5. Receiver Gain and AGC

We find that a detector/demodulator likewise has a dynamic range, a value that has important ramifications in receiver design.

HO: Instantaneous Dynamic Range

Q: *We have calculated the overall gain of the receiver, but what should this gain be?*

A: HO: Receiver Gain

Q: *How can we build a receiver with variable gain? What microwave components do we need?*

A: HO: Automatic Gain Control (AGC)

HO: AGC Dynamic Range

Q: *How do we implement our AGC design?*

A: HO: AGC Implementation

Instantaneous Dynamic Range

Q: *So, let's make sure I have the right—**any** input signal with power exceeding the receiver sensitivity but below the saturation point **will** be adequately demodulated by the detector, right?*

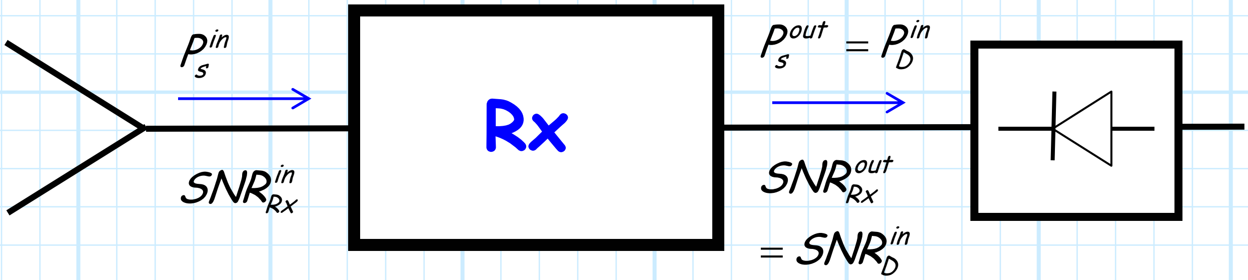
A: Not **necessarily!** The **opposite** is true, any signal with power **outside** the receiver dynamic range **cannot** be properly demodulated. However, signals **entering** the receiver within the proper dynamic range will be properly demodulated **only** if it **exits** the receiver with the proper **power**.

The reason for this is that **demodulators**, in addition to requiring a **minimum** ***SNR*** (i.e., SNR_{min}), likewise require a certain amount of **power**.

If the signals enters the receiver with power greater that the MDS, then the signal will **exit** the receiver with **sufficient SNR.** However, the signal **power** can be **too large** or **too small,** depending on the overall receiver gain G.

Q: ***How*** *can the exiting signal power be too large or too small? What would **determine** these limits?*

A: Recall that the signal **exiting** the receiver is the signal **entering** the detector/demodulator. This **demodulator** will have a **dynamic range** as well!



Say the signal **power** entering the **demodulator** (i.e., exiting the receiver) is denoted P_D^{in}. The **maximum** power that a demodulator can "handle" is thus denoted P_D^{max}, while the **minimum** amount of power required for proper demodulation is denoted as P_D^{min}. I.E.,:

$$P_D^{min} \leq P_D^{in} \leq P_D^{max}$$

Thus, every **demodulator** has its own dynamic range, which we call the **Instantaneous Dynamic Range** (IDR):

$$IDR = \frac{P_D^{max}}{P_D^{min}} \quad or \quad IDR\left(dB\right) = P_D^{max}\left(dBm\right) - P_D^{min}\left(dBm\right)$$

Typical IDRs range from 30 dB to 60 dB.

To differentiate the Instantaneous Dynamic Range from the receiver dynamic range, we refer to the **receiver** dynamic range as the **Total Dynamic Range** (TDR):

$$TDR = \frac{P_{in}^{sat}}{MDS} \quad or \quad TDR(dB) = P_{in}^{sat}(dBm) - MDS(dBm)$$

Q: *How do we insure that a signal will exit the receiver within the dynamic range of the demodulator (i.e., within the IDR)?*

A: The relationship between the signal power when **entering** the receiver and its power when **exiting** the receiver is simply determined by the **receiver gain** G_{Rx} :

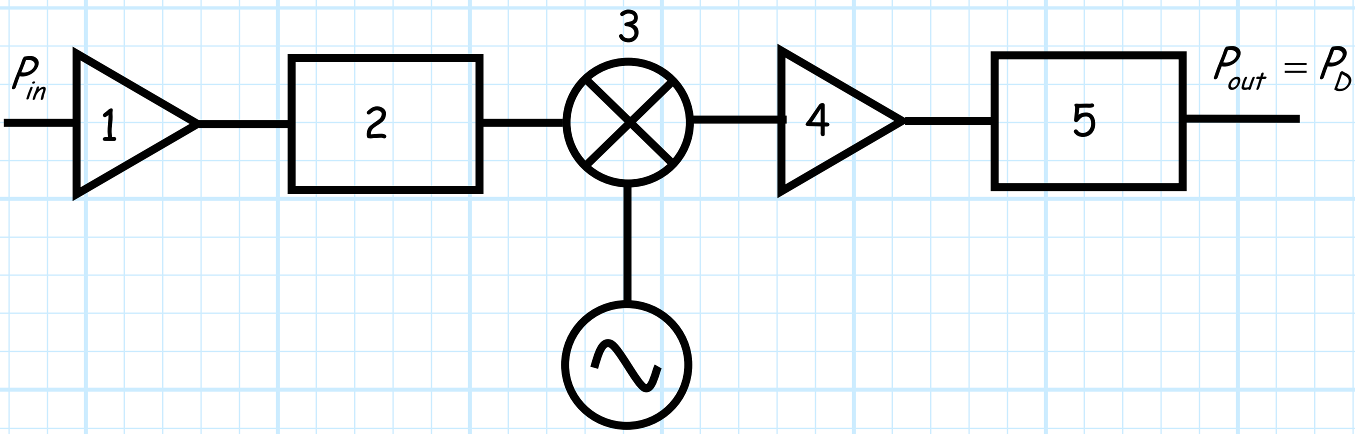
$$P_D^{in} = G_{Rx}\, P_s^{in}$$

We simply need to design the receiver gain such that P_D lies within the IDR for **all** signals P_s^{in} that lie within the TDR.

Big Problem → We find that typically TDR >> IDR. This can make setting the receiver gain G_{Rx} very complicated!

Receiver Gain

Let's consider **each element** of a **basic** super-het receiver:



1. LNA - Required to make the receiver **noise figure** F as small as possible, thus making the receiver very **sensitive.**

2. Preselector – Required to **reject** all spurious-signal creating frequencies, while simultaneously letting the desired RF bandwidth pass to the mixer.

3. Mixer - Required for down-conversion; often sets the receiver **compression point**.

4. IF Filter - Required to **suppress** all mixer IF output signals, with the **exception** of the one desired signal that we wish to demodulate. Also determines the **noise bandwidth** B of the receiver.

5. IF Amp - **Q:** ***Why*** *is this device required?* ***What*** *receiver parameter does it determine?*

A: It **is** true that the IF amplifier does **not** generally affect receiver bandwidth, or sensitivity, or saturation point, or image rejection.

→ However, the IF amp **is** the component(s) that we use to properly set the overall **receiver gain**.

Say that we have designed a receiver with some specific TDR (i.e., MDS and P_{in}^{sat}). This receiver will be connected to a demodulator with a specific IDR (i.e., P_D^{min} and P_D^{max}). All we have left to do is determine the proper gain of the **IF amplifier** to give us the **required gain** of the overall receiver.

This gain must satisfy two requirements:

Requirement 1 -We know that the overall receiver gain G_{Rx} must be **sufficiently large** such that the **smallest** possible receiver input signal ($P_s^{in} = MDS$) is boosted **at least** to the level of the smallest required demodulator signal (P_D^{min}). Thus, the absolute **smallest** value that the receiver gain should be is G_{Rx}^{min}:

$$G_{Rx}^{min} \doteq \frac{P_D^{min}}{MDS} \quad or \quad G_{min}(dB) \doteq P_D^{min}(dBm) - MDS(dBm)$$

Requirement 2 - Likewise, the overall receiver gain G_{Rx} must be **sufficiently small** to insure that the **largest** possible receiver input signal (i.e., $P_s^{in} = P_{in}^{sat}$) arrives at the demodulator with a power **less** than to the maximum level P_D^{min}. Thus, the absolute **largest** value that the receiver gain should be is G_{Rx}^{max}:

$$G_{Rx}^{max} \doteq \frac{P_D^{max}}{P_{in}^{sat}} \quad or \quad G_{Rx}^{max}(dB) \doteq P_D^{max}(dBm) - P_{in}^{sat}(dBm)$$

Q: *Seems **simple** enough! Just select an **IF amplifier** so that the overall receiver gain lies **between** these two limits:*

$$G_{Rx}^{min} < G_{Rx} < G_{Rx}^{max}$$

Right?

A: Not exactly. We are typically faced with a **big problem** at this point in our receiver design. To illustrate this problem, let's do an **example**.

Say our receiver has these **typical** values:

$$P_{in}^{sat} = -10dBm$$

$$P_D^{max} = -20dBm$$

$$P_D^{min} = -60dBm$$

$$MDS = -90dBm$$

Note then that $TDR = 80dB$ and $IDR = 40dB$.

Thus, this receiver must have a gain of **at least**:

$$\begin{aligned} G_{Rx}^{min}(dB) &= P_D^{min}(dBm) - MDS(dBm) \\ &= -60 - (-90) \\ &= 30\,dB \end{aligned}$$

But likewise have a gain of **no more** than:

$$\begin{aligned} G_{Rx}^{max}(dB) &= P_D^{max}(dBm) - P_{in}^{sat}(dBm) \\ &= -20 - (-10) \\ &= -10\ dB \end{aligned}$$

So **here's** our solution! The receiver gain must be any value **greater than 30 dB**, as long as it is simultaneously **less than -10dB**:

$$30dB < G_{Rx}(dB) < -10dB$$

Hopefully, it is evident that there are **no solutions** to the equation above!!

Q: *Yikes! Is this receiver **impossible** to build?*

A: Note that the values used in this example is are very **typical**, and thus the problem that we have encountered is likewise **very typical**.

We almost **always** find that $G_{Rx}^{min} > G_{Rx}^{max}$, making the solution G_{Rx} to the equation $G_{Rx}^{min} < G_{Rx} < G_{Rx}^{max}$ **non-existent**!

To see why, consider the **ratio** $G_{Rx}^{max} / G_{Rx}^{min}$:

$$\frac{G_{Rx}^{max}}{G_{Rx}^{min}} = \frac{P_D^{max} / P_{in}^{sat}}{P_D^{min} / MDS} = \frac{P_D^{max} / P_D^{min}}{P_{in}^{sat} / MDS} = \frac{IDR}{TDR}$$

In other words, for G_{max} to be **larger** than G_{min} (i.e., for $G_{max}/G_{min} > 1$), then the IDR must be **larger** than the TDR (i.e., $IDR/TDR > 1$).

But, we find that almost always the demodulator dynamic range (IDR) is **much less** than the receiver dynamic range (TDR), thus G_{max} is **almost never** larger than G_{min}.

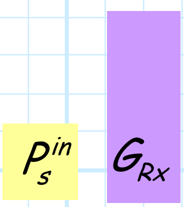
Typically, $TDR >> IDR$

Big Solution → However, there is **one** fact that leads to a solution to this **seemingly** intractable problem.

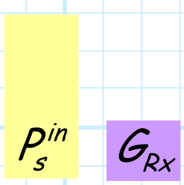
> The **one** desired input signal power can be as small as MDS **or** as large as P_{in}^{sat}, but it cannot have **both** values **at the same time**!

Thus, the receiver gain G_{Rx} may need to be **larger** than G_{Rx}^{min} (i.e., when $P_s^{in} = MDS$) or **smaller** as G_{Rx}^{max} (i.e., when $P_s^{in} = P_{in}^{sat}$), but it does **not** need to be to be both **at the same time**!

In other words, we can make the gain of a receiver **adjustable** (i.e., adaptive), such that:



1. the gain becomes **large** enough ($G_{Rx} > G_{Rx}^{min}$) when the input signal power P_s^{in} is **small**, but:



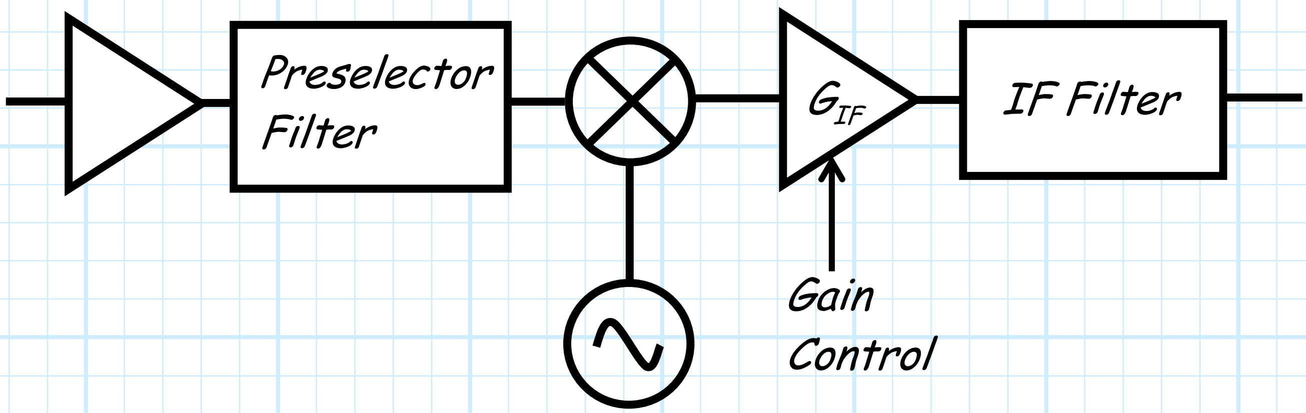
2. the gain becomes **small** enough ($G_{Rx} < G_{Rx}^{max}$) when the input signal power P_s^{in} is **large**.

Q: ***Change** the gain of the receiver, how can we possibly do **that**?*

A: We can make the gain of the **IF** amplifier **adjustable**, thus making the overall receiver gain adjustable. This gain is automatically adjusted in response to the signal power, and we call this process **Automatic Gain Control** (AGC).

Automatic Gain Control

To implement **Automatic Gain Control** (AGC) we need to make the gain of the IF amplifier **adjustable**:

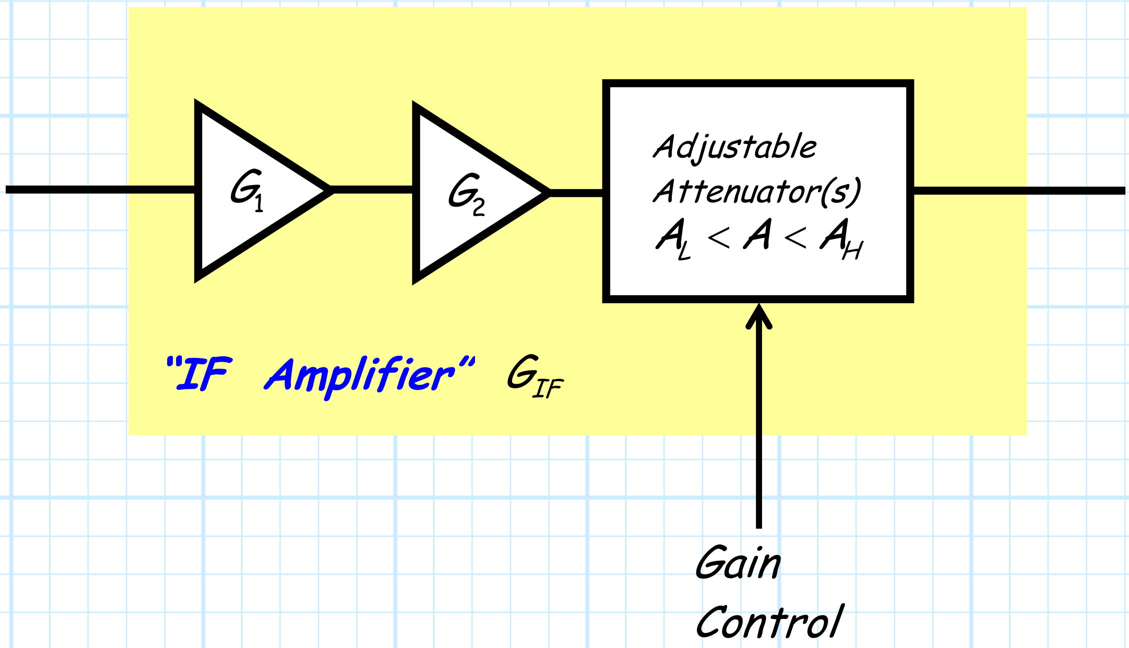


Q: *__Are__ there such things as __adjustable gain__ amplifiers?*

A: Yes and no.

Typically, voltage controlled amplifiers work **poorly**, have **limited** gain adjustment, or **both**.

Instead, receiver designers implement an adjustable gain amplifier using **one or more** fixed gain amplifiers and **one or more** variable attenuators (e.g., digital attenuators).



Two amplifiers are used in the design above, although one, two, three, or even four amplifiers are sometimes used.

The adjustable **attenuator** can likewise be implemented in a number of ways. Recall the attenuator can be either **digital** or **voltage controlled**. Likewise, the attenuator can be implemented using either **one** attenuator, or with **multiple** cascaded attenuator components.

However it is implemented, the **gain** of the overall "IF amplifier" is simply the **product** of the fixed amplifier gains, **divided** the total attenuation A. Thus, for the **example above**:

$$G_{IF} = \frac{G_1 G_2}{A} \qquad G_{IF}(dB) = G_1(dB) + G_2(dB) - A(dB)$$

Now, the key point here is that this gain is **adjustable**, since the attenuation can be varied from:

$$A_L < A < A_H$$

Thus, the "IF amplifier" gain can **vary** from:

$$G_{IF}^{L} < G_{IF} < G_{IF}^{H}$$

Where G_{IF}^{L} is the **lowest** possible "IF amplifier" gain:

$$G_{IF}^{L} = \frac{G_1 G_2}{A_H} \qquad G_{IF}(dB) = G_1(dB) + G_2(dB) - A_H(dB)$$

And G_{IF}^{H} is the **highest** possible "IF amplifier" gain:

$$G_{IF}^{H} = \frac{G_1 G_2}{A_L} \qquad G_{IF}(dB) = G_1(dB) + G_2(dB) - A_L(dB)$$

Note the **gain** is the **highest** when the **attenuation** is the **lowest**, and vice versa (this should make **perfect** sense to **you**!).

However, recall that the value of the **lowest attenuation** value is **not equal to one** (i.e., $A_L > 1$)! Instead A_L represents the **insertion loss** of the attenuators when in their minimum attenuation state. The **highest** attenuation value A_H must likewise reflect this insertion loss!

Recall also that the **total receiver gain** is the product of the gains of **all** the components in the receiver chain. For example:

$$G_{Rx} = G_{LNA}\, G_{preselector}\, G_{mixer}\, G_{IF}\, G_{IFfilter}$$

Note, however, that the only **adjustable** gain in this chain is the "**IF amplifier**" gain G_{IF}, thus the remainder of the receiver gain is **fixed**, and we can thus define this **fixed gain** G_{Rx}^{fixed} as:

$$G_{Rx}^{fixed} \doteq \frac{G_{Rx}}{G_{IF}}$$

Thus, G_{Rx}^{fixed} is simply the gain of the entire receiver, with the **exception** of the "IF amplifier".

Since the gain of the "**IF amplifier**" is adjustable, the gain of **entire receiver** is likewise adjustable, varying over:

$$G_{Rx}^{L} < G_{Rx} < G_{Rx}^{H}$$

where:

$$G_{Rx}^{L} = G_{Rx}^{fixed}\; G_{IF}^{L}$$

and:

$$G_{Rx}^{H} = G_{Rx}^{fixed}\; G_{IF}^{H}$$

Q: *So what should the values of G_{IF}^{L} and G_{IF}^{H} **be**? How will I know if my design produces a G_{IF}^{L} that is **sufficiently** low, or a G_{IF}^{H} that is **sufficiently** high?*

A: Let's think about the requirements of each of these **two** gain values.

1: G_{IF}^{H}

Remember, a receiver designer must design their "IF Amplifier" such that the **largest possible** receiver gain G_{Rx}^{H} **exceeds** the minimum gain requirement (i.e., $G_{Rx}^{H} > G_{Rx}^{min}$)—a requirement that is necessary when the receiver input signal is at its **smallest** (i.e., when $P_s^{in} = MDS$).

To accomplish this, we find that:

$$G_{Rx}^{H} > G_{Rx}^{min}$$

$$G_{Rx}^{fixed} G_{IF}^{H} > G_{Rx}^{min}$$

$$G_{IF}^{H} > \frac{G_{Rx}^{min}}{G_{Rx}^{fixed}}$$

Thus, since $G_{Rx}^{min} = P_D^{min} / MDS$ we can conclude that our "IF amplifier" **must be designed** such that its **highest possible** gain G_{IF}^{H} **exceeds**:

$$G_{IF}^{H} > \frac{P_D^{min}}{G_{Rx}^{fixed}\, MDS}$$

or

$$G_{IF}^{H}(dB) > P_D^{min}(dBm) - G_{Rx}^{fixed}(dB) - MDS(dBm)$$

2: G_{IF}^{L}

Additionally, a receiver designer must design their "IF Amplifier" such that the **smallest possible** receiver gain G_{IF}^{L} is **less** that the maximum gain requirement (i.e., $G_{L} < G_{max}$)—a requirement that is applicable when the receiver input signal is at its **largest** (i.e., when $P_{in} = P_{in}^{sat}$).

To accomplish this, we find that:

$$G_{Rx}^{L} < G_{Rx}^{max}$$

$$G_{Rx}^{fixed} G_{IF}^{L} < G_{Rx}^{max}$$

$$G_{IF}^{L} < \frac{G_{Rx}^{max}}{G_{Rx}^{fixed}}$$

Thus, since $G_{Rx}^{min} = P_{D}^{min} / MDS$ we can conclude that our "IF amplifier" **must be designed** such that its **highest possible** gain G_{IF}^{H} **exceeds**:

Thus, since $G_{Rx}^{max} = P_{D}^{max} / P_{in}^{sat}$ we can conclude that our "IF amplifier" **must be designed** such that its **lowest possible** gain G_{IF}^{L} is below:

$$G_{IF}^{L} < \frac{P_D^{max}}{G_{Rx}^{fixed}\ P_{in}^{sat}}$$

or

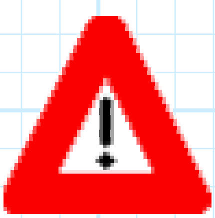
$$G_{IF}^{L}(dB) < P_D^{max}(dBm) - G_{Rx}^{fixed}(dB) - P_{in}^{sat}(dBm)$$

Q: *I'm still a bit confused. Now what is the **difference** between $G_{Rx}^{min}, G_{Rx}^{max}$ and G_{Rx}^{L}, G_{Rx}^{H}?*

A: The values G_{Rx}^{min} and G_{Rx}^{max} are in fact **requirements** that are placed on the receiver designer.

* In other words, there **must** be some IF gain setting that will result in a receiver gain G_{Rx} greater than G_{Rx}^{min} (a requirement for detecting $P_s^{in} = MDS$), and there **must** be some IF gain setting that will result in a receiver gain G_{Rx} less than G_{Rx}^{max} (a requirement for detecting $P_s^{in} = P_{in}^{sat}$)

* In contrast, the values G_{IF}^{L} and G_{IF}^{H} are the **actual** minimum and maximum values of the receiver gain. They state the performance of a **specific receiver design**.



Properly designed, we will find that $G_{Rx}^{H} > G_{Rx}^{min}$, and $G_{Rx}^{L} < G_{Rx}^{max}$. However, this is true **only** if we have properly design our "IF Amplifier"!

AGC Dynamic Range

Now let's consider the **dynamic range** of our ***AGC***, defined as:

$$AGC \text{ Dynamic Range} = \frac{G_{Rx}^{H}}{G_{Rx}^{L}} = \frac{G_{Rx}^{fixed}\, G_{IF}^{H}}{G_{Rx}^{fixed}\, G_{IF}^{L}} = \frac{G_{IF}^{H}}{G_{IF}^{L}}$$

Therefore:

$$\begin{aligned} AGC \text{ Dynamic Range}(dB) &= G_{Rx}^{H}(dB) - G_{Rx}^{L}(dB) \\ &= G_{IF}^{H}(dB) - G_{IF}^{L}(dB) \end{aligned}$$

Q: *Just how much dynamic range do we* ***need?***

A: Since for a **properly designed** receiver, $G_{Rx}^{H} > G_{Rx}^{min}$ and $G_{Rx}^{L} < G_{Rx}^{max}$, we can conclude that for a **properly designed** receiver:

$$AGC \text{ Dynamic Range} = \frac{G_{Rx}^{H}}{G_{Rx}^{L}} > \frac{G_{Rx}^{min}}{G_{Rx}^{max}}$$

Meaning that, since $G_{Rx}^{min} = P_D^{min} / MDS$ and $G_{Rx}^{max} = P_D^{max} / P_{in}^{sat}$:

$$\begin{aligned} AGC \text{ Dynamic Range} &> \frac{P_D^{min}}{MDS} \frac{P_{in}^{sat}}{P_D^{max}} \\ &> \frac{P_D^{min}}{P_D^{max}} \frac{P_{in}^{sat}}{MDS} \\ &> \frac{TDR}{IDR} \end{aligned}$$

Thus, we conclude that for a **properly designed** receiver:

$$AGC \text{ Dynamic Range} > \frac{TDR}{IDR}$$

or

$$AGC \text{ Dynamic Range}(dB) > TDR(dB) - IDR(dB)$$

From the standpoint of "IF Amplifier" **design**, this result has a **specific** meaning.

Since the gain of the **amplifiers** used in the "IF Amplifier" design is fixed (e.g., $G_1\ G_2$), the **ratio** of the largest and smallest IF amplifier gain is simply the ratio of the largest and smallest **attenuator** values:

$$AGC \text{ Dynamic Range} = \frac{G_{IF}^{H}}{G_{IF}^{L}} = \frac{G_1 G_2}{A_L}\frac{A_H}{G_1 G_2} = \frac{A_H}{A_L}$$

or

$$AGC \text{ Dynamic Range}(dB) = A_H(dB) - A_L(dB)$$

Thus, we can conclude that the variable attenuator(s) in an "IF amplifier" **must** be selected such that the **range of attenuation**, from A_H to A_L satisfies:

$$\frac{A_H}{A_L} > \frac{TDR}{IDR}$$

or

$$A_H(dB) - A_L(dB) > TDR(dB) - IDR(dB)$$

Note this is a necessary requirement for proper receiver operation, but it is not a sufficient one!

In other words, the expression above provides only **one** "IF Amplifier" design equation. We must **also** select the gains of the **amplifiers** in the "IF Amplifier" such that:

$$G_{IF}^{H} = \frac{G_1 G_2}{A_L} > \frac{G_{Rx}^{min}}{G_{Rx}^{fixed}}$$

where we recall that G_{Rx}^{fixed} represents the gain of all the receiver components, **except** those components comprising the "IF Amplifier".