out}}\left(\frac{R_{in}}{R_s+R_{in}}\right)^2 A_v^2$$

- **Available source power**

$$V_s^2\left(\frac{R_s}{R_s+R_s}\right)^2 / R_{in} = \frac{V_s^2}{4R_s}$$

$$\boxed{\Rightarrow \quad A_p = \frac{R_s}{R_{out}}\left(\frac{R_{in}}{R_s+R_{in}}\right)^2 A_v^2 \qquad (\leq 1 \text{ for passive networks})}$$

Equivalent Noise Model and Resulting NF Calculation



- **Total noise at output**

$$\overline{e_{nout}^2}\left(\frac{R_L}{R_L+R_{out}}\right)^2 = 4kTR_{out}\left(\frac{R_L}{R_L+R_{out}}\right)^2$$

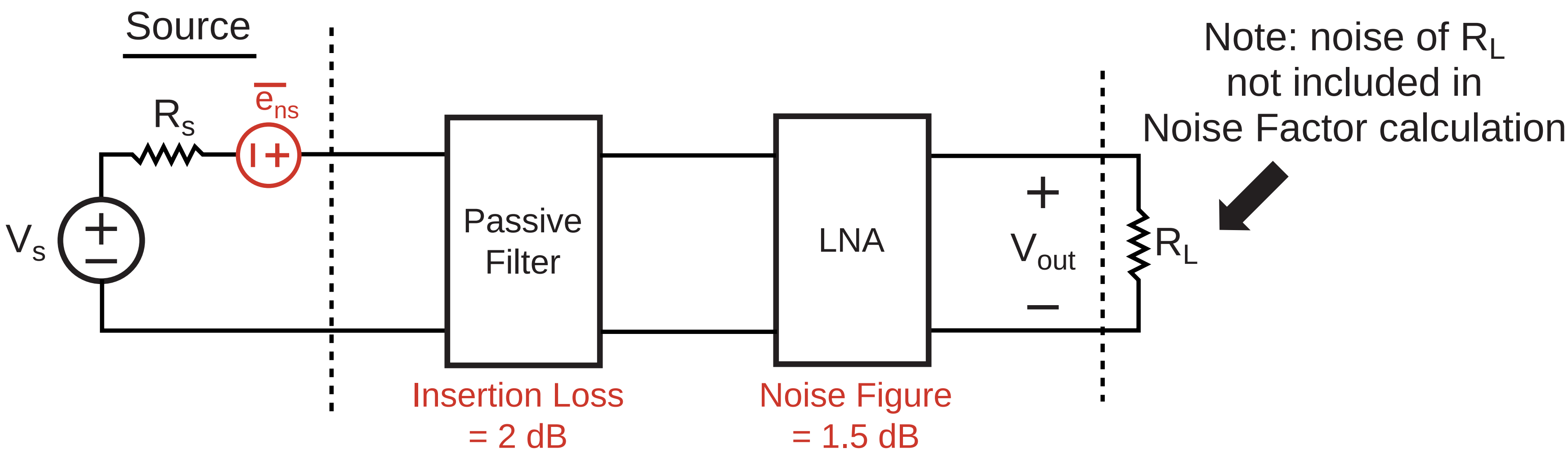
- **Noise due to source (referred to output)**

$$4kTR_s\left(\frac{R_{in}}{R_s+R_{in}}\right)^2 A_v^2\left(\frac{R_L}{R_L+R_{out}}\right)^2$$

- **Noise factor**

$$NF = \frac{R_{out}}{R_s}\left(\frac{R_s+R_{in}}{R_{in}}\right)^2\frac{1}{A_v^2} = \boxed{1/A_p}$$

Example: Impact of Cascading Passive Filter with LNA



- **Noise Factor calculation**

$$\mathrm{NF} = 1 + (\mathrm{NF_{filt}} - 1) + \frac{\mathrm{NF_{LNA}} - 1}{A_{\mathrm{p\_filt}}}$$

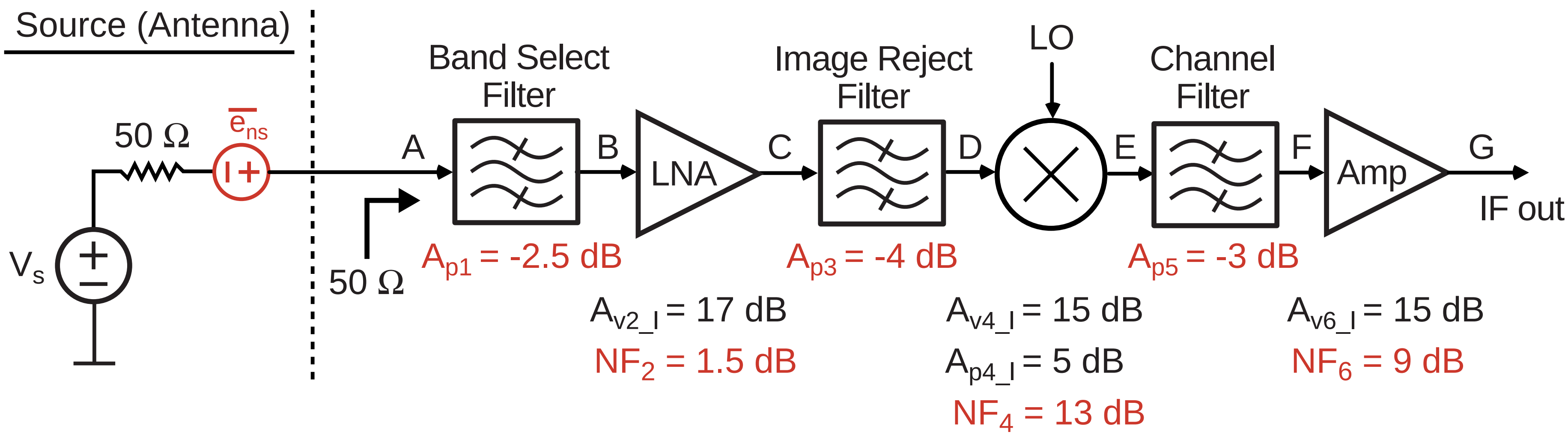
$$= 1 + (1/A_{\mathrm{p\_filt}} - 1) + \frac{\mathrm{NF_{LNA}} - 1}{A_{\mathrm{p\_filt}}} = \boxed{1/A_{\mathrm{p\_filt}} \cdot \mathrm{NF_{LNA}}}$$

- **Noise Figure**

$$10\log(\mathrm{NF}) = -10\log(A_{\mathrm{p\_filt}}) + 10\log(\mathrm{NF_{LNA}})$$

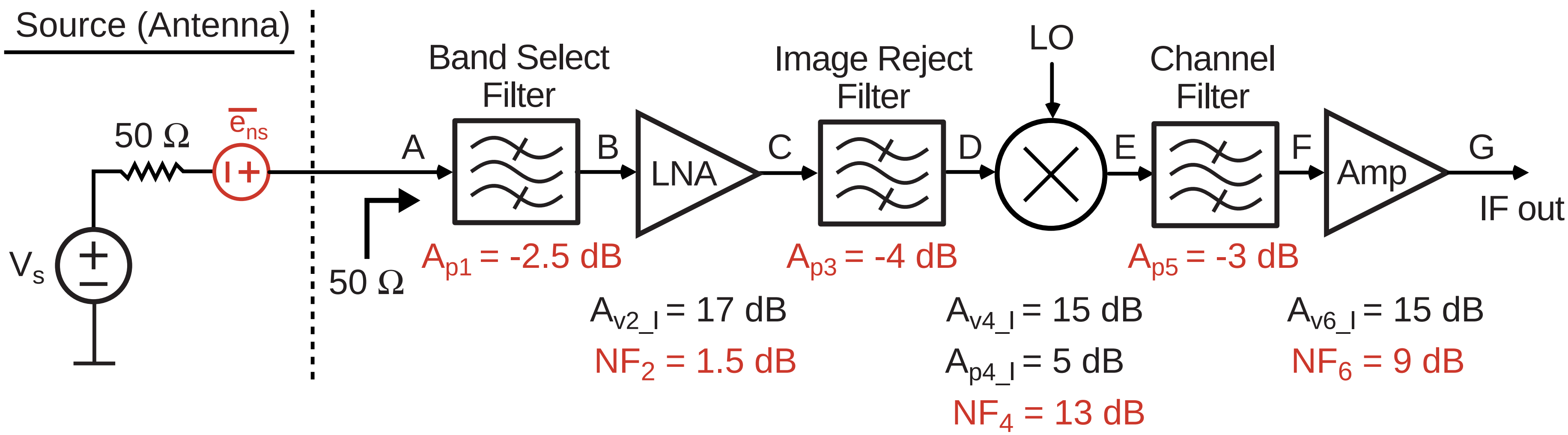
$$\boxed{= 2 + 1.5 = 3.5\ dB}$$

Example: Noise Factor Calculation for RF Receiver



- **Ports A, B, C, and D are conjugate-matched for an impedance of 50 Ohms**
  - **Noise figure of LNA and mixer are specified for source impedances of 50 Ohms**
- **Ports E and F and conjugate-matched for an impedance of 500 Ohms**
  - **Noise figure of rightmost amplifier is specified for a source impedance of 500 Ohms**

Methodology for Cascaded NF Calculation



- **Perform Noise Figure calculations from right to left**
- **Calculation of cumulative Noise Factor at node k**

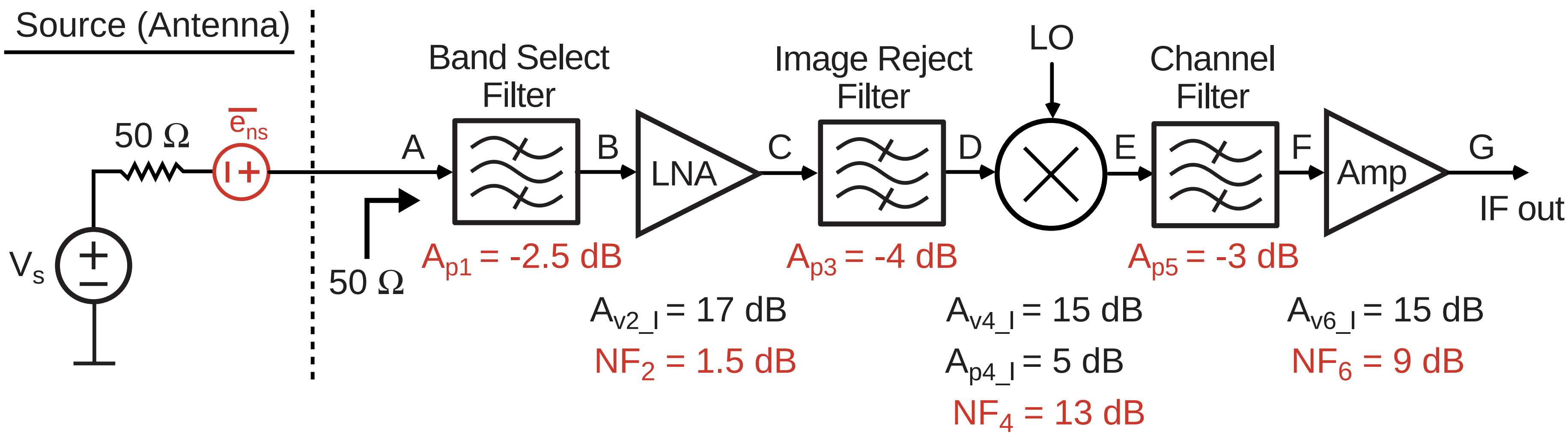
$$\mathrm{NF\_cum}_k = \mathrm{NF}_k + \frac{(\mathrm{NF}_{k+1} - 1)}{A_{pk}}$$

  - **If source and load impedances are equal**

$$\mathrm{NF\_cum}_k = \mathrm{NF}_k + \frac{(\mathrm{NF}_{k+1} - 1)}{A_{vk}^2}$$

    - True for all blocks except mixer above

Cumulative Noise Factor Calculations



$$\mathrm{NF}_E = 10^{(3+9)/10} = 15.85 \quad (12\ \mathrm{dB})$$

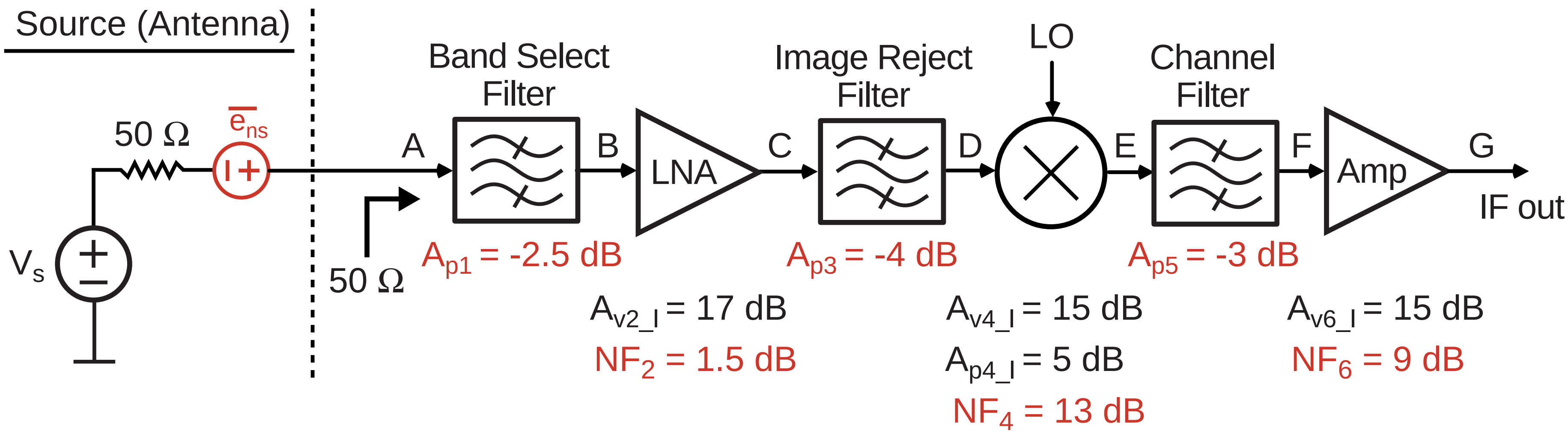
$$\mathrm{NF}_D = 10^{(13)/10} + (15.85-1)/10^{(5/10)} = 24.65 \quad (13.9\ \mathrm{dB})$$

$$\mathrm{NF}_C = 10^{(13.9+4)/10} = 61.7 \quad (17.9\ \mathrm{dB})$$

$$\mathrm{NF}_B = 10^{1.5/10} + (61.7-1)/10^{17/10} = 2.62 \quad (4.2\ \mathrm{dB})$$

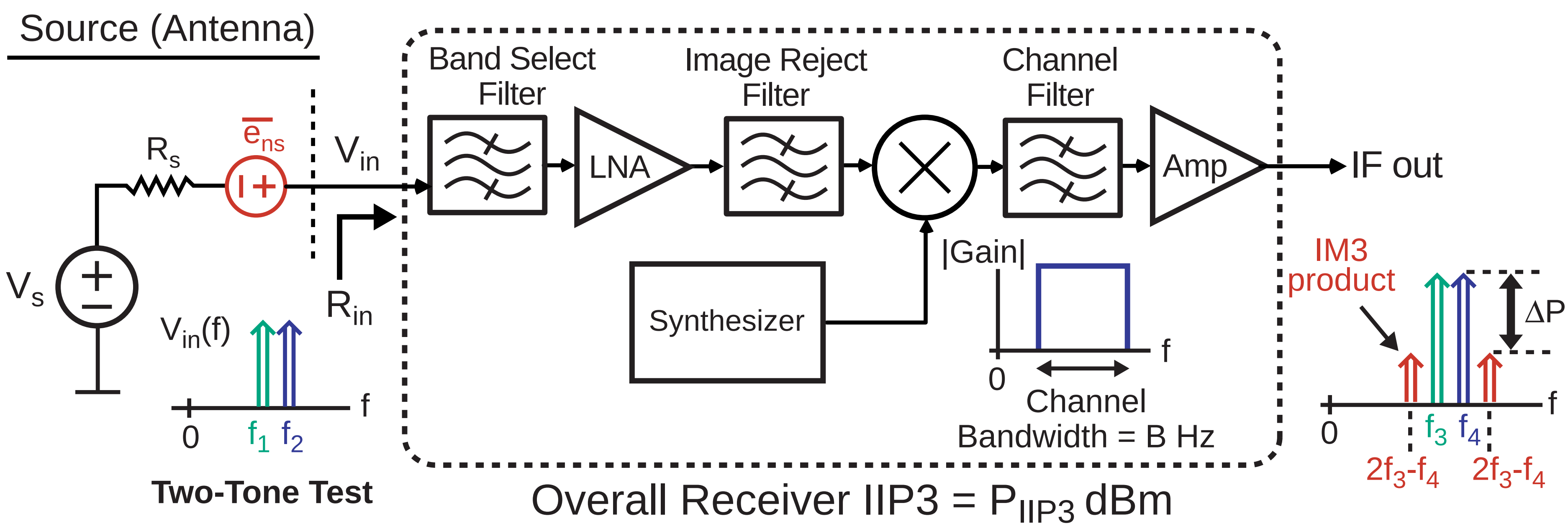
$$\mathrm{NF}_A = 10^{(2.5+4.2)/10} = 4.68 \quad (6.7\ \mathrm{dB})$$

"Level Diagram" for Gain, NF Calculation



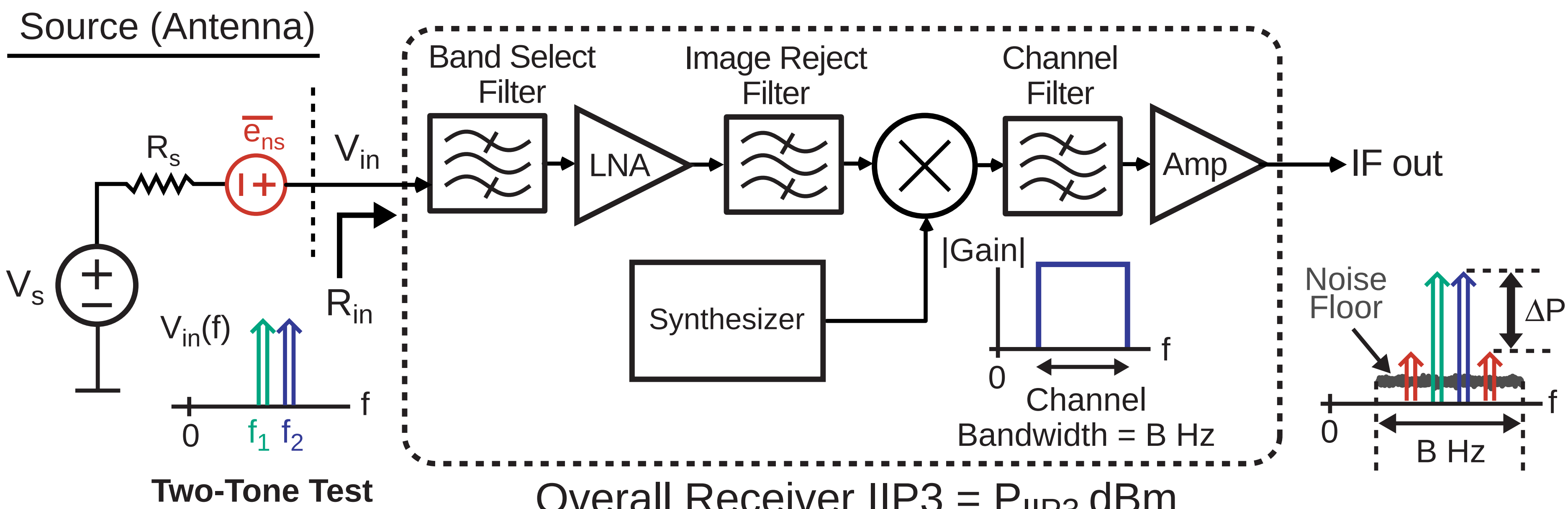
	A		B		C		D		E		F		G
Stage Gain (dB)													
Voltage (loaded)		-2.5		17		-4		15		-3		15	
Power		-2.5		17		-4		5		-3		15	
Cumulative Voltage Gain (dB)			-2.5		14.5		10.5		25.5		22.5		37.5
Stage NF (dB)		2.5		1.5		4		13		3		9	
Cumulative NF (dB)	6.7		4.2		17.9		13.9		12		9		

The Issue of Receiver Nonlinearity



- **Lower limit of input power into receiver is limited by sensitivity (i.e., required SNR, Noise Figure, etc.)**
- **Upper limit of input power into receiver is determined by nonlinear characteristics of receiver**
  - **High input power will lead to distortion that reduces SNR (even in the absence of blockers)**
  - **Nonlinear behavior often characterized by IIP3 performance of receiver**

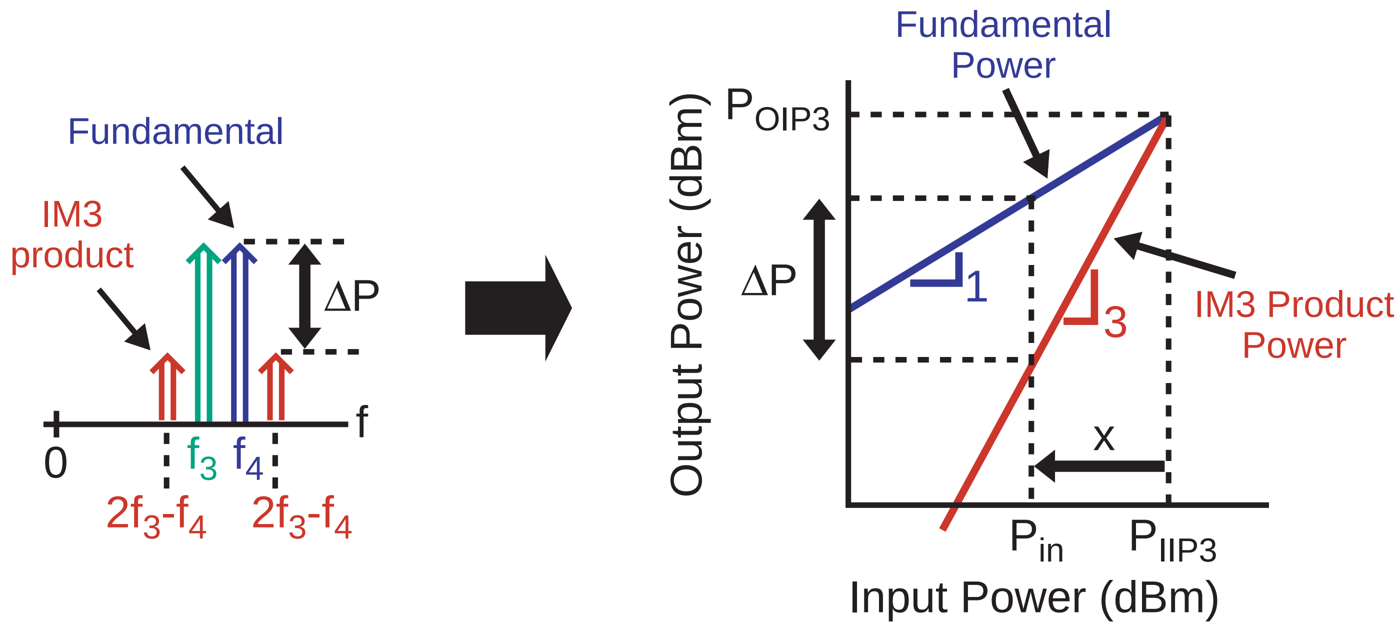
Receiver Dynamic Range



Overall Receiver IIP3 = P_{IIP3} dBm
Overall Receiver Noise Factor = NF

- **Defined as difference (in dB) between max and min input power levels to receiver**
  - **Min input power level set by receiver sensitivity**
  - **Max input power set by nonlinear characteristics of receiver**
    - Often defined as max input power for which third order IM products do not exceed the noise floor in a two tone test

A Key IIP3 Expression



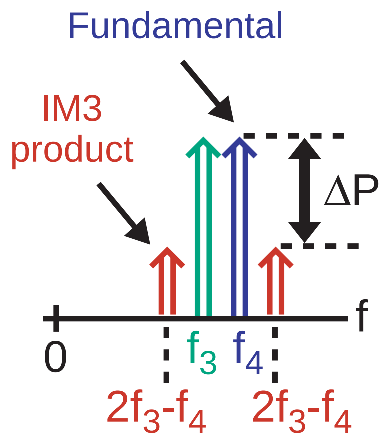
- **By inspection of the right figure**

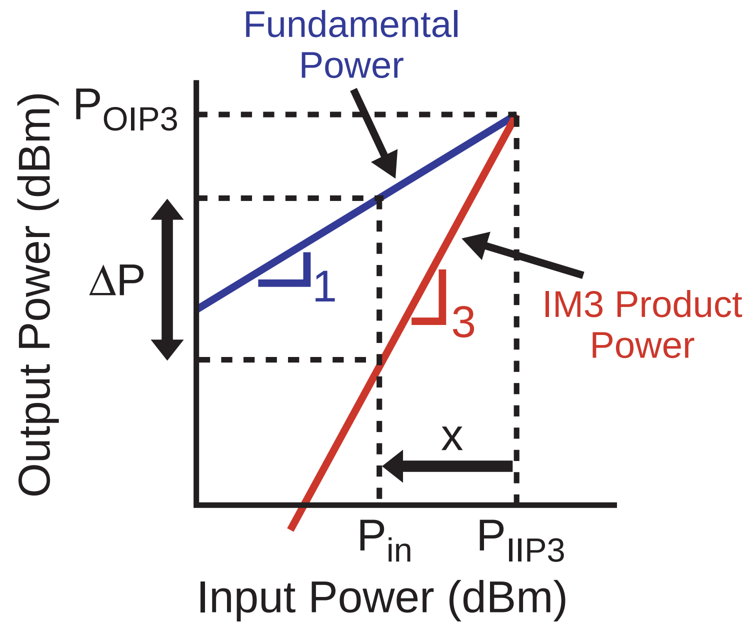
$$P_{IIP3} = P_{in} + x \qquad\qquad \Delta P = 3x - x = 2x$$

- **Combining the above expressions:**

$$\Rightarrow \quad P_{IIP3} = P_{in} + \frac{\Delta P}{2} = P_{in} + \frac{P_{out} - P_{IM3,out}}{2}$$

Refer All Signals to Input in Previous IIP3 Expression





- **Difference between fundamental and IM3 products, ΔP, is the same (in dB) when referred to input of amplifier**
  - **Both are scaled by the inverse of the amplifier gain**

$$\Rightarrow \quad P_{IIP3} = P_{in} + \frac{\Delta P}{2} = P_{in} + \frac{P_{in} - P_{IM3,in}}{2}$$

- **Applying algebra:**

$$P_{in} = \frac{2P_{IIP3} + P_{IM3,in}}{3}$$

Calculation of Spurious Free Dynamic Range (SFDR)

- **Key expressions:**
  - **Minimum P_{in} (dBm) set by SNR_{min} and noise floor**

$$\boxed{P_{in,min} = F + SNR_{out,min}}$$

    - Where F is the input referred noise floor of the receiver

$$F = -174 + 10\log(B) + dB(NF)$$

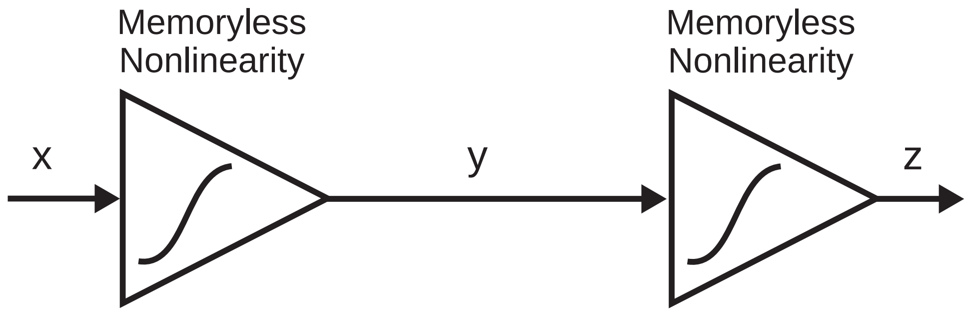
  - **Max P_{in} (dBm) occurs when IM3 products = noise floor**

$$P_{in,max} = \frac{2P_{IIP3} + P_{IM3,in,max}}{3} \Rightarrow \boxed{P_{in,max} = \frac{2P_{IIP3} + F}{3}}$$

- **Dynamic range: subtract min from max P_{in} (in dB)**

$$\boxed{SFDR = \frac{2P_{IIP3} + F}{3} - (F + SNR_{out,min})}$$

Calculation of Overall IIP3 for Cascaded Stages



- **Assume nonlinearity of each stage characterized as**

$$y(t) = \alpha_1 x(t) + \alpha_2 x^2(t) + \alpha_3 x^3(t)$$

$$z(t) = \beta_1 y(t) + \beta_2 y^2(t) + \beta_3 y^3(t)$$

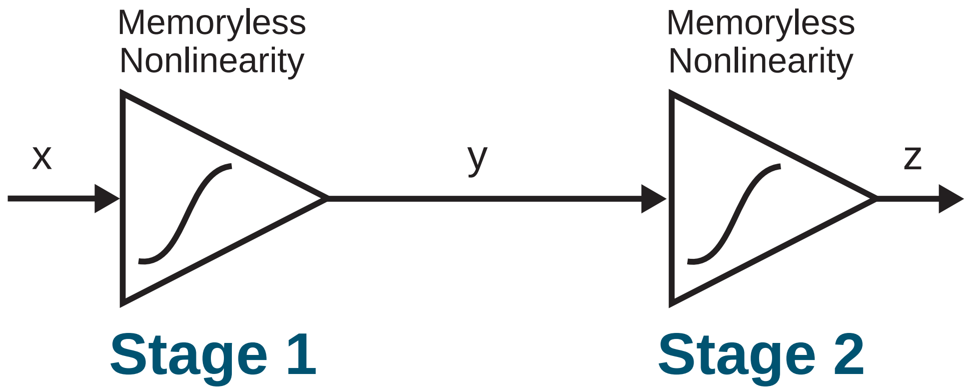
- **Multiply nonlinearity expressions and focus on first and third order terms**

$$z(t) = \alpha_1\beta_1 x(t) + (\alpha_3\beta_1 + 2\alpha_1\alpha_2\beta_2 + \alpha_1^3\beta_3)x^3(t) + \cdots$$

- **Resulting IIP3 expression**

$$A_{IP3} = \sqrt{\frac{4}{3}\left|\frac{\alpha_1\beta_1}{\alpha_3\beta_1 + 2\alpha_1\alpha_2\beta_2 + \alpha_1^3\beta_3}\right|}$$

Alternate Expression for Overall IIP3



- **Worst case IIP3 estimate – take absolute values of terms**

$$A_{IP3} \approx \sqrt{\frac{4}{3}\frac{|\alpha_1\beta_1|}{|\alpha_3\beta_1| + |2\alpha_1\alpha_2\beta_2| + |\alpha_1^3\beta_3|}}$$

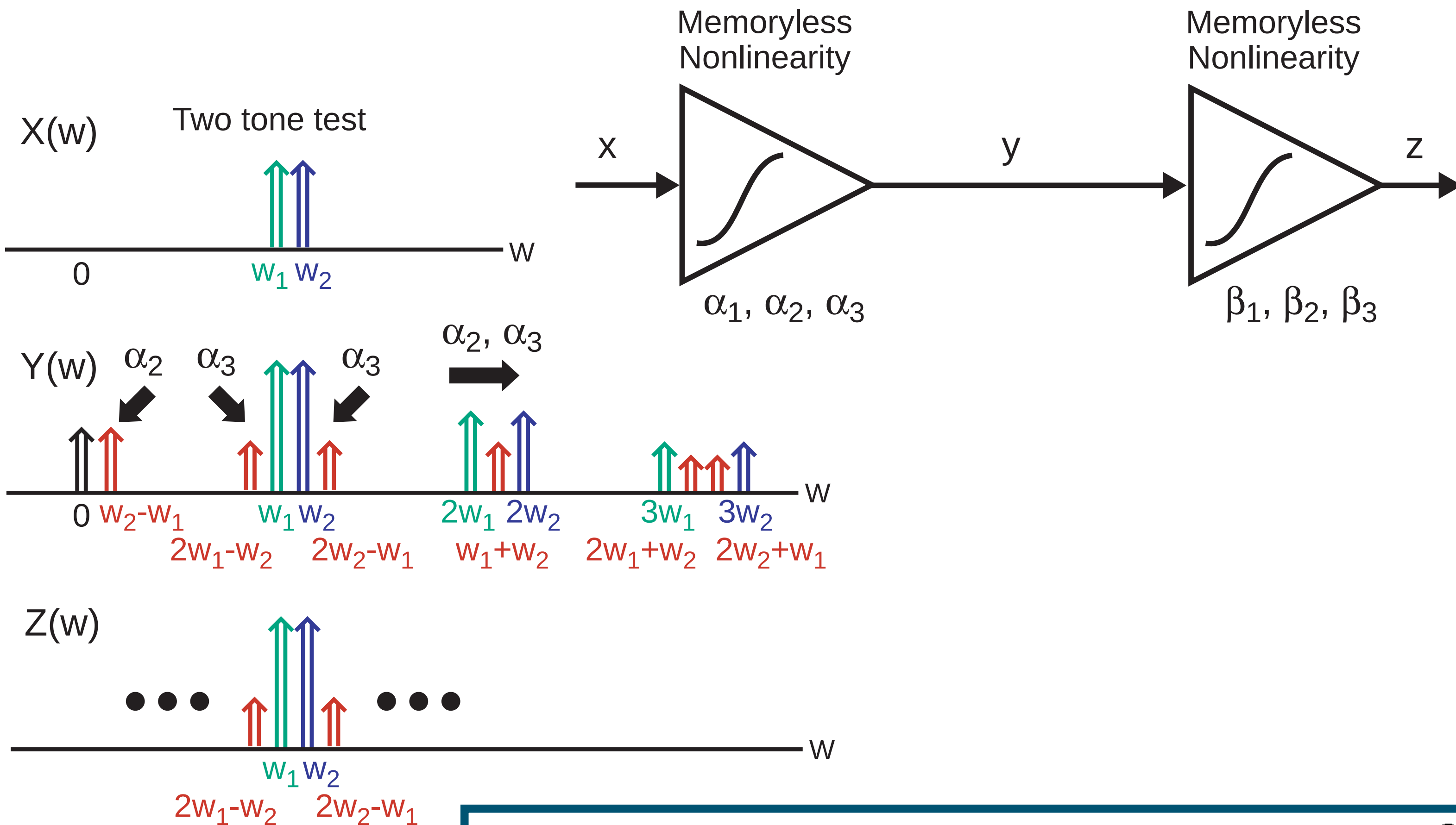
- **Square and invert the above expression**

$$\frac{1}{A_{IP3}^2} \approx \frac{3}{4}\frac{|\alpha_3\beta_1| + |2\alpha_1\alpha_2\beta_2| + |\alpha_1^3\beta_3|}{|\alpha_1\beta_1|}$$

- **Express formulation in terms of IIP3 of stage 1 and stage 2**

$$\frac{1}{A_{IP3}^2} \approx \frac{1}{A_{IP3,1}^2} + \frac{3|\alpha_2\beta_2|}{2|\beta_1|} + \frac{\alpha_1^2}{A_{IP3,2}^2}$$

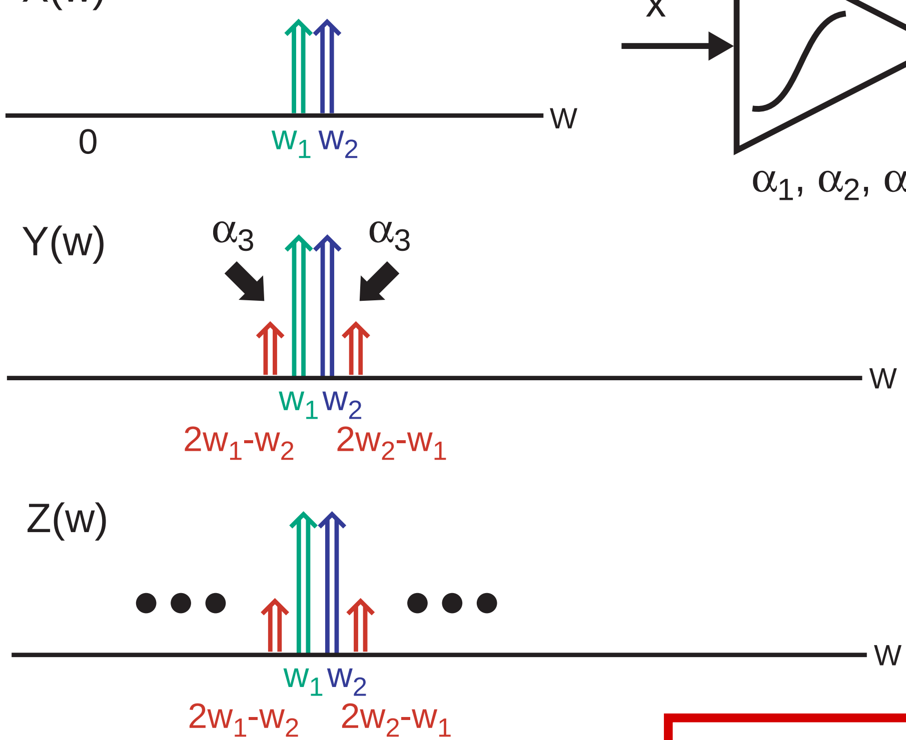
A Closer Look at Impact of Second Order Nonlinearity

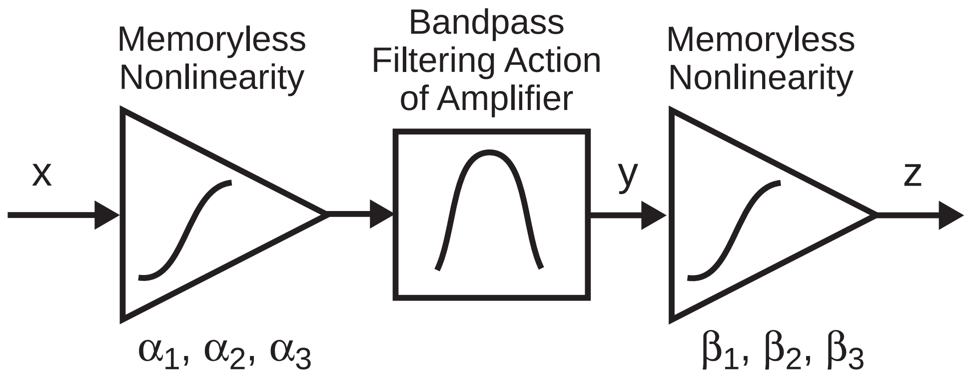


$$\boxed{\frac{1}{A_{IP3}^2} \approx \frac{1}{A_{IP3,1}^2} + \frac{3|\alpha_2\beta_2|}{2|\beta_1|} + \frac{\alpha_1^2}{A_{IP3,2}^2}}$$

- **Influence of α_2 of Stage 1 produces tones that are at frequencies far away from two tone input**

Impact of Having Narrowband Amplification

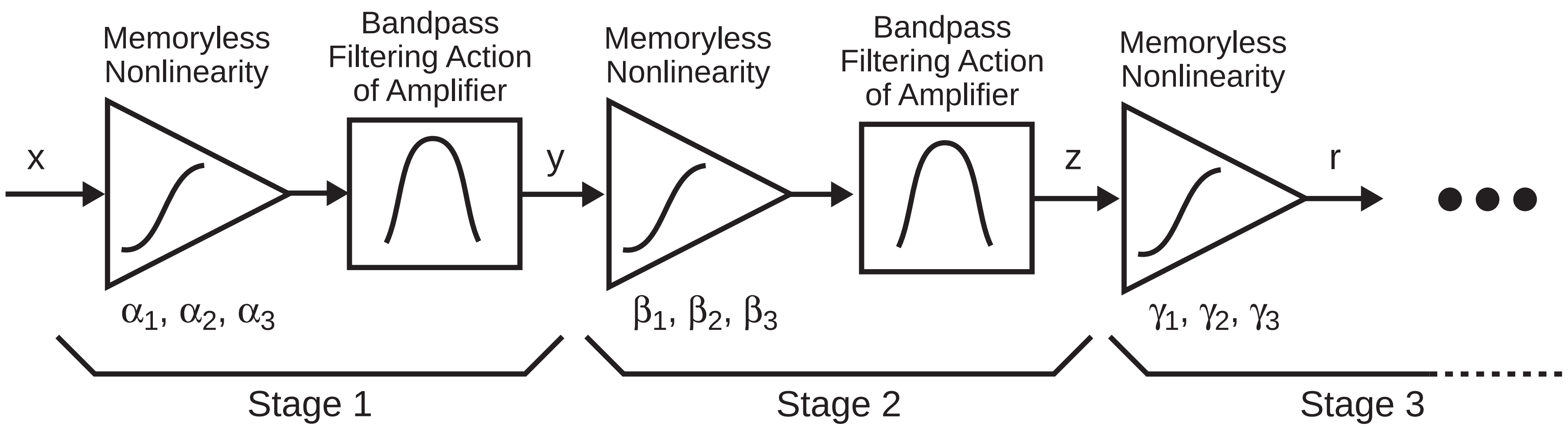




$$\frac{1}{A_{IP3}^2} \approx \frac{1}{A_{IP3,1}^2} + \frac{\alpha_1^2}{A_{IP3,2}^2}$$

- **Removal of outside frequencies dramatically simplifies overall IIP3 calculation**

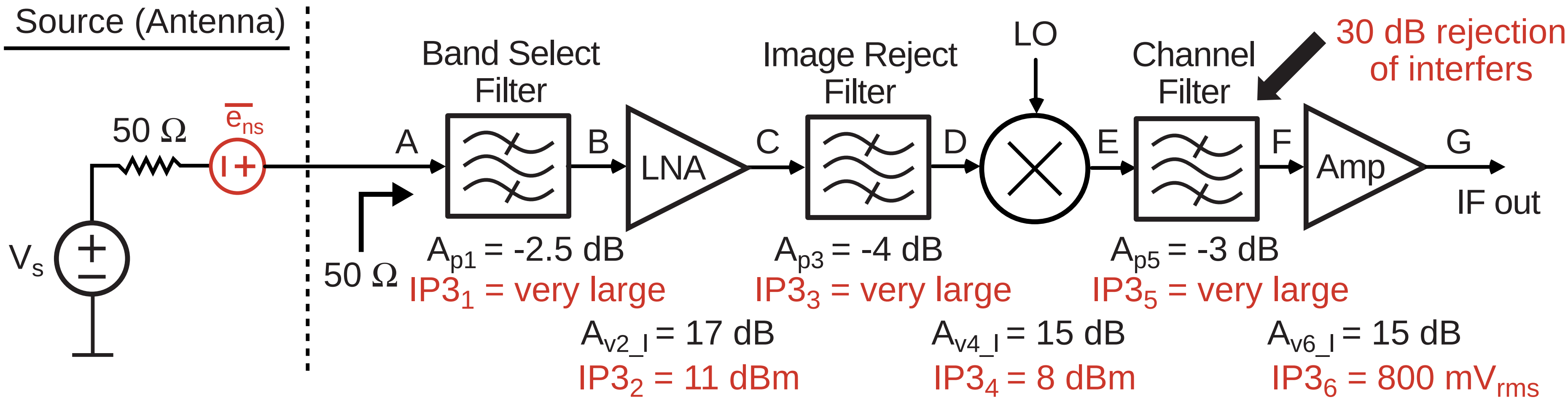
Cascaded IIP3 Calculation with Narrowband Stages



$$\frac{1}{A_{IP3}^2} \approx \frac{1}{A_{IP3,1}^2} + \frac{\alpha_1^2}{A_{IP3,2}^2} + \frac{\alpha_1^2\beta_1^2}{A_{IP3,3}^2} + \cdots$$

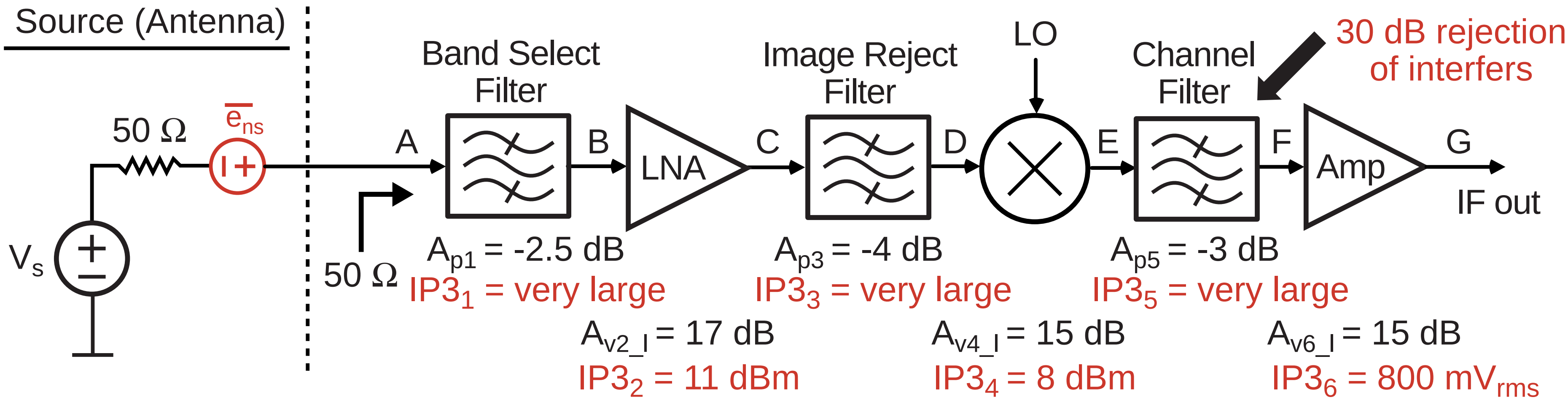
- **Note that α_1 and β_1 correspond to the loaded voltage gain values for Stage 1 and 2, respectively**

Example: IIP3 Calculation for RF Receiver



- **Ports A, B, C, and D are conjugate-matched for an impedance of 50 Ohms**
  - **IIP3 of LNA and mixer are specified for source impedances of 50 Ohms**
- **Ports E and F and conjugate-matched for an impedance of 500 Ohms**
  - **IIP3 of rightmost amplifier is specified for a source impedance of 500 Ohms**

Key Formulas for IIP3 Calculation



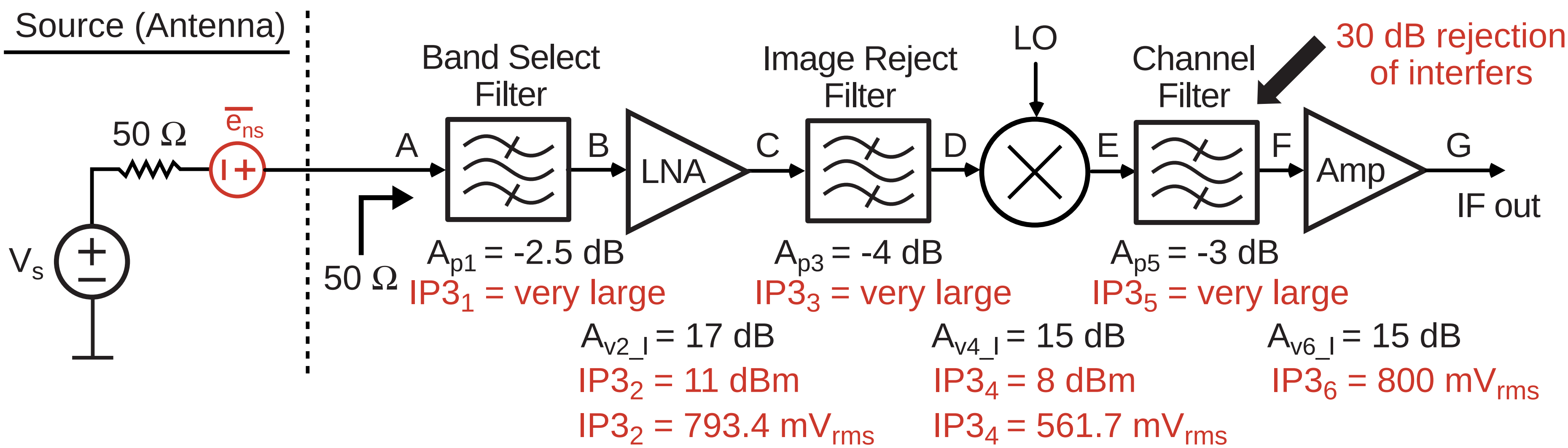
- **Perform IIP3 calculations from right to left**
- **Calculation of cumulative IIP3 at node k (IIP3 in units of rms voltage)**

$$\mathrm{IIP3\_cum}_k = 1/\sqrt{1/\mathrm{IIP3}_k^2 + A_{vk_I}^2/\mathrm{IIP3}_{k-1}^2}$$

  - **Conversion from rms voltage to dBm**

$$dBm = 10\log(1e3 \cdot V_{rms}^2/R)$$

Cumulative IIP3 Calculations



$$\mathrm{IIP3}_E = 1/\sqrt{1/\infty + 10^{(-30/10)}/0.8^2} = 25.3\ V_{rms}$$

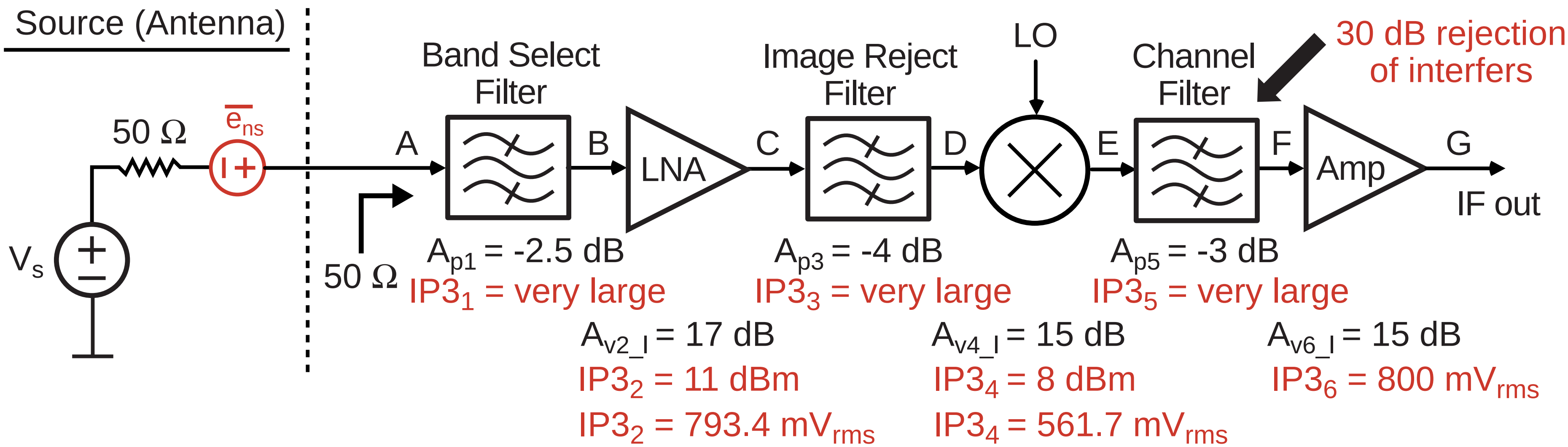
$$\mathrm{IIP3}_D = 1/\sqrt{1/0.5617^2 + 10^{(15/10)}/25.3^2} = 557.4\ mV_{rms}$$

$$\mathrm{IIP3}_C = 1/\sqrt{1/\infty + 10^{(-4/10)}/0.5574^2} = 883.4\ mV_{rms}$$

$$\mathrm{IIP3}_B = 1/\sqrt{1/0.7934^2 + 10^{(17/10)}/0.8834^2} = 123.3\ mV_{rms}$$

$$\mathrm{IIP3}_A = 1/\sqrt{1/\infty + 10^{(-2.5/10)}/0.1233^2} = 164.4\ mV_{rms}$$

“Level Diagram” for Gain, IIP3 Calculations



	A–B	B–C	C–D	D–E	E–F	F–G
Stage Gain (dB): Voltage (loaded)	-2.5	17	-4	15	-3	15
Stage Gain (dB): Power	-2.5	17	-4	5	-3	15
Stage IIP3: Power (dBm)	Very large	11	Very large	8	Very large	1.07
Stage IIP3: Voltage (mV_{rms})	Very large	793.4	Very large	561.7	Very large	800

	A	B	C	D	E	F	G
Cumulative Voltage Gain (dB)		-2.5	14.5	10.5	25.5	22.5	37.5
Cumulative IIP3 Voltage (mV_{rms})	164.4	123.3	883.4	557.4	25.3e3	800	
Cumulative IIP3 Power (dBm)	-2.67	-5.17	11.93	7.93	91	1.07	

Final Comments on IIP3 and Dynamic Range

- **Calculations we have presented assume**
  - **Narrowband stages**
    - Influence of second order nonlinearity removed
  - **IM3 products are the most important in determining maximum input power**
- **Practical issues**
  - **Narrowband operation cannot always be assumed**
  - **Direct conversion architectures are also sensitive to IM2 products (i.e., second order distortion)**
  - **Filtering action of channel filter will not reduce in-band IM3 components of blockers (as assumed in the previous example in node E calculation)**

Must perform simulations to accurately characterize IIP3 (and IIP2) and dynamic range of RF receiver