2. The Super-Heterodyne Receiver

HO: The Super-Heterodyne Receiver

Q: *So how do we **tune** a super-het? To what **frequency** should we set the local oscillator?*

A: **HO: Super-Heterodyne Tuning**

HO: The Preselector Filter

Q: *So what should this preselector filter be? How should we determine the required order of this filter?*

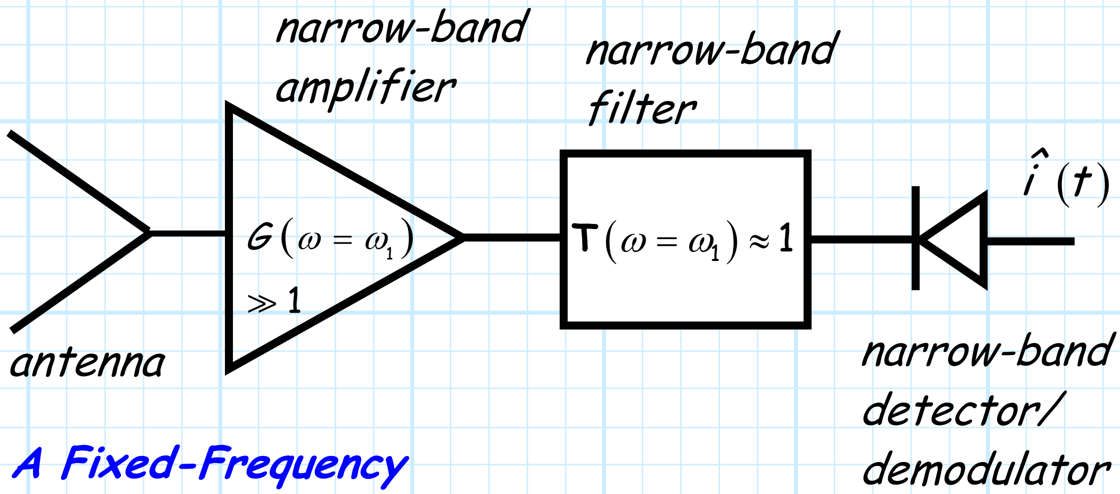
A: **HO: The Image and Third-Order Signal Rejection**

There are many **variants** of the basic super-het receiver that can **improve** receiver performance.

HO: Advanced Receiver Designs

The Super-Heterodyne Receiver

Note that the heterodyne receiver would be an excellent design if we **always** wanted to receive a signal at **one** particular signal frequency (ω_1, say):



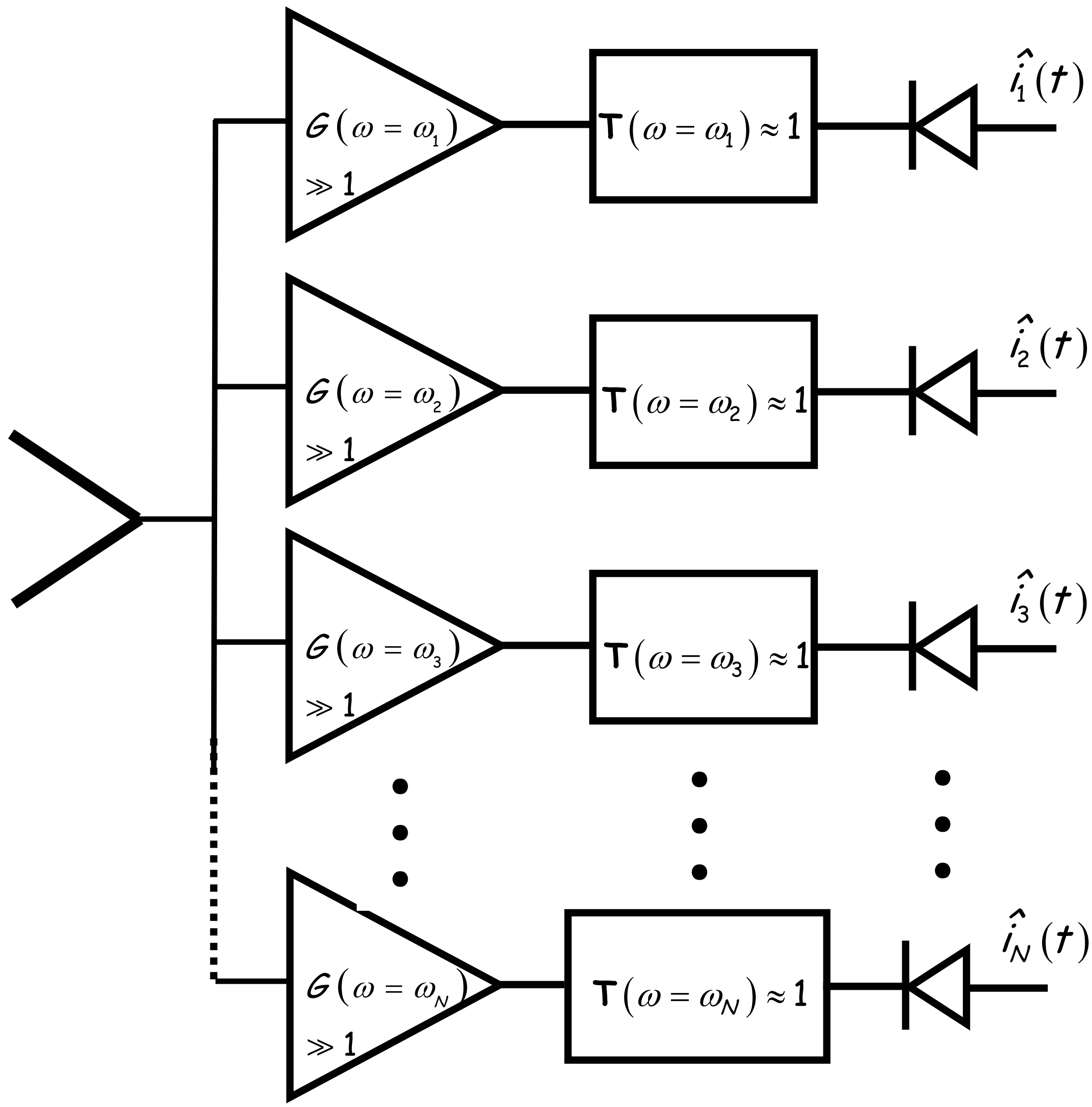
A Fixed-Frequency Heterodyne Receiver

No tuning is required!

Moreover, we can **optimize** the amplifier, filter, and detector performance for **one**—and **only** one—signal frequency (i.e., ω_1).

Q: *Couldn't we just build one of these fixed-frequency heterodyne receivers for **each** and every signal frequency of interest?*

A: Absolutely! And we sometimes (but not often) do. We call these receivers **channelized receivers**.



A Channelized Receiver

But, there are several important **problems** involving channelized receivers.

→ They're big, power hungry, and **expensive**!

For **example**, consider a design for a channelized FM radio. The FM band has a **bandwidth** of 108-88 = 20 MHz, and a channel **spacing** of 200 kHz. Thus we find that the **number** of FM **channels** (i.e., the number of possible FM radio stations) is:

$$\frac{20 \text{ MHz}}{200 \text{ kHz}} = 100 \quad \text{channels !!!}$$

Thus, a channelized **FM radio** would require **100 heterodyne receivers**!

Q: *Yikes! Aren't there* ***any*** *good receiver designs!?!*

A: Yes, there **is** a good receiver solution, one developed more than 80 years ago by—**Edwin Howard Armstrong**! In fact, is was such a good solution that it is **still** the **predominant** receiver architecture used today.

Armstrong's approach was both **simple** and **brilliant**:

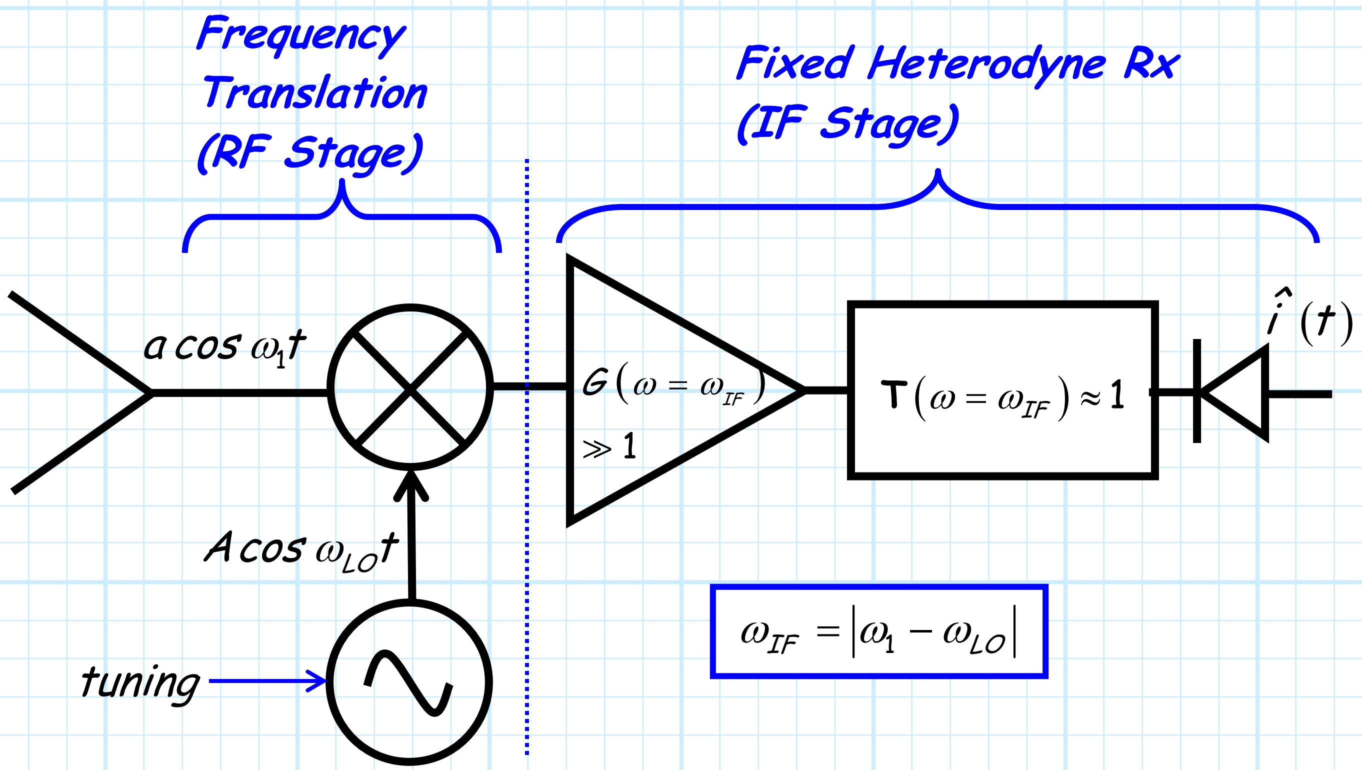
> **Instead** of changing (tuning) the receiver hardware to match the desired signal frequency, we should change the **signal** frequency to match the receiver **hardware**!

Q: *Change the signal **frequency**? How can we possibly do **that**?*

A: We **know** how to do this! We **mix** the signal with a **Local Oscillator**!

We call this design the **Super-Heterodyne Receiver**!

A super-heterodyne receiver can be viewed as simply as a **fixed frequency heterodyne** receiver, proceeded by a **frequency translation** (i.e., down-conversion) stage.



A Simple Super-Het Receiver Design

The **fixed** heterodyne receiver (the one that we match the signal frequency **to**), is known as the **IF stage**. The fixed-frequency ω_{IF} that this heterodyne receiver is designed (and optimized!) for is called the **Intermediate Frequency** (IF).

Q: *So what is the value of this Intermediate Frequency ω_{IF} ?? How does a receiver design engineer choose this value?*

A: **Selecting** the "IF frequency" value is perhaps the most **important** choice that a "super-het" receiver designer will make. It has **many** important ramifications, both in terms of **performance** and **cost**.

* We will discuss most of these ramifications **later**, but right now let's simply point out that the IF should be selected such that the cost and performance of the (IF) **amplifier**, (IF) **filter**, and detector/**demodulator** is **good**.

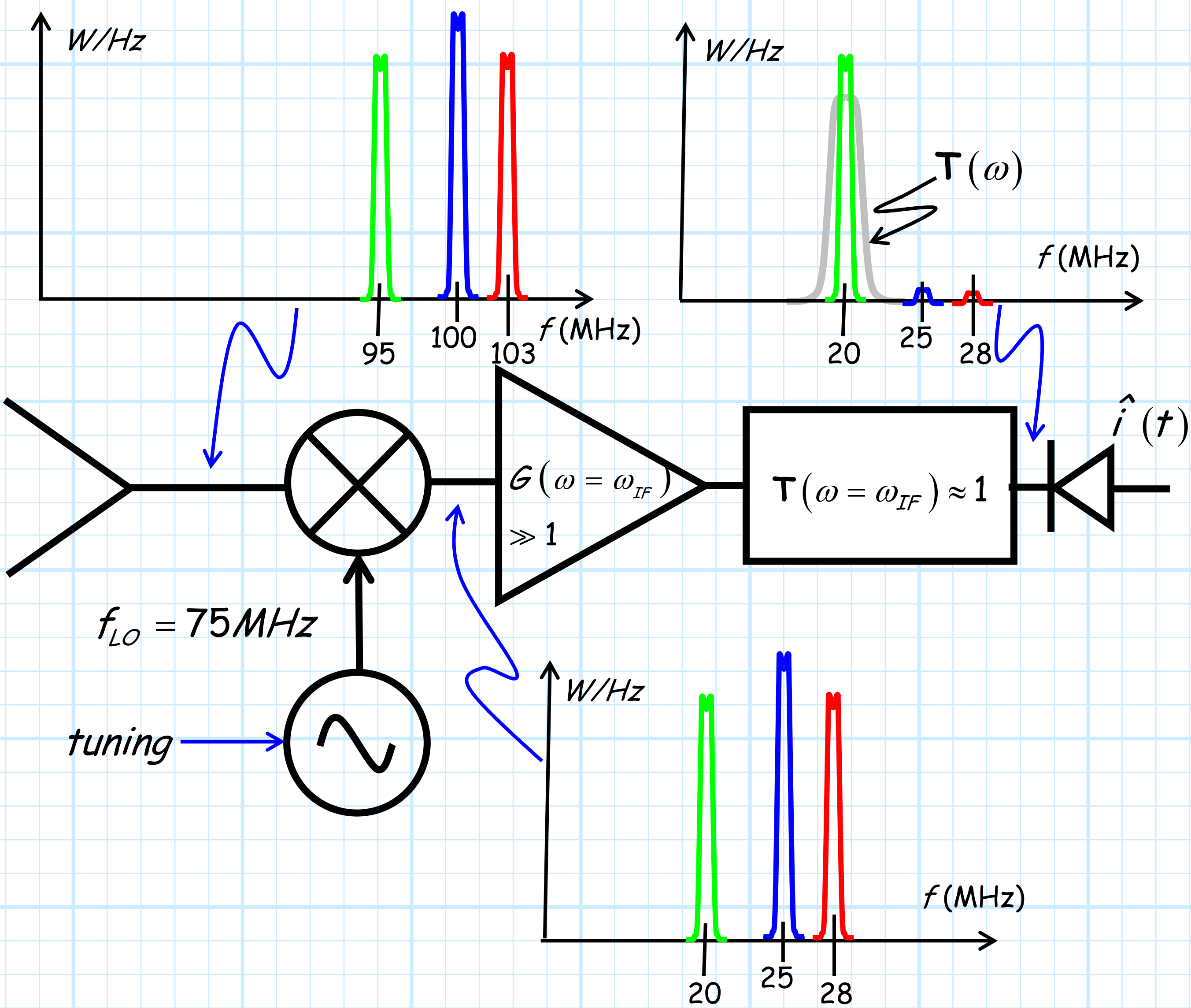
* Generally speaking, as we go **lower** in frequency, the cost of components go **down**, and their performance **increases** (these are both good things!). As a result, the IF frequency is **typically** (but **not** always!) selected such that it is much **less** (e.g., an order of magnitude or more) than the RF signal frequencies we are attempting to demodulate.

* Therefore, we typically use the mixer/LO to **down-convert** the signal frequency from its relatively **high RF** frequency to a relatively **low IF** frequency. We are thus interested in the **second-order** mixer term $|\omega_{RF} - \omega_{LO}|$.

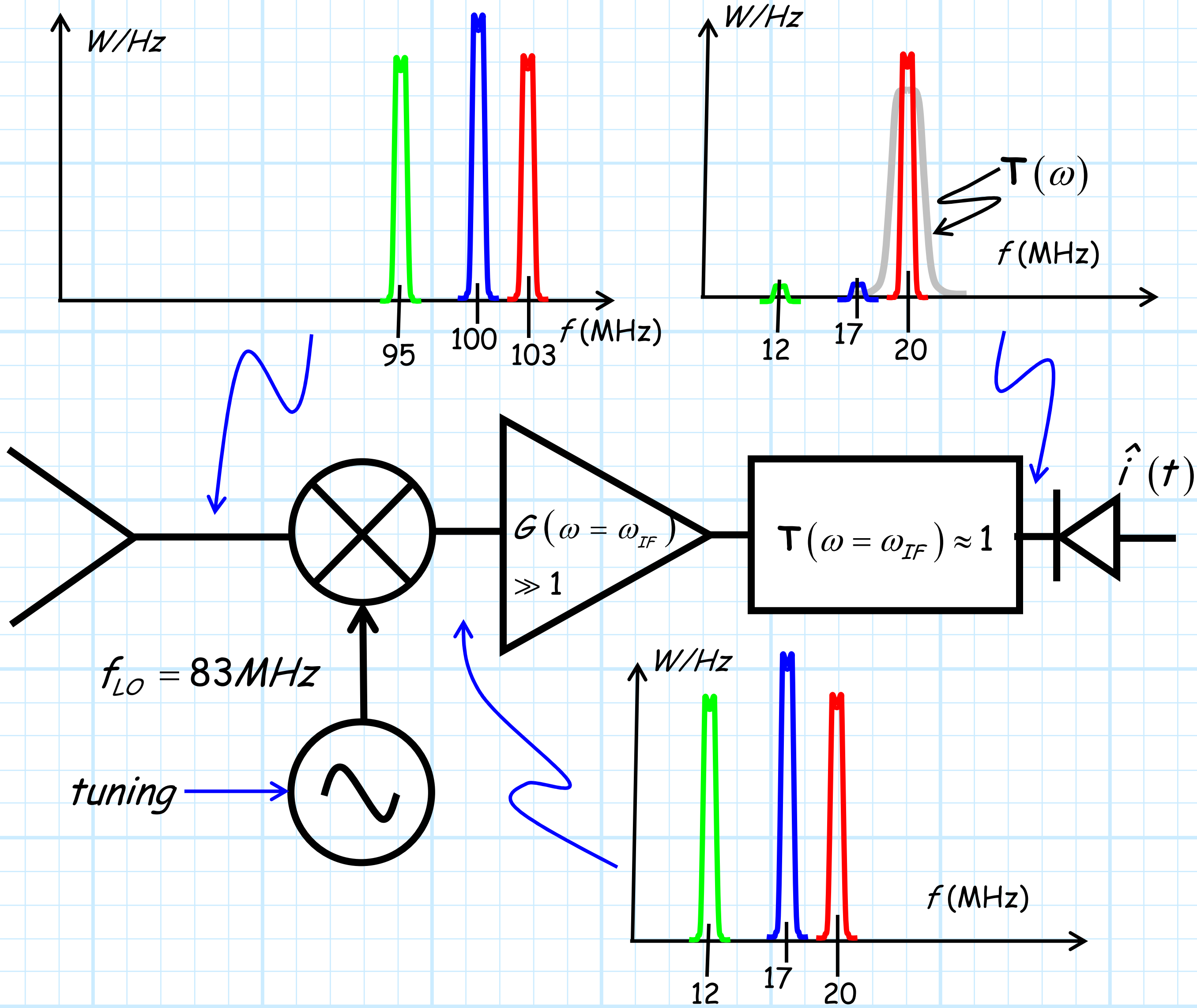
As a result, we must **tune** the LO so that $|\omega_1 - \omega_{LO}| = \omega_{IF}$—that is, if we wish to demodulated the RF signal at frequency ω_1!

For example, say there exits radio signals (i.e., radio stations) at 95 MHz, 100 MHz, and 103 MHz. Likewise, say that the **IF** frequency selected by the receiver design engineer is f_{IF} = **20 MHz.**

We can tune to the station at **95 MHz** by setting the Local Oscillator to 95-20=**75 MHz**:



Or, we could tune to the station at **103 MHz** by tuning the **Local Oscillator** to 103-20=**83 MHz**:



Q: *Wait a second! You mean we need to* ***tune*** *an oscillator. How is that any* ***better*** *than having to* ***tune*** *an amplifier and/or filter?*

A: Tuning the LO is **much** easier than tuning a band-pass filter. For an oscillator, we just need to change a **single** value—its **carrier frequency**! This can typically be done by changing a **single** component value (e.g., a varactor diode).

Contrast that to a **filter**. We must somehow change its center frequency, **without** altering its bandwidth, roll-off, or phase delay. Typically, this requires that **every** reactive element in the filter be altered or changed as we modify the center frequency (remember all those **control knobs**!).

*A 1934 advertisement enticing "men" to enter the **glamorous** and **lucrative** field of radio.*

Super-Het Tuning

Say we wish to **recover** the information encoded on a radio signal operating at a frequency that we shall call f_0. Recall that (typically) we must **down-convert** to an IF frequency f_{IF}, by **tuning** the LO frequency f_{LO} to a frequency such that:

$$\left| f_0 - f_{LO} \right| = f_{IF}$$

Note for a given f_0 and f_{IF}, there are **two** possible **solutions** for value of LO frequency f_{LO}:

$$\begin{aligned} f_0 - f_{LO} &= \pm f_{IF} \\ -f_{LO} &= -f_0 \pm f_{IF} \\ f_{LO} &= f_0 \mp f_{IF} \end{aligned}$$

In other words, the LO frequency should be set such that it is a value f_{IF} **higher** than the desired signal frequency, **or** set such that it is a value f_{IF} **lower** than the desired signal frequency.

The first case, where $f_{LO} > f_0$, we call **high-side tuning.**

The second case, where $f_{LO} < f_0$, we call **low-side tuning**.

For **example**, consider again the FM band. Say a radio engineer is designing an **FM radio**, and has selected an **IF** frequency of **30 MHz**. Since the FM band extends from 88 MHz to 108 MHz, the radio engineer has two choices for LO bandwidth.

If she chooses **high-side** tuning, the LO bandwidth must be $f_{IF} = 30MHz$ **higher** than the RF bandwidth, i.e.,:

$$88\ MHz + f_{IF} < f_{LO} < 108\ MHz + f_{IF}$$
$$118\ MHz < f_{LO} < 138\ MHz$$

Alternatively, she can choose **low-side** tuning, with an LO bandwidth of:

$$88\ MHz - f_{IF} < f_{LO} < 108\ MHz - f_{IF}$$
$$58\ MHz < f_{LO} < 78\ MHz$$

Q: *Which of these two solutions **should** she choose?*

A: It **depends**! **Sometimes** high-side tuning is better, **other** times low-side is the best choice.

Let's be positive and look at the **advantages** of each solution:

Advantages of low-side tuning:

1. Lower oscillator frequency generally means **lower cost**.

2. Likewise, lower frequency generally means greater **output power.**

Advantages of high-side tuning:

1. Higher LO frequency means **harmonics** and other higher-order mixer terms are higher in frequency, and thus generally **easier** to filter out.

2. Higher LO frequency results in a smaller **percentage bandwidth**, which generally results in a more stable and better performing local oscillator.

Q: ***Percentage*** *bandwidth? Jut what does* ***that*** *mean?*

A: Percentage bandwidth is simply the LO bandwidth Δf_{LO}, **normalized** to its center (i.e., average) frequency:

$$\% \text{ bandwidth} \doteq \frac{f_{LO} \text{ bandwidth}}{f_{LO} \text{ center frequency}}$$

For our example, **each** local oscillator solution (low-side and high-side) has a bandwidth of **20 MHz** (the same width as the FM band!).

However, the **center** (average) frequency of each solution is of course very **different**.

For **low-side** tuning:

$$\frac{58+78}{2} = 68 \text{ MHz}$$

And thus the **percentage bandwidth** is:

$$\% \text{ bandwidth} \doteq \frac{20}{68} = 0.294 = 29.4\,\%$$

For **high-side** tuning:

$$\frac{118+138}{2} = 128 \text{ MHz}$$

And thus the **percentage bandwidth** is a far **smaller** value of:

$$\% \text{ bandwidth} \doteq \frac{20}{128} = 0.156 = 15.6\,\%$$

Stability concerns are generally **not** a substantial issue as long as % bandwidth is relatively small (i.e., > 50%). However, if the LO % bandwidth begins to **approach 100%,** then we begin to worry!

In fact, wide LO bandwidth is generally **not** specified in terms of its % bandwidth, but instead in terms of the ratio of its highest and lowest frequency. For our examples, either:

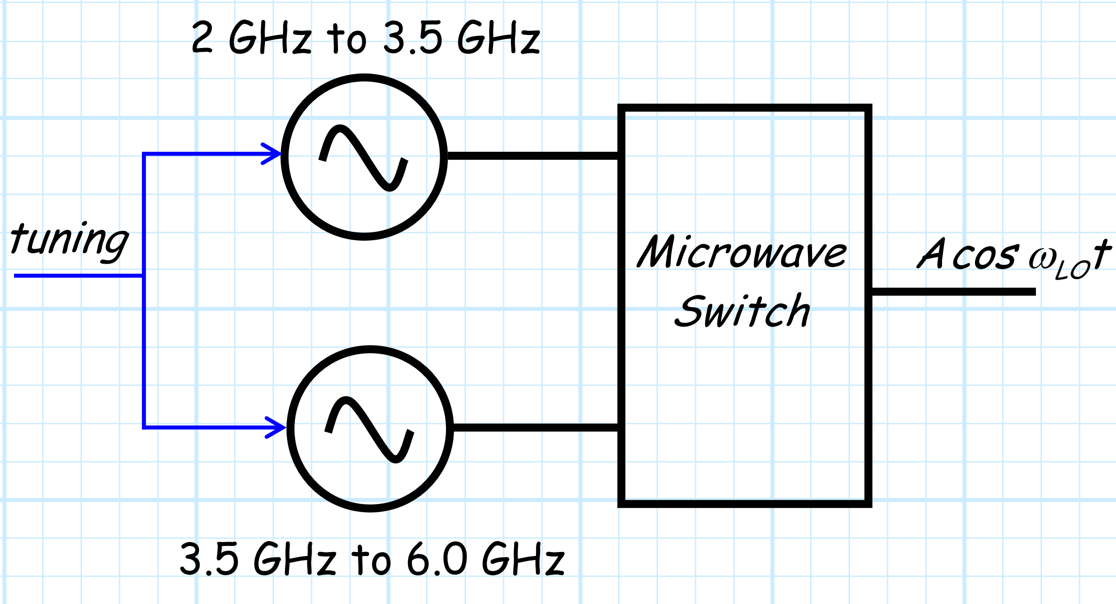
$$\frac{78}{58} = 1.34 \qquad \text{or} \qquad \frac{138}{118} = 1.17$$

Again, a **smaller** value is generally **better**.

If the LO bandwidth is **exceptionally** wide, this ratio can approach or exceed the value of 2.0. If the ratio is equal to 2.0, we say that the LO has an **octave** bandwidth → do **you** see why?

Generally speaking, it is **difficult** to build a **single** oscillator with a octave or greater bandwidth. If our receiver design requires an octave or greater LO bandwidth, then the LO typically must be implemented using **multiple oscillators**, along with a microwave **switch**.

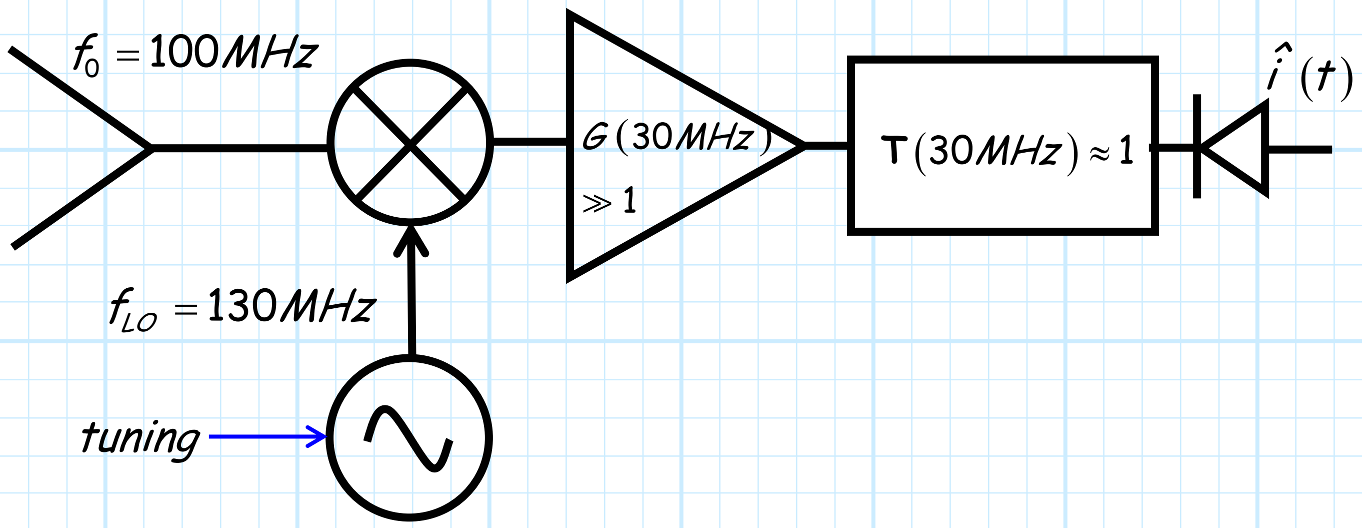
For example, an LO oscillator with a bandwidth from 2 to 6 GHz might be implemented as:



The Preselector Filter

Say we wish to **tune** a super-het receiver to receive a **radio station** broadcasting at **100 MHz**.

If the receiver uses and **IF** frequency of $f_{IF} = 30\ MHz$, and uses **high-side** tuning, we must adjust the **local oscillator** to a frequency of $f_{LO} = 130\ MHz$.



Thus, the **desired** RF signal will be **down-converted** to the IF frequency of **30 MHz**.

But **BEWARE**, the desired radio station is **not** the only signal that will appear at the output of the mixer **at 30 MHz**!

Q: *Oh yes,* ***we*** *remember. The mixer will create all sorts of nasty, non-ideal* ***spurious*** *signals at the mixer IF port. Among these are signals at frequencies:*

1st order: $f_{RF} = 100 MHz, f_{LO} = 130 MHz$

2nd order:

$$2f_{RF} = 200 MHz, 2f_{LO} = 260 MHz,$$
$$f_{RF} + f_{LO} = 230 MHz$$

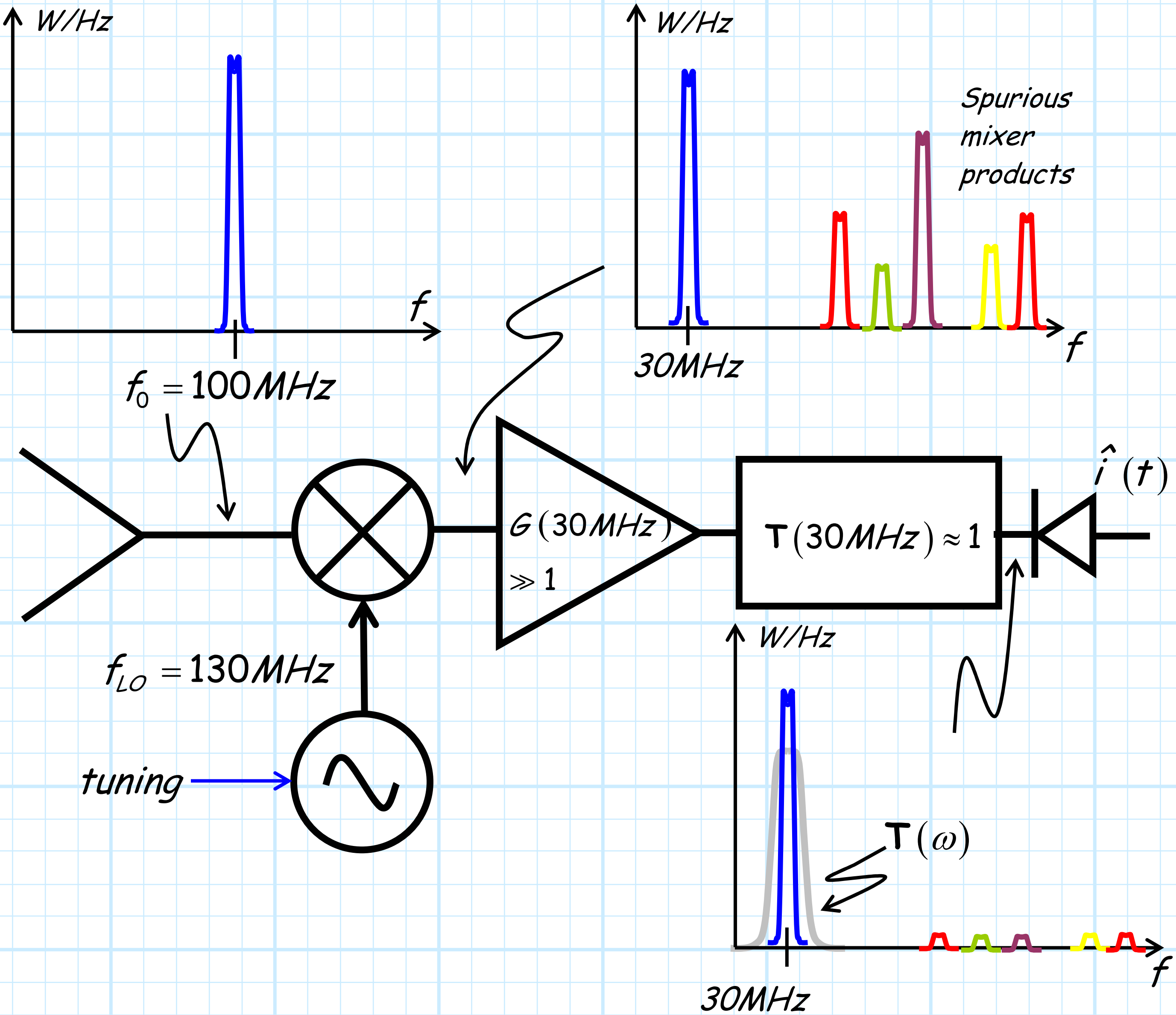
3rd order:

$$|2f_{RF} - f_{LO}| = 70 MHz,$$
$$|2f_{LO} - f_{RF}| = 160 MHz,$$
$$3f_{RF} = 300 MHz, 3f_{LO} = 390 MHz,$$
$$2f_{RF} + f_{LO} = 330 MHz,$$
$$f_{RF} + 2f_{LO} = 360 MHz$$

Right*?*

A: Not exactly. Although it **is** true that all of these products **will** exist at the IF mixer port—they will **not** pose any particular problem to us as radio engineers. The reason for this is that there is a narrow-band **IF filter** between the mixer IF port and the demodulator!

Look at the **frequencies** of the spurious signals created. They are all quite a bit **larger** than the filter center frequency of **30MHz**. All of the spurious signals are thus **rejected** by the filter—**none** (effectively) reach the detector/demodulator!

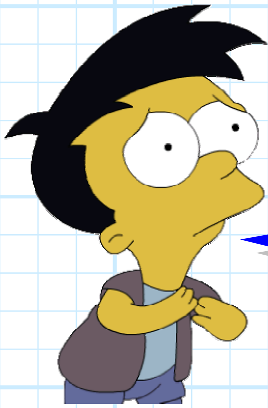


Look **again** at the statement I just made:

"But **BEWARE**, the desired radio station is **not** the only signal that will appear at the output of the mixer **AT 30 MHz**!"

In other words, there can be **spurious signals** that appear **precisely** at our IF frequency of **30 MHz**. The IF filter will **not** of course filter **these** out (after all—they're at **30 MHz**!), but instead let them pass through **unimpeded** to the **demodulator**.

The **result** → demodulated signal $\hat{i}(t)$ is an inaccurate, distorted **mess**!



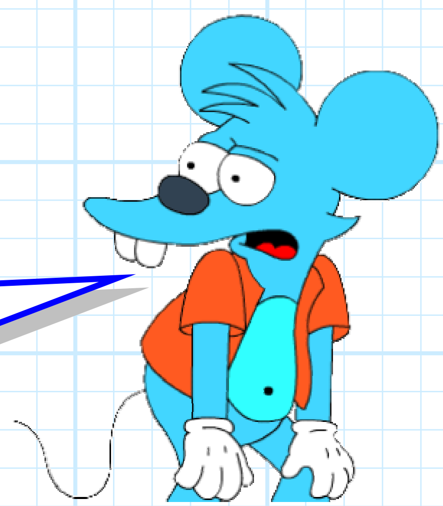
Q: *I'm just **totally** baffled! **Where** do these unfilterable signals come from? **How** are they produced?*

A: The answer is a **profound** one—an **incredibly important** fact that every radio engineer worth his or her salt must keep in mind at **all** times:

> *The electromagnetic spectrum is **full** of radio signals. We must **assume** that the antenna delivers signals operating at **any** and **all** RF frequencies!*

In other words, we are only **interested** in a signal at 100 MHz; but that does **not** mean that other signals don't exist. **You** must always consider this fact!

Q: *But I'm **still** confused. How do all these RF signals cause multiple signals **at** our IF frequency?*



A: Remember, **each** of the RF signals will mix with the LO drive signal, and thus **each** RF signal will produce its very **own** set of **mixer products** (1^{st} order, 2^{nd} order, 3^{rd} order, etc.)

Here's the **problem**→ some of these mixer products might lie **at** our IF frequency of **30 MHz**!

* To see **which** RF input signal frequencies will cause this problem, we must **reverse** the process of determining our mixer output products.

* Recall earlier we started with **known** values of f_{RF} (100 MHz) and f_{LO} (130 MHz), and then determined all of the spurious signal frequencies created at the mixer IF port.

* Now, we start with a know f_{LO} (130 MHz), and a know value of the **spurious IF signal frequency** (30 MHz), and try to determine the frequency of the **RF** signal that would be required to produce it.

For example, let's start with the 3^{rd} order product $|2f_{RF} - f_{LO}|$. In order for this product to be equal to 30 MHz, we find that:

$$
\begin{aligned}
|2f_{RF} - 130| &= 30 \\
2f_{RF} - 130 &= \pm 30 \\
2f_{RF} &= 130 \pm 30 \\
f_{RF} &= \frac{130 \pm 30}{2} \\
f_{RF} &= 50, 80
\end{aligned}
$$

Thus, when attempting to tune to a radio station at 100 MHz, we find that radio stations at both **50 MHz** and **80 MHz** could **create** a 3rd order product at **30 MHz**—precisely at our **IF** filter center frequency!

But the **bad** news continues—there are **many** other mixer products to consider:

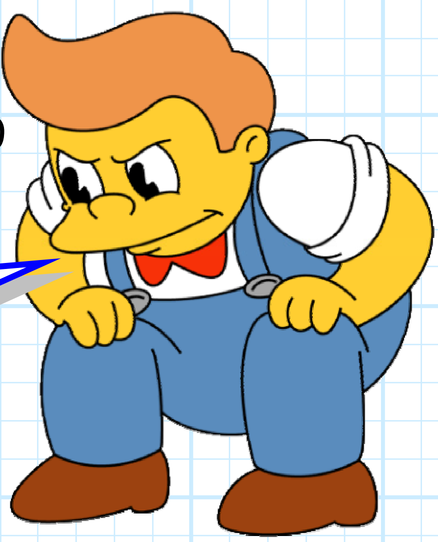
$|2f_{LO} - f_{RF}|$

$$\begin{aligned} |2(130) - f_{RF}| &= 30 \\ 260 - f_{RF} &= \pm 30 \\ f_{RF} &= 260 \mp 30 \\ &= 290, 230 \end{aligned}$$

$2f_{LO} + f_{RF}$

$$\begin{aligned} 2(130) + f_{RF} &= 30 \\ 260 + f_{RF} &= 30 \\ f_{RF} &= 30 - 260 \\ &= -230 \end{aligned}$$

Q: *What?! A radio station operating at a* ***negative*** *frequency of -230 MHz? Does this have any meaning?*



A: Not in any **physical** sense! We **ignore** any **negative** frequency solutions—they are **not** a concern to us.

$2f_{RF} + f_{LO}$

$$\begin{aligned} 2f_{RF} + f_{LO} &= 30 \\ 2f_{RF} + 130 &= 30 \\ f_{RF} &= \frac{30 - 130}{2} \\ f_{RF} &= -50 \end{aligned}$$

Again, a **negative** solution that we can **ignore**.

$3f_{RF}$

$$\begin{aligned} 3f_{RF} &= 30 \\ f_{RF} &= \frac{30}{3} \\ f_{RF} &= 10 \end{aligned}$$

OK, that's all the **3rd order** products, now let's consider the **second-order** terms:

$|f_{LO} - f_{RF}|$

$$\begin{aligned} |130 - f_{RF}| &= 30 \\ 130 - f_{RF} &= \pm 30 \\ f_{RF} &= 130 \mp 30 \\ &= 100, 160 \end{aligned}$$

* Note that this term is the term created by an **ideal** mixer. As a result, we find that **one** of the RF signals that will create a mixer product at 30 MHz is f_{RF} = **100 MHz** – the frequency of the **desired** radio station !

* However, we find that even this **ideal** mixer term causes **problems**, as there is a **second** solution. An RF signal at **160 MHz** would likewise result in a mixer product at 30 MHz—even in an **ideal** mixer!

* We will find this **second** solution to this **ideal** mixer (i.e., down-conversion) term can be particularly **problematic** in receiver design. As such, this solution is given a specific name—the **image frequency**.

For this example, 160 MHz is the **image frequency** when we tune to a station at 100 MHz.

$f_{LO} + f_{RF}$

$$\begin{aligned} 130 + f_{RF} &= 30 \\ 130 f_{RF} &= 30 - 130 \\ f_{RF} &= -100 \end{aligned}$$

No problem here!

$2f_{RF}$

$$\begin{aligned} 2f_{RF} &= 30 \\ f_{RF} &= \frac{30}{2} \\ f_{RF} &= 15 \end{aligned}$$

Finally, we must consider **one** 1st order term:

f_{RF}

$$f_{RF} = 30$$

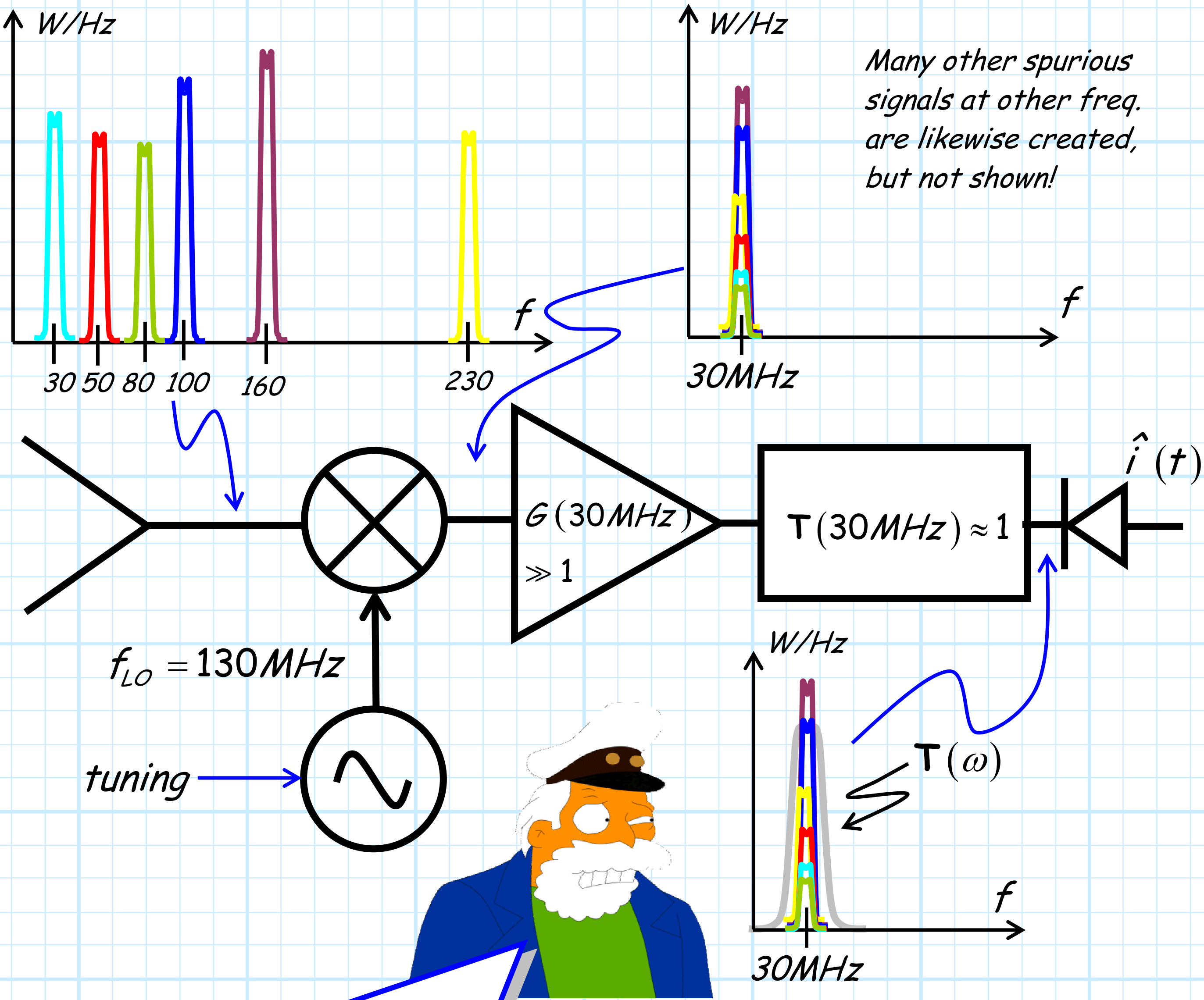
In other words, an RF signal at 30 MHz can "**leak**" through the mixer (recall mixer **RF isolation**) and appear at the IF port—after that there's **no stopping** it until it reaches the demodulator!

In **summary**, we have found that that:

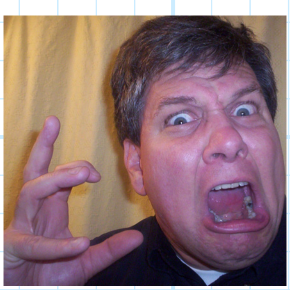
1. An RF signal (e.g., radio station) at **30 MHz** can cause a **1st-order** product at our IF filter frequency of 30 MHz.

2. RF signals (e.g., radio stations) at either **15 MHz** or **160 MHz** can cause **a 2nd -order** product at our IF filter frequency of 30 MHz.

3. RF signals (e.g., radio stations) at **10 MHz**, **50MHz**, **80 MHz**, **230 MHz**, or **290 MHz** can cause a **3rd -order** product at our IF filter frequency of 30 MHz.



Q: *I now **see** the problem! There is **no** way to separate the **spurious** signals at the IF frequency of 30 MHz from the **desired** station at 30 MHz. Clearly, your hero **E.H. Armstrong** was **wrong** about this Super-Heterodyne receiver design!*



A: Armstrong **wrong** !?!

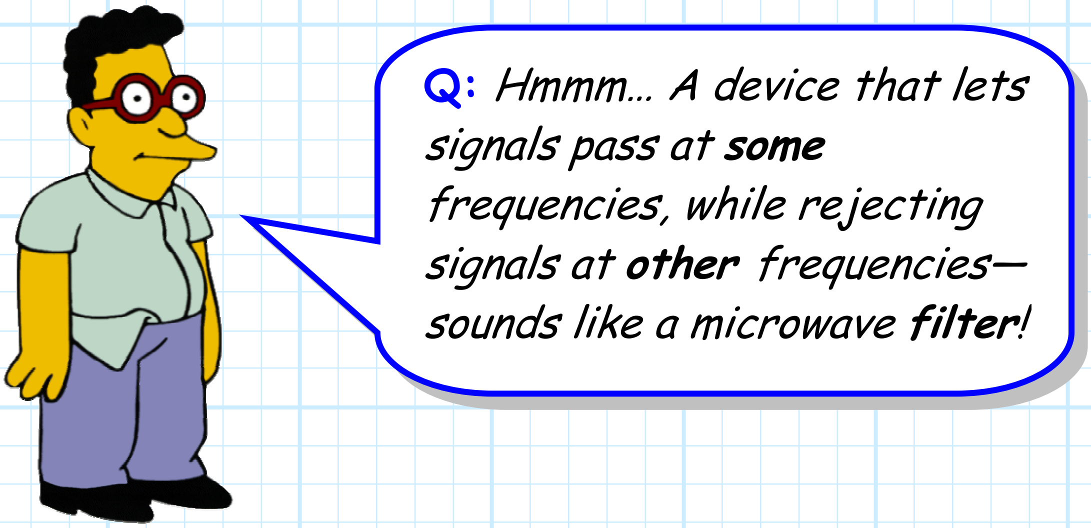
→ **NEVER!**

There is an **additional** element of Armstrong's super-het design that we have **not** yet discussed.

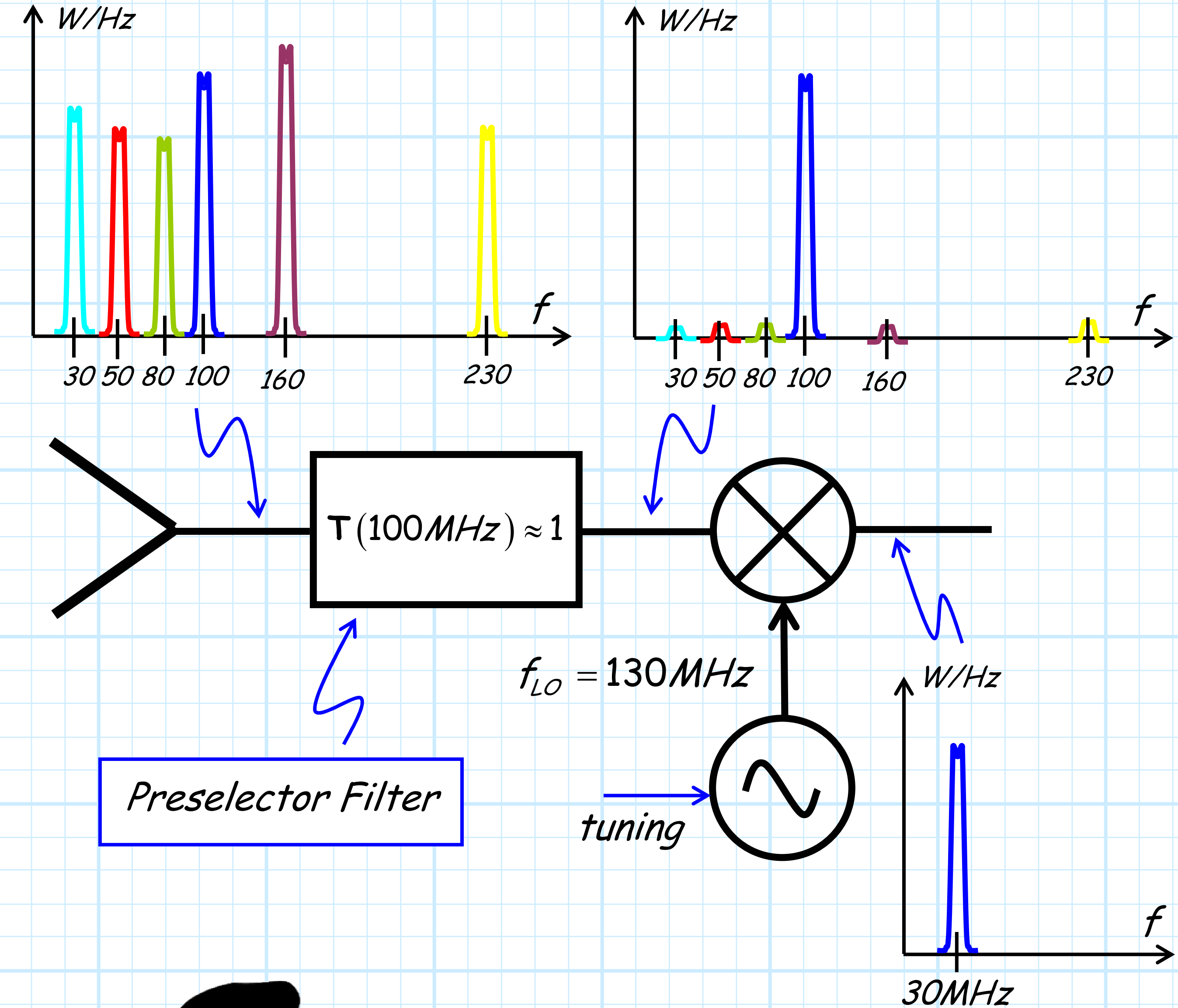
→ The **preselector filter**.

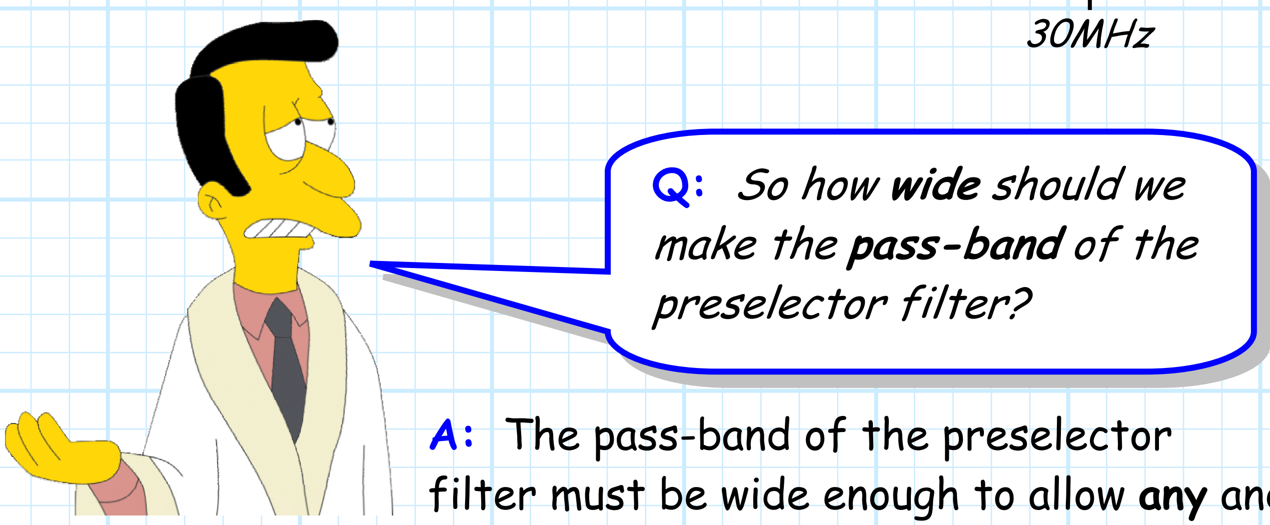
The **only** way to keep the mixer from **creating** these spurious signals at our IF filter center frequency is to **keep** the RF signals that produce them **from** the mixer!

Of course, we must **simultaneously** let the desired station reach the mixer.



A: That's correct! By inserting a **preselector filter** between the antenna and the mixer, we can **reject** the signals that create spurious signals at our IF center frequency, while **allowing** the desired station to pass through to the mixer unimpeded.





A: The pass-band of the preselector filter must be wide enough to allow **any** and **all** potential **desired** signals to pass through.

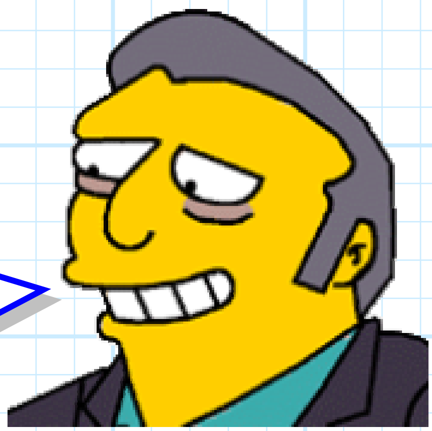
* Consider our example of f_0= 100 MHz. This signal is **smack-dab** in the middle of the **FM radio band**, and so let's assume it is an **FM radio station** (if it were, it would actually be at frequency 100.1 or 99.9 MHz).

* If we are interested in tuning to **one** FM station, we might be interested in tuning into **any** of the others, and thus the preselector filter pass-band **must** extend from 88 MHz to 108 MHz (i.e., the FM band).

* Note we would **not** want to extend the pass-band of the preselector filter any wider than the FM band, as we are (presumably) **not** interested in signals outside of this band, and those signals could **potentially** create spurious signals at our IF center frequency!

As a result, we find that the **preselector filter** effectively defines the **bandwidth** of a super-heterodyne receiver.

Q: *OK, **one** last question. When calculating the products that could create a spurious signal **at** the IF center frequency, you **neglected** the terms f_{LO}, $2f_{LO}$ and $3f_{LO}$. Are these terms **not** important?*



A: They are actually **very** important! However, the value of f_{LO} is **not** an unknown to be solved for, but in fact was (for our example) a **fixed** value of $f_{LO} = 130 MHz$.

Thus, $2f_{LO} = 260 MHz$, and $3f_{LO} = 390 MHz$—**none** of these are anywhere near the **IF** center frequency of **30 MHz**, and so these products are easily **rejected** by the **IF filter**. However, this need not **always** be true!

* Consider, for example, the case were we again have designed a receiver with an IF center frequency of **30 MHz**. This time, however, we desire to tune to radio signal operating at **60 M**Hz.

* Say we use **low-side** tuning in our design. In that case, the **LO** signal frequency must be $f_{LO} = 60 - 30 = 30 MHz$.

* Yikes! You **must** see the problem! The Local Oscillator frequency is **equal** to our IF center frequency ($f_{LO} = f_{IF}$). The LO signal will "**leak**" through mixer (recall mixer LO isolation) and into the IF, where it will pass **unimpeded** by the IF filter to the demodulator (this is a very **bad** thing).

> Thus, when designing a receiver, it is **unfathomably important** that the LO frequency, along with **any** of its harmonics, lie **nowhere** near the **IF** center frequency!

Image and Third-Order Signal Rejection

Recall in a previous handout the **example** where a receiver had an IF frequency of $f_{IF} = 30\ MHz$. We desired to demodulate a radio station operating at 100 *MHz*, so we set the LO to a frequency of $f_{LO} = 130\ MHz$ (i.e., high-side tuning).

We discovered that **RF** signals at many **other** frequencies would likewise produce signals at **precisely** the **IF** frequency of 30 MHz—a very serious problem that can only be solved by the addition of a **preselector** filter.

Recall that this preselector filter must allow the **desired** signal (or band of signals) to pass through **unattenuated**, but likewise must sufficiently **reject** (i.e., attenuate) all the RF signals that could create **spurious** signals at the IF frequency.

We found for this **example** that these RF signals reside at frequencies:

10 *MHz*, 15 *MHz*, 30 *MHz*, 80 *MHz*,
160 *MHz*, 230 *MHz*, and 290 *MHz*

Note that the most **problematic** of these RF signals are the two at **80 *MHz*** and **160 *MHz***.

Q: *Why do **these** two signals pose the greatest problems?*

A: Because the frequencies 80 *MHz* and 160 *MHz* are the **closest** to the **desired** signal frequency of 100 *MHz.* Thus, they must be the closest to the **pass-band** of the preselector filter, and so will be attenuated the **least** of all the RF signals in the list above.

As a result, the 30 MHz mixer products produced by the RF signals at 80 *MHz* and 160 *MHz* will be **likely** be **larger** than those produced by the other problem frequencies—they are the ones most need to **worry** about!

Let's look closer at each of these two signals.

Image Frequency Rejection

We determined in an earlier handout that the radio frequency signal at 160 *MHz* was the **image** frequency for this particular example.

Recall the image frequency is the **other** f_{RF} solution to the (ideal) second-order mixer term $|f_{RF} - f_{LO}| = f_{IF}$!

For **low-side** tuning, the **desired** RF signal is (by definition) the solution that is **greater** than f_{LO}:

$$f_{RF} = f_{LO} + f_{IF} \qquad \text{(low-side tuning)}$$

And thus the image signal is the solution that is **less** than f_{LO}:

$$f_{image} = f_{LO} - f_{IF} \qquad \text{(low-side tuning)}$$

Similarly, for **high-side** tuning, the **desired** RF signal is (by definition) the solution that is **less** than f_{LO}:

$$f_{RF} = f_{LO} - f_{IF} \qquad \text{(high-side tuning)}$$

And thus the **image** signal is the solution that is **greater** than f_{LO}:

$$f_{image} = f_{LO} + f_{IF} \qquad \text{(high-side tuning)}$$

Note for both high-side and low-side tuning, the **difference** between the desired RF signal and its image frequency is $2f_{IF}$:

$$\left| f_{RF} - f_{image} \right| = 2 f_{IF}$$

This is a **very** important result, as is says that we can **increase** the "distance" between a desired RF signal and its image frequency by simply **increasing** the IF frequency of our receiver design!

For **example**, again consider the FM band (88 MHz to 108 MHz). Say we decide to design an FM radio with an IF of **20 MHz,** using high-side tuning.

Thus, the **LO bandwidth** must extend from:

$$88 + f_{IF} < f_{LO} < 108 + f_{IF}$$
$$88 + 20 < f_{LO} < 108 + 20$$
$$108 < f_{LO} < 128$$

The **image bandwidth** is therefore:

$$108 + f_{IF} < f_{image} < 128 + f_{IF}$$
$$108 + 20 < f_{image} < 128 + 20$$
$$128 < f_{image} < 148$$

Thus, the **preselector filter** for this FM radio must have pass-band that extends from 88 to 108 MHz, but must **also** sufficiently **attenuate** the image signal band extending from 128 to 148 MHz.

Note that 128 MHz is **very** close to 108 MHz, so that attenuating the signal may be very **difficult**.

Q: *By **how much** do we need to attenuate these image signals?*

A: A very **good question**; one that leads to a very important point. Since the image frequency creates the **same** second-order product as the desired signal, the **conversion loss** associated with each signal is **precisely** the same (e.g. 6 dB)!

As a result, the IF signal created by image signals will typically be **just** as large as those created by the desired FM station.

This means that we must **greatly attenuate** the image band, typically by **40 dB** or more!

Q: *Yikes! It sounds like we might require a filter of very **high order**!?!*

A: That's certainly a **possibility.** However, we can always reduce this required preselector filter order if we simply **increase** our IF design frequency!

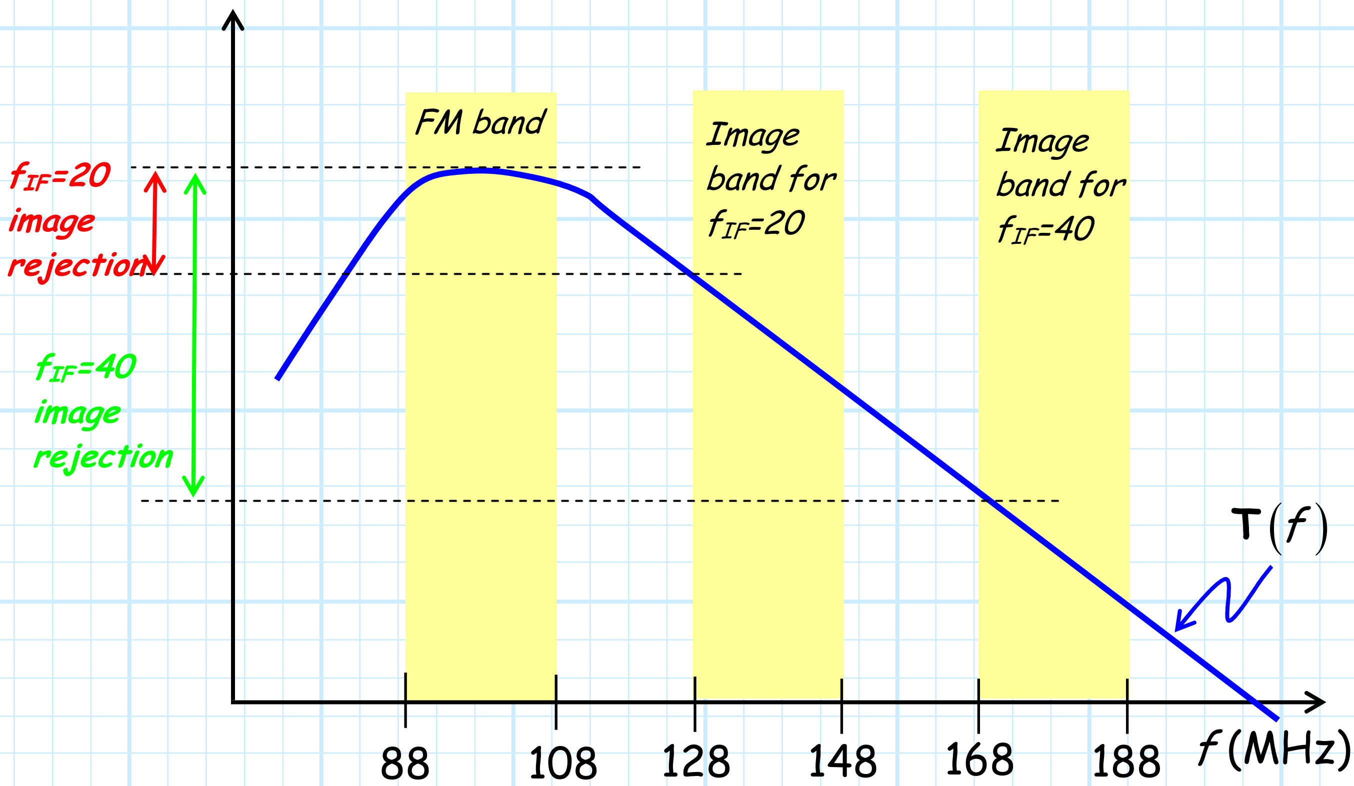
To see how this works, consider what happens if we **increase** the receiver IF frequency to $f_{IF} = 40MHz$. For this **new** IF, the LO bandwidth must increase to:

$$
\begin{aligned}
88 + f_{IF} < f_{LO} < 108 + f_{IF} \\
88 + 40 < f_{LO} < 108 + 40 \\
128 < f_{LO} < 148
\end{aligned}
$$

The new **image** bandwidth has therefore **increased** to:

$$108 + f_{IF} < f_{image} < 128 + f_{IF}$$
$$128 + 40 < f_{image} < 148 + 40$$
$$168 < f_{image} < 188$$

Note this image band is now **much** higher in frequency than the FM band—and thus much more **easily filtered**!



The amount by which the preselector attenuates the image signals is known as the **image rejection** of the receiver.

For **example**, if the preselector filter attenuates the image band by at least 50 dB, we say that the receiver has 50 dB of image rejection.

So by increasing the IF frequency, we can **either** get greater image rejection from the same preselector filter order, **or** we can reduce the preselector filter order while maintaining sufficient image rejection.

But be **careful**! Increasing the IF frequency will also tend to increase cost and reduce detector performance.

3^{rd}-Order Signal Rejection

In addition to the image frequency (the **other** solution to the second order term $|f_{RF} - f_{LO}| = f_{IF}$), the other radio signals that are particularly difficult to reject are the f_{RF} solutions to the **3^{rd} order** product terms $|2f_{RF} - f_{LO}| = f_{IF}$ and $|2f_{LO} - f_{RF}| = f_{IF}$.

There are **four** possible RF solutions (two for each term):

$$f_1 = \frac{f_{LO} + f_{IF}}{2} \quad \leftarrow$$

$$f_2 = \frac{f_{LO} - f_{IF}}{2}$$

$$f_3 = 2f_{LO} + f_{IF}$$

$$f_4 = 2f_{LO} - f_{IF} \quad \leftarrow$$

Each of these four solutions represents the frequency of a radio signal that will create a 3rd order product precisely at the IF frequency, and thus all four must be adequately rejected by the preselector filter.

However, solutions f_1 and f_4 will **typically** be the **most** problematic (i.e., closest to the desired RF frequency band). For instance, in our original **example**, the "problem" signal at **80 MHz** is the term f_1 (i.e., $f_1 = 80\ MHz$).

Q: *By **how much** do we need to attenuate **these** signals?*

A: Since these signals produce **3rd order** mixer products, the IF signal power produced is generally much **less** than that of the (2nd order) image signal product. As a result, we can at times get by with as little as **20 dB** of 3rd order signal rejection—but this **depends** on the mixer used.

Q: ***Just** 20 dB of rejection? It sounds like achieving this will be a "**piece of cake**"—at least compared with satisfying the **image** rejection requirement!*

A: Not so fast! Often we will find that these 3rd order signals will be **very close** to the **desired RF band**. In fact (if we're not careful when designing the receiver) these 3rd order signals can lie **inside** the desired RF band—then they **cannot** be attenuated at all!

Thus, rejecting these 3rd order radio signals can be **as** difficult (or even **more** difficult) than rejecting the image signal.

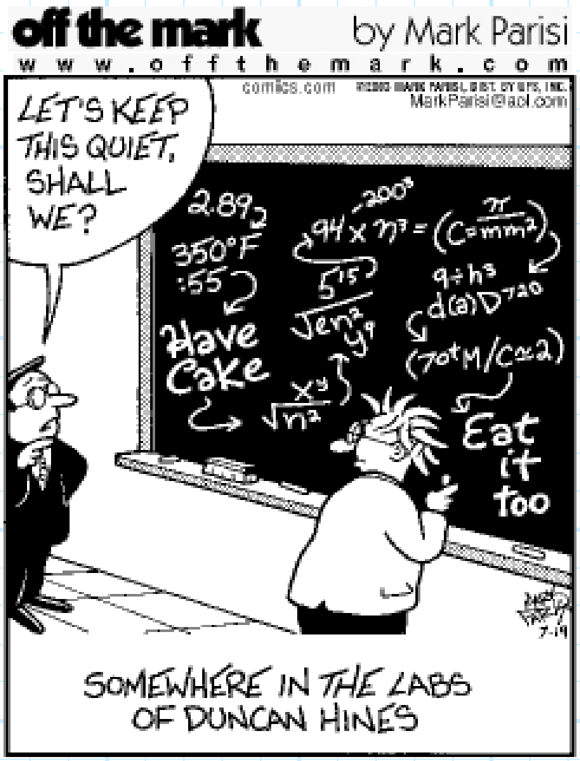
Q: *We found earlier that by **increasing** the IF frequency, we could make the **image rejection** problem much easier. Is there a **similar** solution to improving 3rd order signal rejection?*

A: Yes there is—but you **won't** like this answer! Generally speaking, we can move the 3rd order signals **away** from the desired RF band (thus making them **easier** to filter) by **decreasing** the IF frequency.

This solution of course is exactly **opposite** of the method used to improve image rejection. Thus, there is a **conflict** between the two design goals. It is **your** job as a receiver designer to arrive at the best possible **design compromise**, providing both sufficient image **and** 3rd order signal rejection.

→ Engineering is **not** easy ! ←

Advanced Receiver Designs



So, we know that as our IF frequency **increases**, the rejection of image and other spurious signals will **improve**.

But, as our IF frequency **decreases**, the cost and performance of our receiver and demodulator will **improve**.

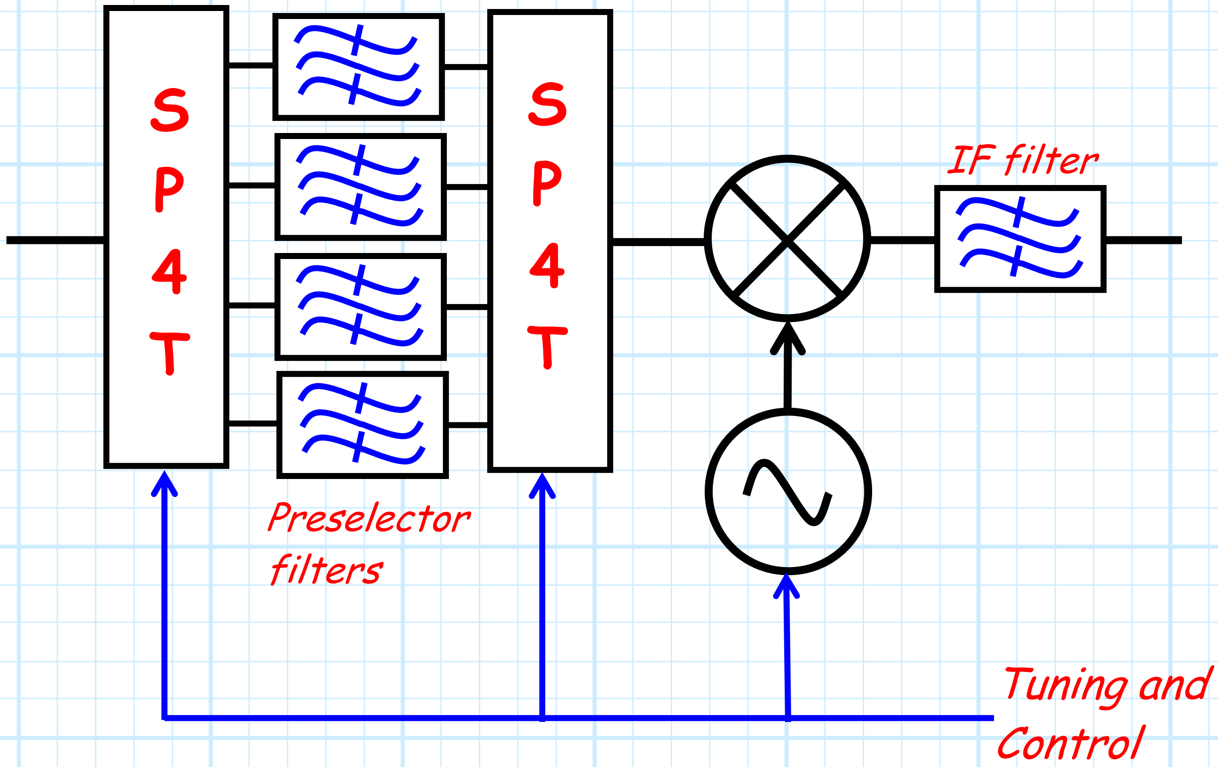
Q: *Isn't there some way to have it* ***both*** *ways? Can't we have our cake and eat it too?*

A: Yes, there is (sort of)!

To achieve **exceptional** image and 3rd –order product rejection, and enjoy the cost and performance benefits of a **low** IF frequency, receiver designers often employ these **two** advanced receiver architectures.

1. Selectable Preselection

Instead of implementing a single preselector filter, we can use a **bank** of **selectable** preselector filters:



In other words, we use multiple preselector filters to **span** the desired receiver RF bandwidth. This is particularly useful for **wideband** receiver design.

Q: *Why? How is this useful? What good is this design?*

A: Consider an **example**. Say we have been tasked to design a receiver with an RF bandwidth extending from 8 GHz to 12 GHz. A **standard** receiver design might implement a **single** preselector filter, extending from 8 GHz to 12 GHz.

Instead, we could implement a **bank** of preselector filters that span the RF bandwidth. We could implement 2, 3, 4, or even more filters to accomplish this.

Let's say we use **four** filters, each covering the bandwidths shown in the table below:

	Bandwidth
Filter #1	8 - 9 GHz
Filter #2	9 - 10 GHz
Filter #3	10 – 11 GHz
Filter #4	11 -12 GHz

Say we wish to receive a signal at 10.3 GHz; we would tune the local oscillator to the proper frequency, **AND** we must select **filter #3** in our filter bank.

Thus, **all** signals from 10-11 GHz would pass through to the RF port of the mixer—a band that includes our **desired** signal at 10.3 GHz.

However, signals from 8-10 GHz and 11-12 GHz will be **attenuated** by **filter #3**—ideally, little signal energy from these bands would reach the RF port of the mixer. If we wish to receive a signal in these bands, we must select a **different** filter (as well as **retune** the LO frequency).

→ As a result, signals over "just" **1GHz** of bandwidth reach the RF port of the mixer, as opposed to the single filter design wherein a signal spectrum **4GHz** wide reaches the mixer RF port!

Q: *Again I ask the question: How is this helpful?*

A: Let's say this receiver design likewise implements **low-side** tuning. If we wish the tune to a RF signal at **12GHz**, we find that the **image** frequency lies at:

$$f_{image} = 12\,GHz - 2\,f_{IF}$$

Of course, we need the preselector filter to reject this image frequency. If we receiver design used just one preselector fitler (from 8 to 12 GHz), then the image signal frequency f_{image} must be **much less** than 8 GHz (i.e., well outside the filter passband). As a result, the receiver IF frequency **must** be:

$$8\,GHz \gg 12\,GHz - 2\,f_{IF}$$

$$8\,GHz + 2\,f_{IF} \gg 12\,GHz$$

$$2\,f_{IF} \gg 4\,GHz$$

$$f_{IF} \gg 2\,GHz$$

In other words, the **4.0 GHz RF bandwidth** results in a requirement that the receiver Intermediate Frequency (**IF**) be much **greater than 2.0 GHz**.

→ This is a **pretty darn high** IF!

Instead, if we implement the bank of preselector filters, we would select **filter #4**, with a passband that extends from 12 GHz down to 11 GHz.

As a result, image rejection occurs **if**:

$$11\,GHz \gg 12\,GHz - 2\,f_{IF}$$
$$11\,GHz + 2\,f_{IF} \gg 12\,GHz$$
$$2\,f_{IF} \gg 1\,GHz$$
$$f_{IF} \gg 0.5\,GHz$$

In other words, **since** the preselector filter has a much **narrower** (i.e., 1GHz) bandwidth than before (i.e., 4GHz), we can get adequate image rejection with a **much lower IF** frequency (this is a good thing)!

Moreover, this improvement in spurious signal rejection likewise applies to other order terms, including that **annoying** 3rd-order term!

Thus, implementing a bank of preselector filters allows us to **either**:

1. Provide **better** image and spurious signal **rejection** at a **given** IF frequency.

2. **Lower** the **IF** frequency necessary to provide a **given** level of image and spurious signal rejection.

As we increase the **number** of preselector filters, the image and spurious signal rejection will increase **and/or** the required IF frequency will decrease.

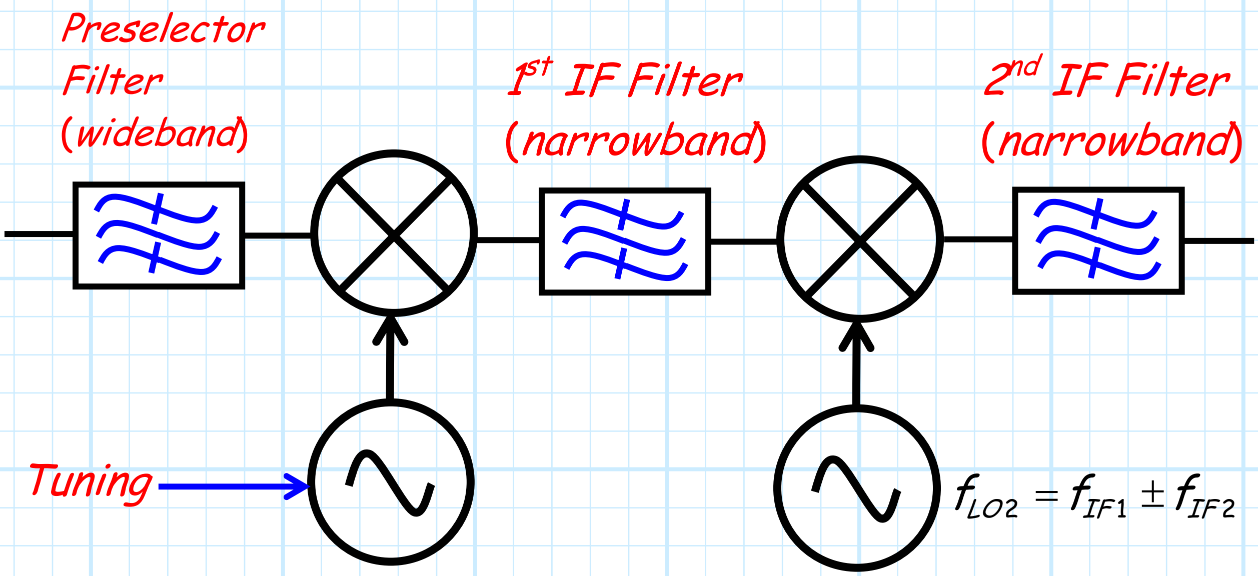
But beware! Adding filters will **increase** the **cost** and size of your receiver!

2. Dual Conversion Receivers

A dual conversion receiver is another great way of achieving exceptional image and spurious rejection, while maintaining the benefits of a low IF frequency.

In this architecture, instead of employing multiple preselector filters, we employ multiple (i.e. two) IF filters!

As the name implies, a **dual** conversion receiver converts the signal frequency—**twice**. As a result, this receiver architecture implements **two** Local Oscillators and **two** mixers.



Q: ***Two** frequency conversions! Why would we want to do **that**?*

A: The first mixer/local oscillator converts the RF signal to the first IF frequency f_{IF1}. The value of this first IF frequency is selected to optimize the **suppression** of the image frequency and all other RF signals that would produce spurious signals (e.g., 3rd order products) at the first IF.

Optimizing spurious signal suppression generally results in an IF frequency f_{IF1} that is **very high**—much higher than a **typical** IF frequency.

Q: *But won't a high IF frequency result in **reduced** IF component and demodulator **performance**, as well as **higher cost**?*

A: That's why we employ a **second conversion**!

The **second** mixer/local oscillator simply down converts the signal to a **lower** IF (f_{IF2})—a frequency where both component performance and cost is **good**.

Q: *What about **spurious signals** produced by this second conversion; don't we need to worry about them?*

A: Nope! The **first** conversion (if designed properly) has adequately suppressed them. The first IF filter (like all IF filters) is **narrow band**, thus allowing **only** the **desired** signal to reach the RF port of the **second** mixer. We then simply need to down-convert this **one** signal to a lower, more **practical** IF frequency!

Now, a **couple** of **very important** points about the dual-conversion receiver.

Point 1

The **first** LO must be **tunable**—just like a "normal" super-het local oscillator. However, the **second** LO has a **fixed** frequency—there is **no need** for it to be tunable!

Q: *Why is that?*

A: **Think** about it.

The signal at the RF port of the second mixer **must** be precisely at frequency f_{IF1} (it woundn't have made it through the first IF filter otherwise!). We need to down-convert this signal to a second IF frequency of f_{IF1}, thus the second LO frequency **must** be:

$$f_{LO2} = f_{IF1} + f_{IF2} \qquad \text{(high-side tuning)}$$

or:

$$f_{LO2} = f_{IF1} - f_{IF2} \qquad \text{(low-side tuning)}$$

Either way, **no tuning** is required!

This of course means that we can use, for example, a **crystal** or **dielectric resonator** oscillator for this second LO.

Point 2

Recall the criteria for selecting the first IF is **solely** image and spurious signal suppression. Since the second conversion reduces the frequency to a lower, more practical value, the first IF frequency f_{IF1} can be as **high as necessary**.

In fact, the first IF frequency can actually be **higher than the RF signal**!

→ In other words, the first conversion can be an **up-conversion**.

For **example**, say our receiver has an **RF bandwith** that extends from 900 MHz to 1300 MHz. We might choose a first

IF at f_{IF1}=2500 MHz, such that the first mixer/LO must perform an **up-conversion** of as much as 1600 MHz.

Q: *Say again; **why** would this be a good idea?*

A: **Typically**, we find that an **extremely high** first IF will make the preselector's job relatively easy—all RF signals that would produce spurious signals at the first IF (e.g., the image signal) are **well outside** the preselector bandwidth, and thus are **easily** and/or **greatly** suppressed.

But be **careful**! The RF signals that cause spurious signals when up-converting are not necessarily the **"usual suspects"** we found when down converting.

You must carefully determine **all** offending RF signals produced from **all** mixer terms (1^{st}, 2^{nd}, and 3^{rd} order)!

*One last point. The **astute** receiver designer will often find that a **combination** of these two architectures (multiple preselection **and** dual conversion) will provide an elegent, effective, and cost efficient solution!*