Selectivity and the IF filter

Q: *What about the **IF filter**?*

*I understand that its **center frequency** f_0^{IF} determines the receiver "Intermediate Frequency",*

*But, what should this filter **bandwidth** $\Delta f_{IF} = B_f$ be?*

A: Remember, we want only **one** signal (the **desired** signal we down-converted) to appear at the demodulator.

So, the IF filter bandwidth should be **just wide enough** to allow for the desired **signal bandwidth** B_s—but **no wider**!

$$\boxed{B_f \cong B_s}$$

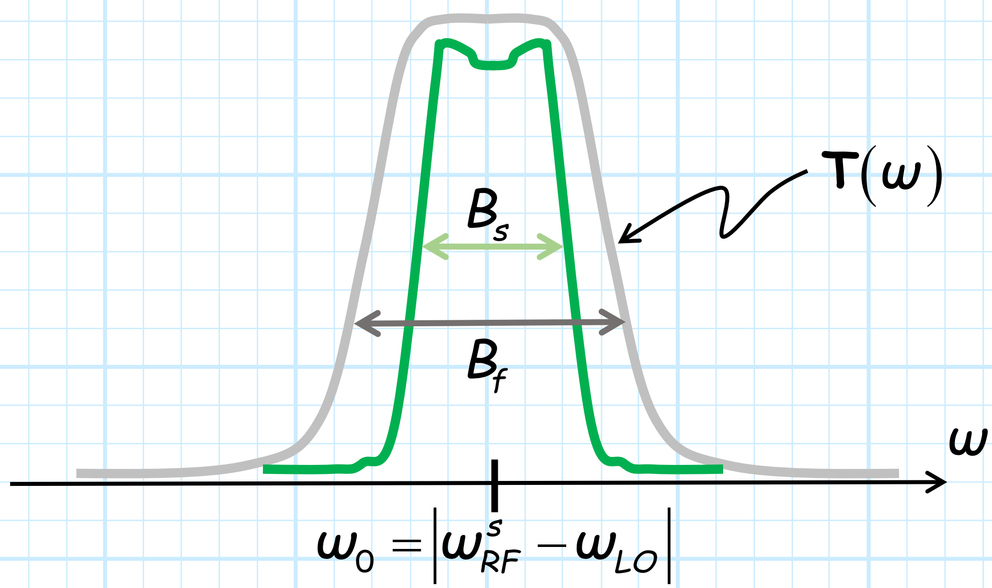
Make wide enough—BUT NO WIDER!

But, be **careful**!

To minimize linear distortion, you **might** need to make the IF filter 3*dB* bandwidth **slightly wider** (e.g. by 20%) than the signal bandwidth.

I.E., set the IF filter bandwidth to be:

$$B_f \cong 1.2\, B_s$$

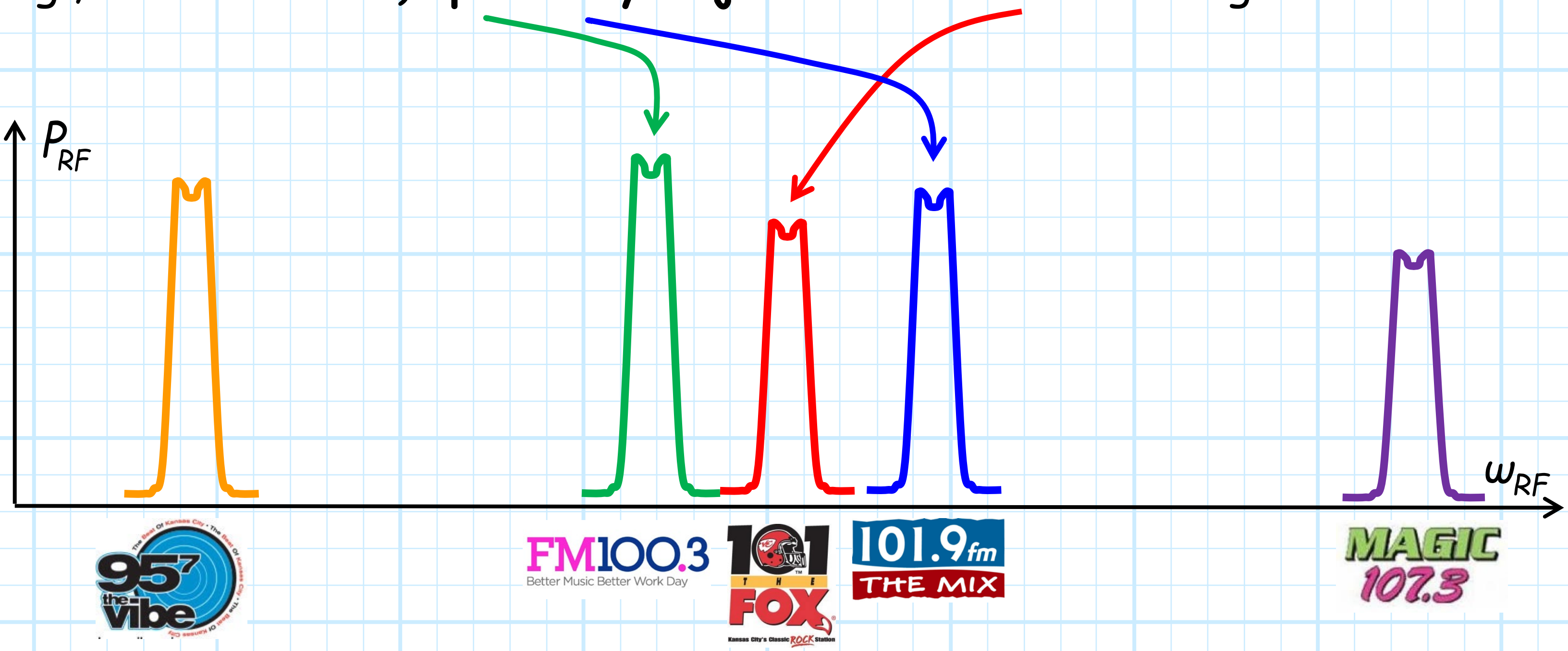


What should the filter order be?

Q: *What about the IF filter **"roll-off"**?*

*How much stop-band **attenuation** is required by the IF filter?*

A: The **most problematic** signals for the IF filter are the **two** signals (e.g., radio stations) **spectrally adjacent** to the **desired** signal.

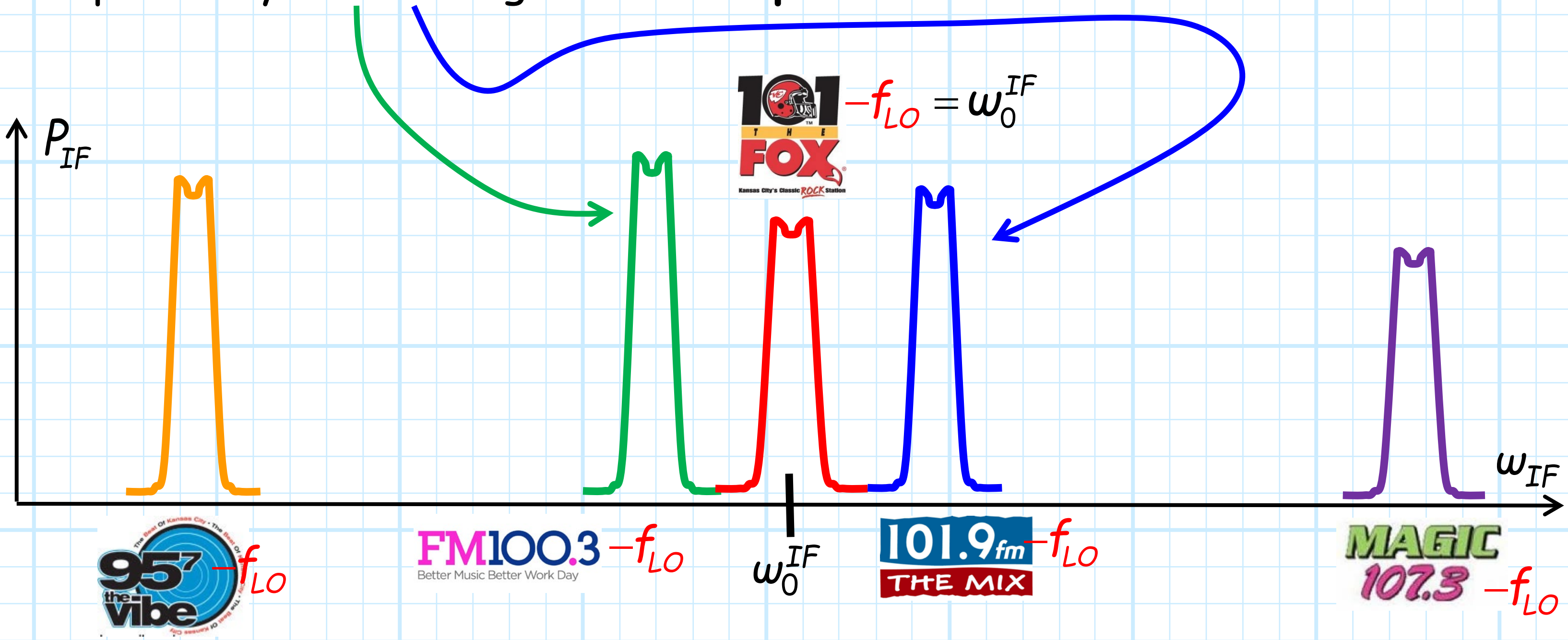


Closest to the IF passband

Q: ***Why** are these "**spectrally adjacent**" signals so problematic?*

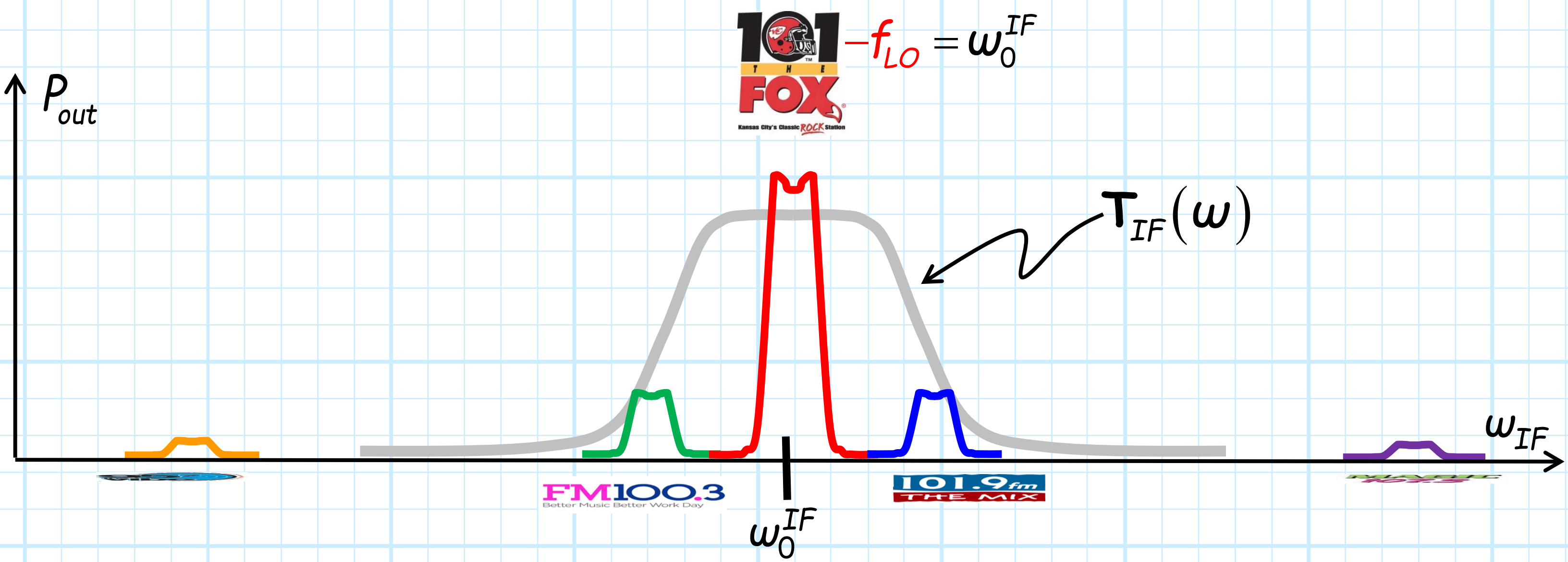
A: Recall the **entire** RF spectrum is "down-converted", such that the desired signal (with frequency ω_{RF}^{s}) is **centered in the passband** of the IF filter (i.e, $\left|\omega_{RF}^{s} - \omega_{LO}\right| = \omega_{0}^{IF}$).

The signals **spectrally adjacent** to this desired signal will therefore be the spectrally **closest** signals to the **passband** of the filter.



The spectrally adjacent signals are attenuated the least

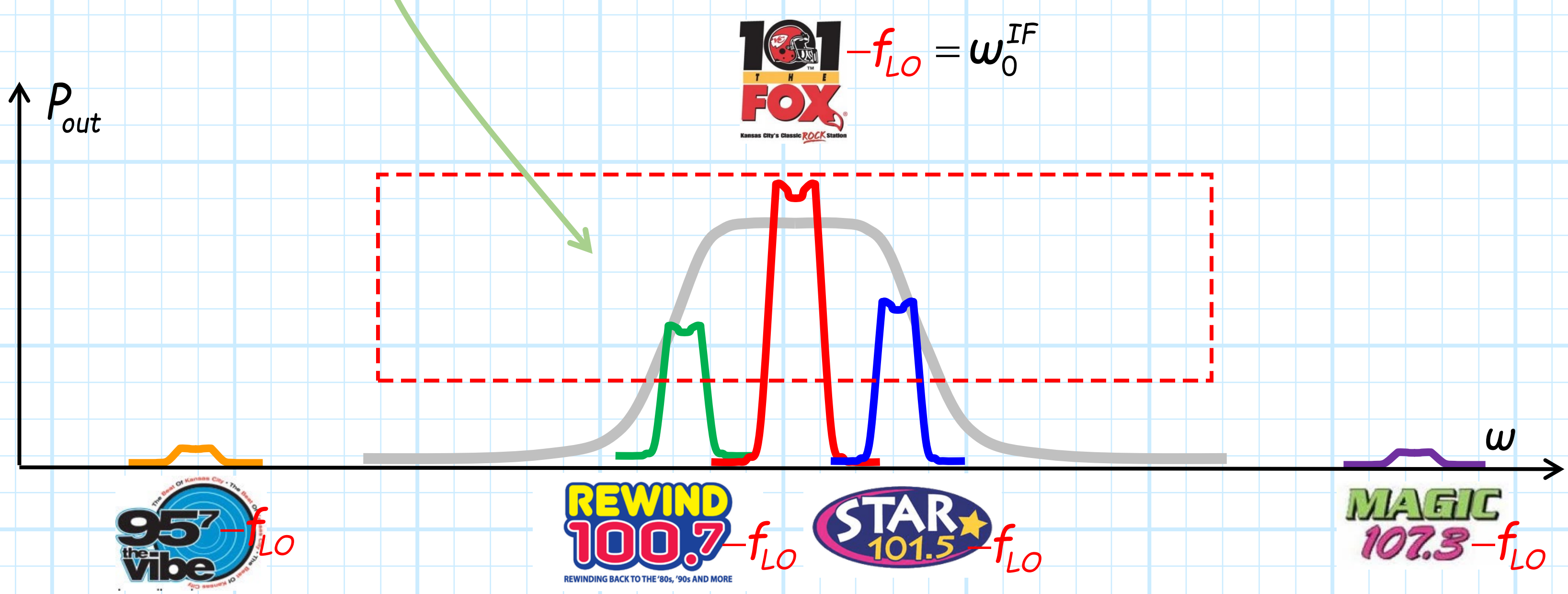
Therefore, after passing through the IF filter, **these spectrally adjacent** signals are **attenuated the least** of any signal outside of the passband.



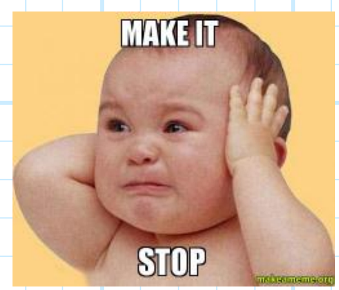
Catastrophe!

Q: *What happens if the **attenuation** of these adjacent signal is **insufficient**?*

A: Then potentially, **more than one** signal will be presented to the **demodulator** (two small signals and one large (desired) signal).



The **result** would be a distorted and **inaccurate** demodulated signal $\hat{i}(t)$!



Only one signal in the "window"

Q: *So "how **far down**" should we attenuate these adjacent signals?*

A: Remember, the **desired** down-converted signal must have an output power **within** the demodulator **"window"**:

$$P_D^{max} \geq P_{out}^{s} \geq P_D^{min}$$

In a **properly designed** receiver, **all** other output signals (including adjacent signals) are **attenuated** to the point that they are **less than** P_D^{min}.

$$P_{out}^{adj} < P_D^{min}$$

where P_{out}^{adj} represents the power of **spectrally adjacent** signals at the **output** of the receiver (i.e., the **input** of the demodulator).

Demodulator Dynamic Range

Now, say that the desired signal at the demodulator input is at its **largest acceptable value** (it's at the very **top** of the window!):

$$P_{out}^{s} = P_{D}^{max}$$

In order for:

$$P_{out}^{adj} < P_{D}^{min}$$

We find that **this** must be true:

$$\frac{P_{out}^{s}}{P_{out}^{adj}} > \frac{P_{D}^{max}}{P_{D}^{min}} \quad !!!$$

The ratio:

$$\frac{P_{D}^{max}}{P_{D}^{min}} \doteq DR_{D}$$

is known as the **Dynamic Range** of the **demodulator**.

Decibel operators!!!!

Note that dynamic range DR_D is a **unitless** value, and so is typically expressed with the **decibel operator**:

$$dB\left[DR_D\right] = dB\left[\frac{P_D^{max}}{P_D^{min}}\right]$$

$$= dBm\left[P_D^{max}\right] - dB\left[P_D^{min}\right]$$

Similarly:

$$dB\left[\frac{P_{out}^{s}}{P_{out}^{adj}}\right] = dBm\left[P_{out}^{s}\right] - dBm\left[P_{out}^{adj}\right]$$

So that the power of the attenuated adjacent signal must satisfy:

$$dBm\left[P_{out}^{adj}\right] < dBm\left[P_{out}^{s}\right] - dB\left[DR_D\right]$$

Make this make sense

Now, **assuming** the power of the **spectral adjacent** signals P_{IF}^{adj} (**before** being attenuated by the filter) is **approximately** that of the **desired signal** power P_{out}^{s}, we can conclude alternatively that:

$$dBm\left[P_{out}^{adj}\right] < dBm\left[P_{IF}^{adj}\right] - dB\left[DR_D\right]$$

Meaning:

$$dB\left[DR_D\right] < dBm\left[P_{IF}^{adj}\right] - dBm\left[P_{out}^{adj}\right]$$

Note that the value:

$$dBm\left[P_{IF}^{adj}\right] - dBm\left[P_{out}^{adj}\right]$$

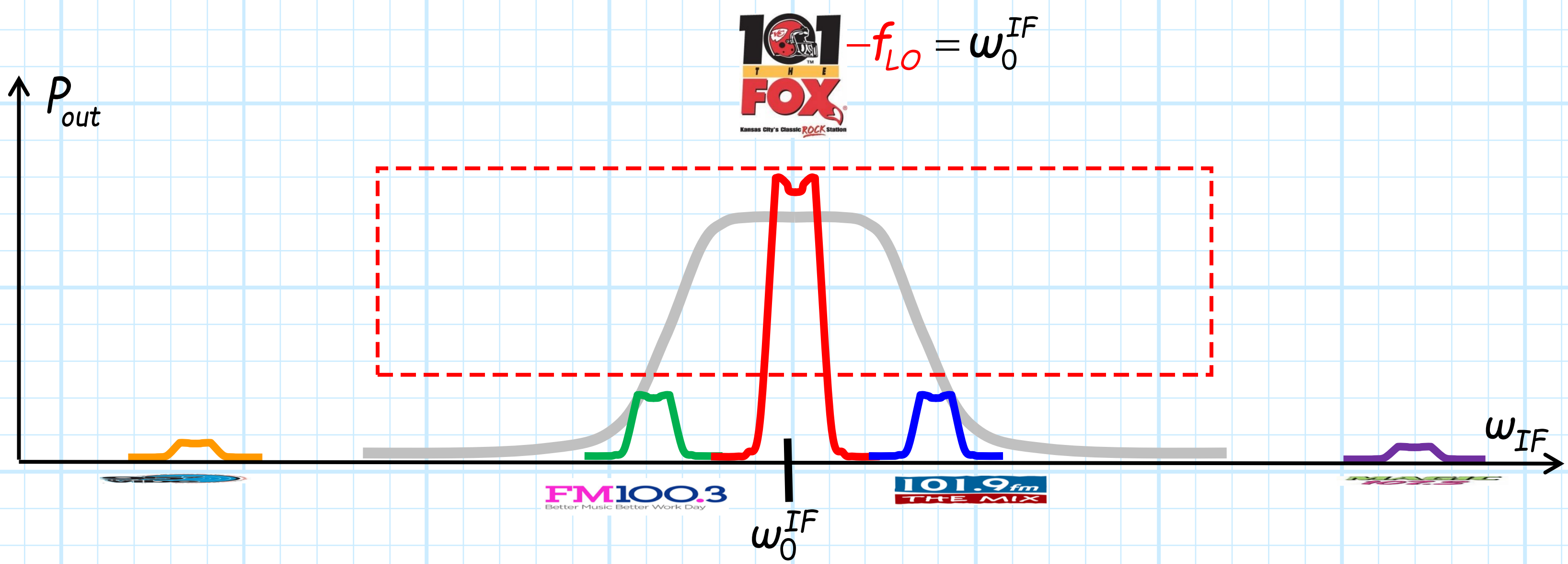
is simply the **attenuation** (in dB) applied to the spectrally adjacent signals by the IF bandpass filter.

Attenuation must be greater than demodulator Dynamic Range!

Thus, the equation

$$dB[DR_D] \; < \; dBm\left[P_{IF}^{adj}\right] - dBm\left[P_{out}^{adj}\right]$$

Simply "says" that the **attenuation of adjacent signals** should be **greater** than the **dynamic range of the demodulator**!

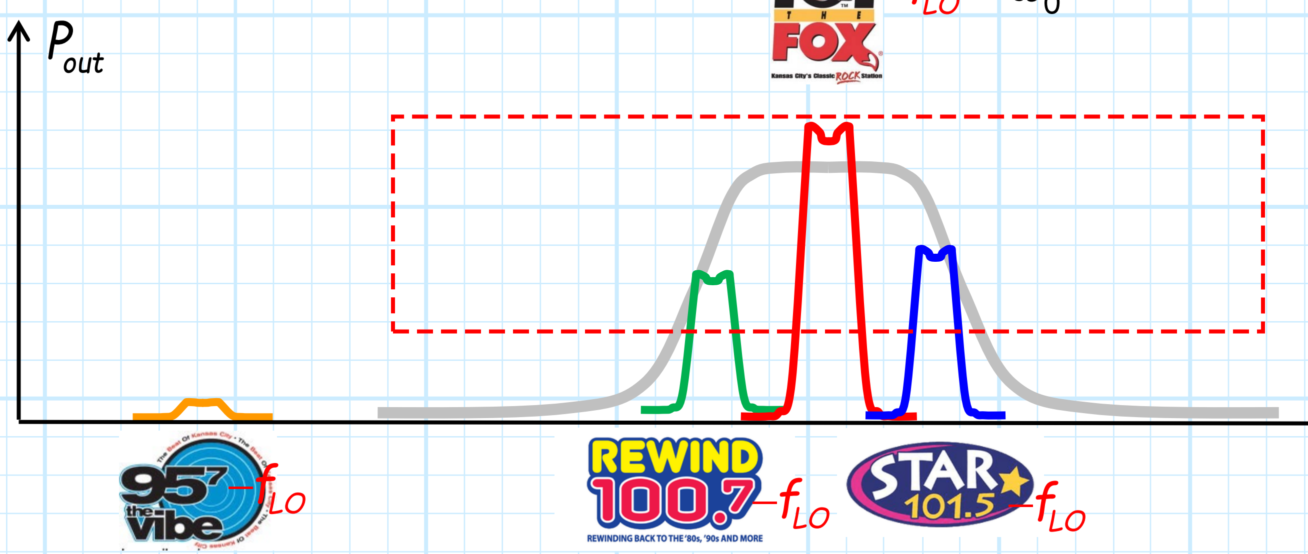


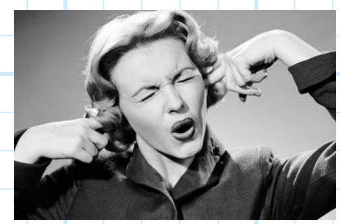
Make. It. Stop!

Q: *The attenuation of these spectrally adjacent signals would seem to depend on how "close" they are to the desired signal frequency (and thus the IF filter pass-band.*

How do we ***know where*** *(i.e., at what frequency) these spectrally adjacent signals* ***lie****?*

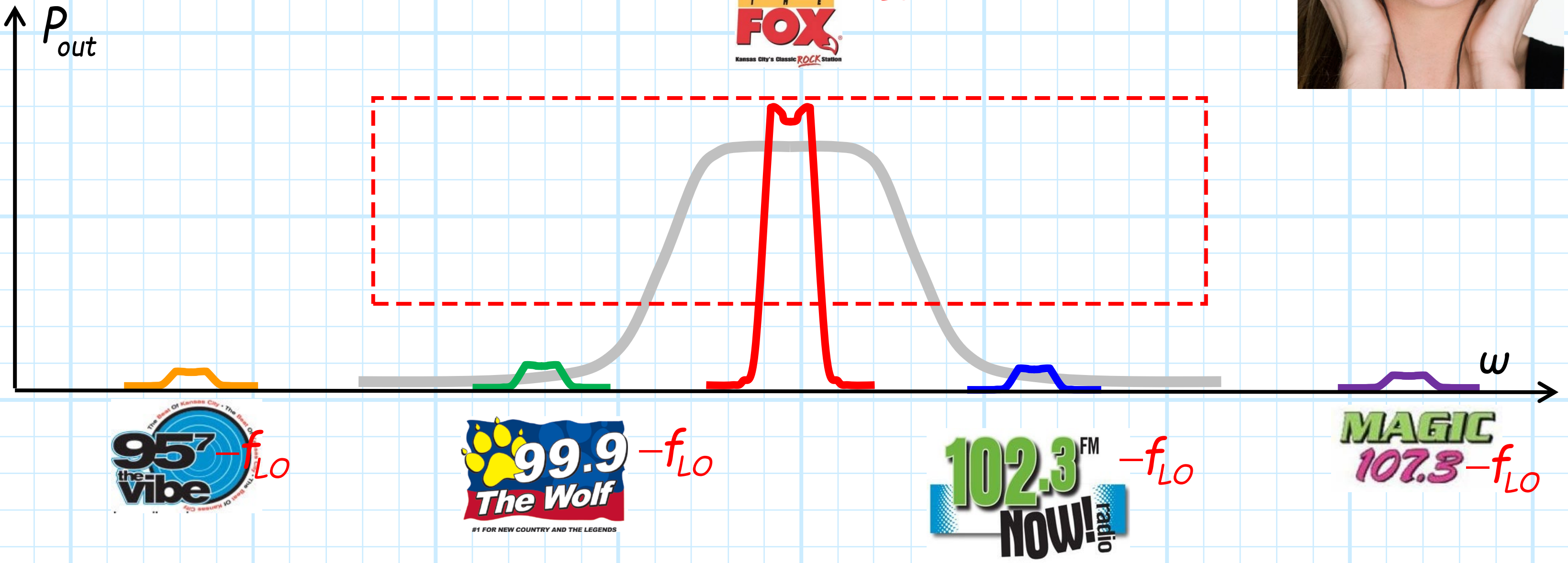
A: It is certainly true that "closer" adjacent signal will be **attenuated less** if they are **closer** in frequency to the desired signal.





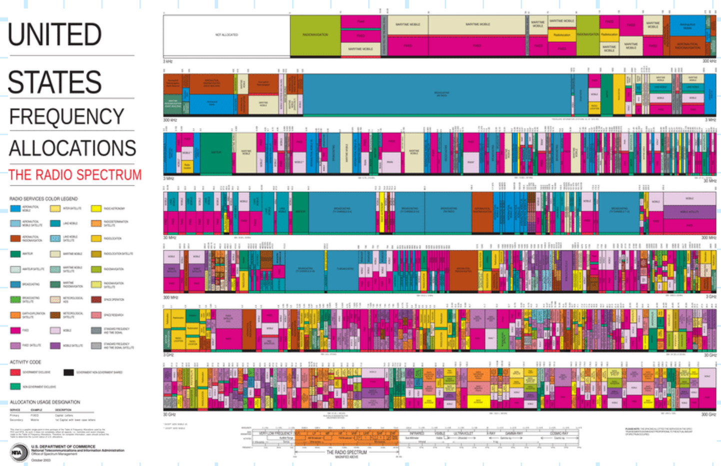
No issues—sounds great!

But adjacent signals are attenuated **more** if they are **further** from the desired signal:



The only agency with an antenna on its seal

Fortunately, we usually know **where** these spectrally adjacent signals are, as their location is **mandated** by the **Federal Communication Commission (FCC)**!



The FCC is charged with **regulating emissions** in the electromagnetic **spectrum**.

In addition to specifying the **precise** frequencies of transmitted signals, they specify also their **spectral separation**!

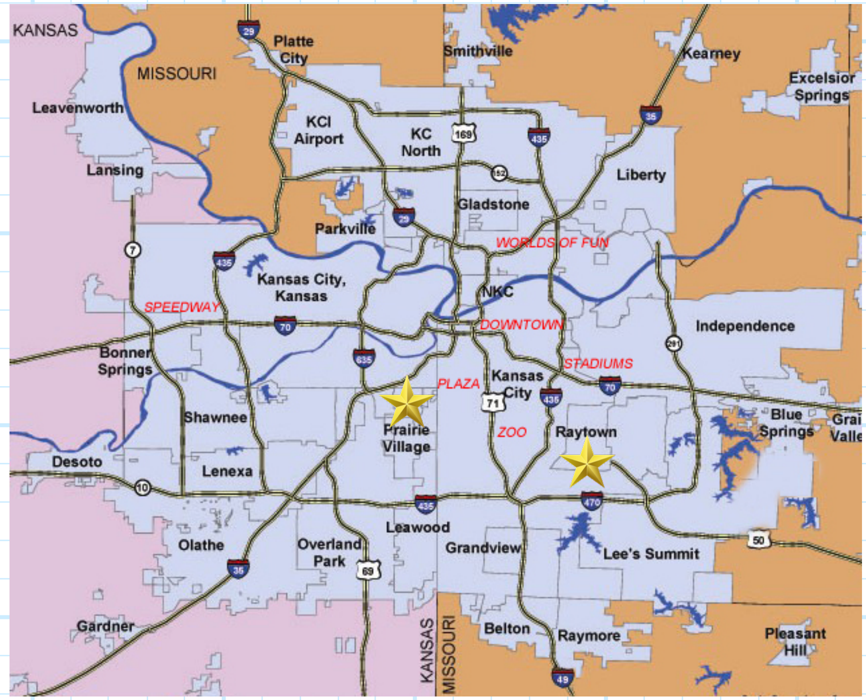
Odd multiples of 100 *kHz*

For example, the FCC **long ago** decided that the FM radio band would span **88 *MHz* to 108 *MHz*.**

Moreover, it specified that all FM stations transmit at frequencies that are **odd-multiples of 0.1 *MHz*** (e.g. 89.3 *MHz*, 95.7 *MHz*, 98.9 *MHz*, 101.1 *MHz*, 106.5 *MHz*).

Channel spacing

Likewise, the FCC has traditionally kept **FM stations** that are ***geographically close*** (e.g., in the Kansas City **metropolitan area**) separated by **at least 0.8 *MHz*.**



Thus, the "channel spacing" of FM radio is **0.8 *MHz*.**

One channel-spacing above and below

Thus, the "**worst-case** scenario" for a radio station centered at 101.1 *MHz* would be to have **spectrally adjacent signals** at:

$$101.1 - 0.8 = 100.3\ MHz$$

$$101.1 + 0.8 = 101.9\ MHz$$

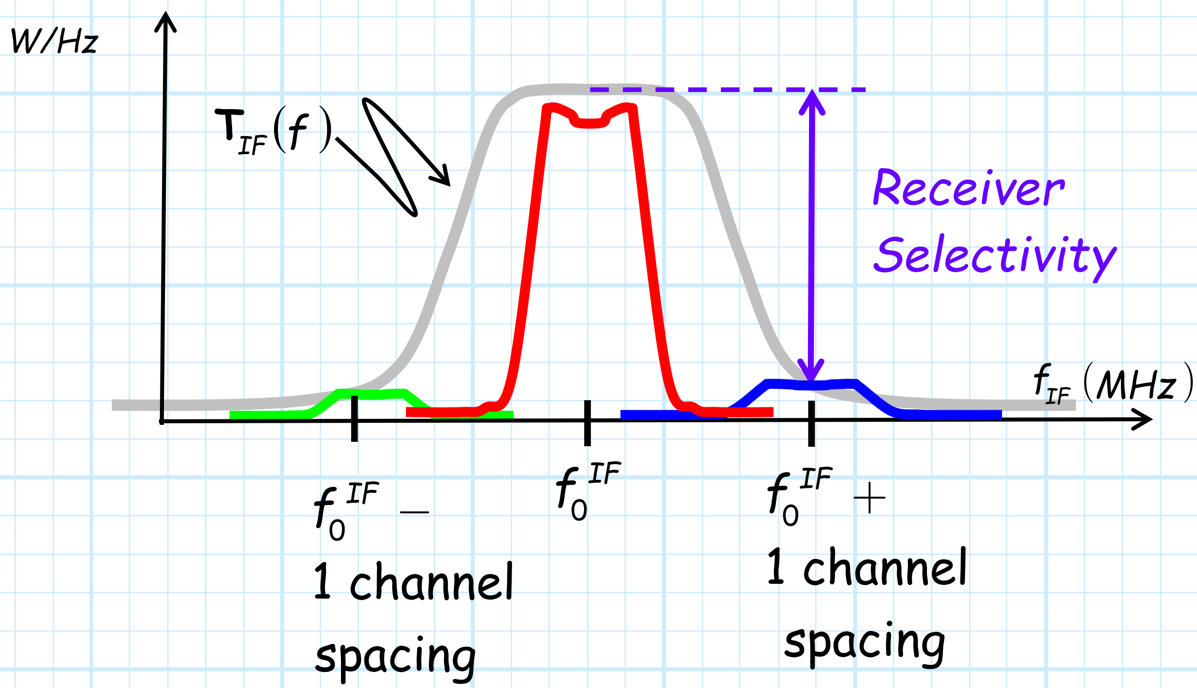
A station broadcasting at **100.3 *MHz*** is thus one "channel spacing" **below** 101.1 *MHz*, while a station at **101.9 *MHz*** is one "channel spacing" **above** 101.1 *MHz*.

Now, we can provide a **formal definition** for receiver selectivity!

Receiver selectivity

The **amount** by which the IF filter **attenuates** (in dB) **adjacent channels** is defined as the **selectivity** of the receiver.

$$\text{Selectivity} \;=\; -10\log_{10}\left[\mathbf{T}_{IF}\left(f_0^{IF} \pm 1 \text{ channel spacing}\right)\right]$$



Typical values of receiver **selectivity** range between 30 dB and 60 dB.

Also selectivity

Using our **earlier notation**, we express **this** transmission as:

$$\mathbf{T}_{IF}\left(f_0^{IF} \pm 1 \text{ channel spacing}\right) = \frac{P_{out}^{adj}}{P_{IF}^{adj}}$$

So that selectivity can **also** be expresses as:

$$\begin{aligned} \text{Selectivity} &= -10\log_{10}\left[\mathbf{T}_{IF}\left(f_0^{IF} \pm 1 \text{ channel spacing}\right)\right] \\ &= -10\log_{10}\left[\frac{P_{out}^{adj}}{P_{IF}^{adj}}\right] \\ &= dBm\left[P_{IF}^{adj}\right] - dBm\left[P_{out}^{adj}\right] \end{aligned}$$

An important receiver design rule

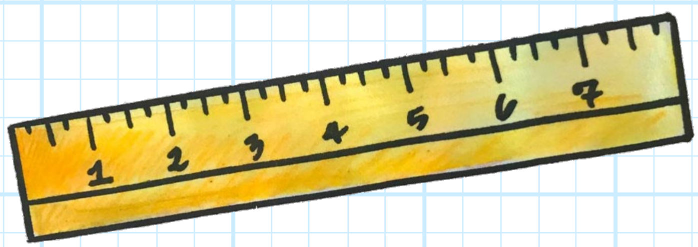
Then our **earlier conclusion**:

$$dB\left[DR_D\right] \; < \; dBm\left[P_{IF}^{adj}\right] - dBm\left[P_{out}^{adj}\right]$$

Can **also** be expressed as:

$$\text{Selectivity} \; > \; dB\left[DR_D\right]$$

The **receiver selectivity** should exceed the **dynamic range** of the demodulator!



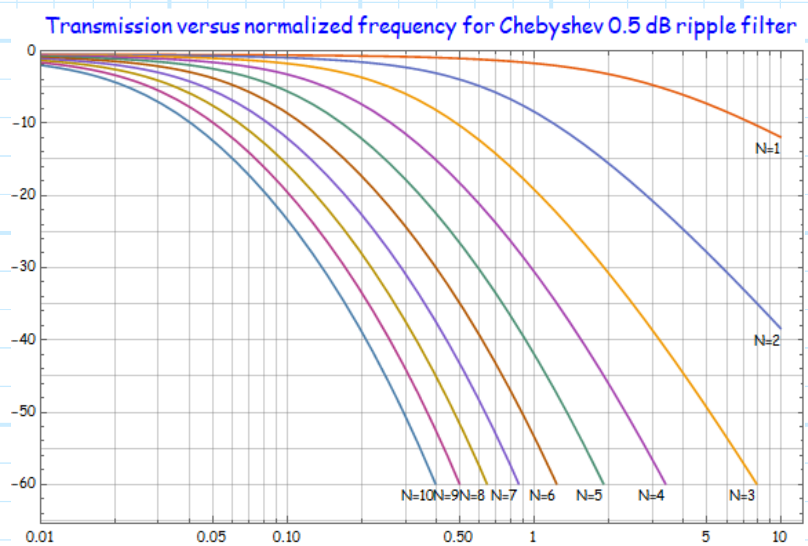
Increase the filter order!

Q: *But **what if** the selectivity **doesn't** exceed the dynamic range of the demodulator?*

*Since the bandwidth B_f of the filter **cannot** be decreased (i.e., $B_f \cong 1.2\,B_s$), how can we **increase** Selectivity?*

A: You **increase** receiver selectivity by increasing the **order** N of the **IF filter**!

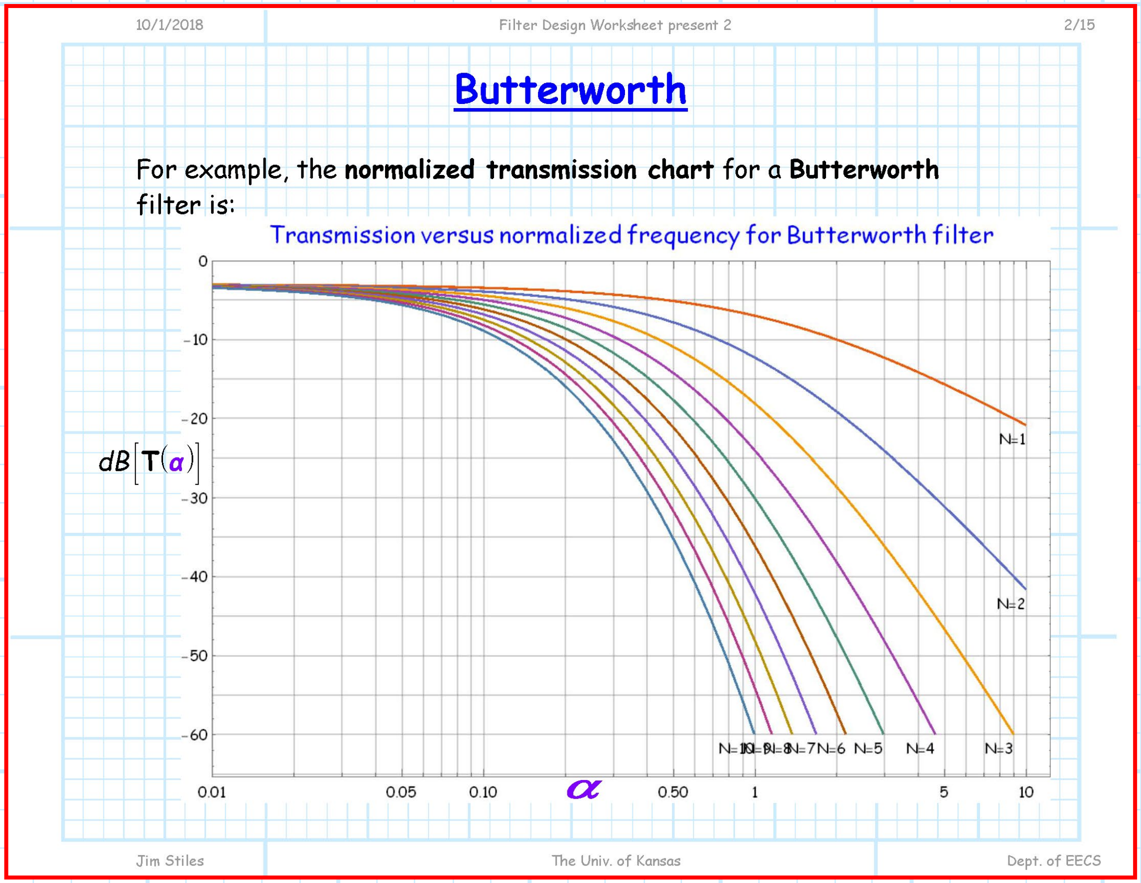
Remember, the larger the order N, the **steeper** the "roll-off"; and thus the **greater** the attenuation and Selectivity.



Remember?

Q: *But **how** would I **determine** the necessary **order value N** of the IF filter?*

A: Remember your "**Filter Design Worksheet**" !



You can do this!

For **example**, let's say **you** are designing an **FM radio receiver**—one that will be connected to an FM **demodulator** with **40 *dB* of dynamic range**.

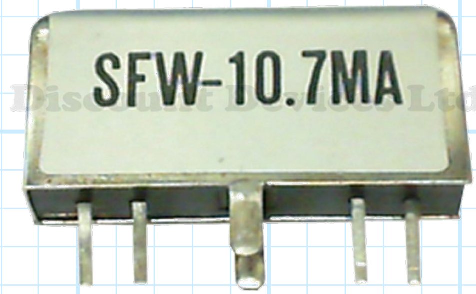
Say then your wish for your receiver to have a Selectivity of at least **50 *dB*** (10 dB **more** than the demodulator dynamic range!).

The **bandwidth** of an FM radio **signal** is about $B_s = 0.17\,MHz$, so **you** make the bandwidth of the IF filter about 200 kHz:

$$B_f \cong 1.2\,B_s = 0.2\,MHz$$

10.7 MHz IF is *the* standard for FM

A **standard** IF center frequency for FM radio stations is:



$$f_0^{IF} = 10.7\ MHz$$

Using **this** IF center frequency, the frequency of signals at **one** channel-spacing away from the desired signal would thus arrive at the **IF filter** with frequencies:

$$f_{IF}^{adj} = 10.7 \pm 0.8\ MHz = 10.1\ MHz,\ 11.5\ MHz$$

Now, the **normalized bandwidth** of the IF filter is:

$$\%\Delta = \frac{f_H - f_L}{f_0} = \frac{B_f}{f_0^{IF}} = \frac{0.2}{10.7} = 0.0187$$

Normalized frequencies

And so for **this** filter, the **normalized** frequency of the **adjacent signal** one channel-spacing **above** is:

$$\begin{aligned}\alpha &= \left|\frac{1}{\%\Delta}\left(\frac{f}{f_0}-\frac{f_0}{f}\right)\right| - 1 \\ &= \left|\frac{1}{0.0187}\left(\frac{11.5}{10.7}-\frac{10.7}{11.5}\right)\right| - 1 \\ &= 6.72\end{aligned}$$

While the **normalized** frequency of the **adjacent signal** one channel-spacing **below** is:

$$\begin{aligned}\alpha &= \left|\frac{1}{\%\Delta}\left(\frac{f}{f_0}-\frac{f_0}{f}\right)\right| - 1 \\ &= \left|\frac{1}{0.0187}\left(\frac{10.1}{10.7}-\frac{10.7}{10.1}\right)\right| - 1 \\ &= 5.18\end{aligned}$$

The lower frequency is the worst case

Notice the **smaller** of these two results:

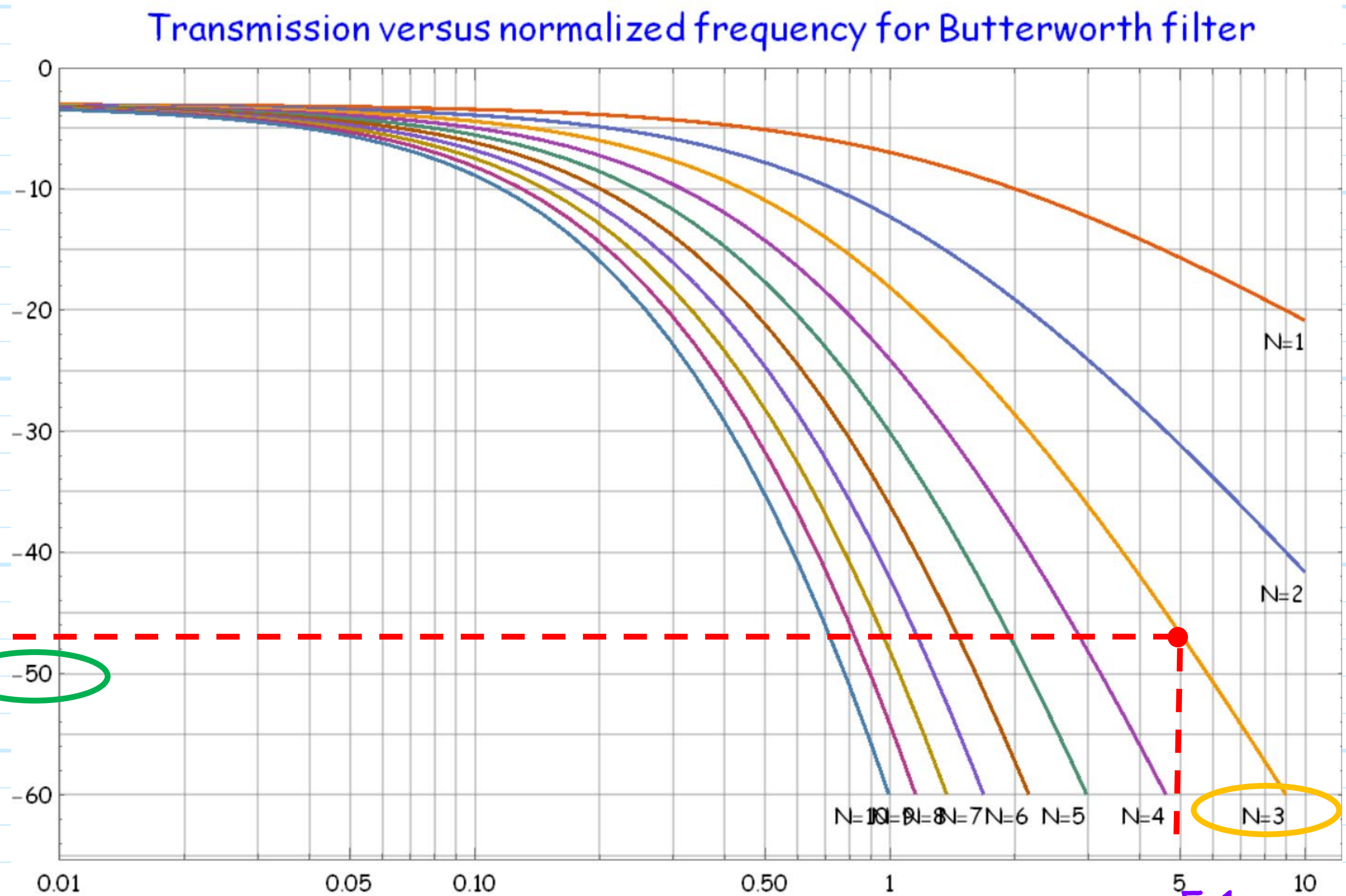
$$\begin{aligned}\alpha &= \left|\frac{1}{\%\Delta}\left(\frac{f}{f_0}-\frac{f_0}{f}\right)\right| - 1 \\ &= \left|\frac{1}{0.0187}\left(\frac{10.1}{10.7}-\frac{10.7}{10.1}\right)\right| - 1 \\ &= 5.18\end{aligned}$$

is the **normalized** frequency of the adjacent signal **one channel-spacing below** (this is **always** the case!).

Thus, the **lower** adjacent signal at 10.1 MHz (i.e., $\alpha = 5.18$) will be **attenuated less** than the other adjacent signal—we should use **this** value determine the proper filter order to achieve **50dB** of Selectivity!

Close, but not close enough

From the normalized **Butterworth** filter transmission chart, we see that a **3rd-order** filter will achieve about **47 dB** of attenuation at $\alpha = 5.18$.



$$dB\left[\mathbf{T}(\alpha = 5.1)\right] = -47$$

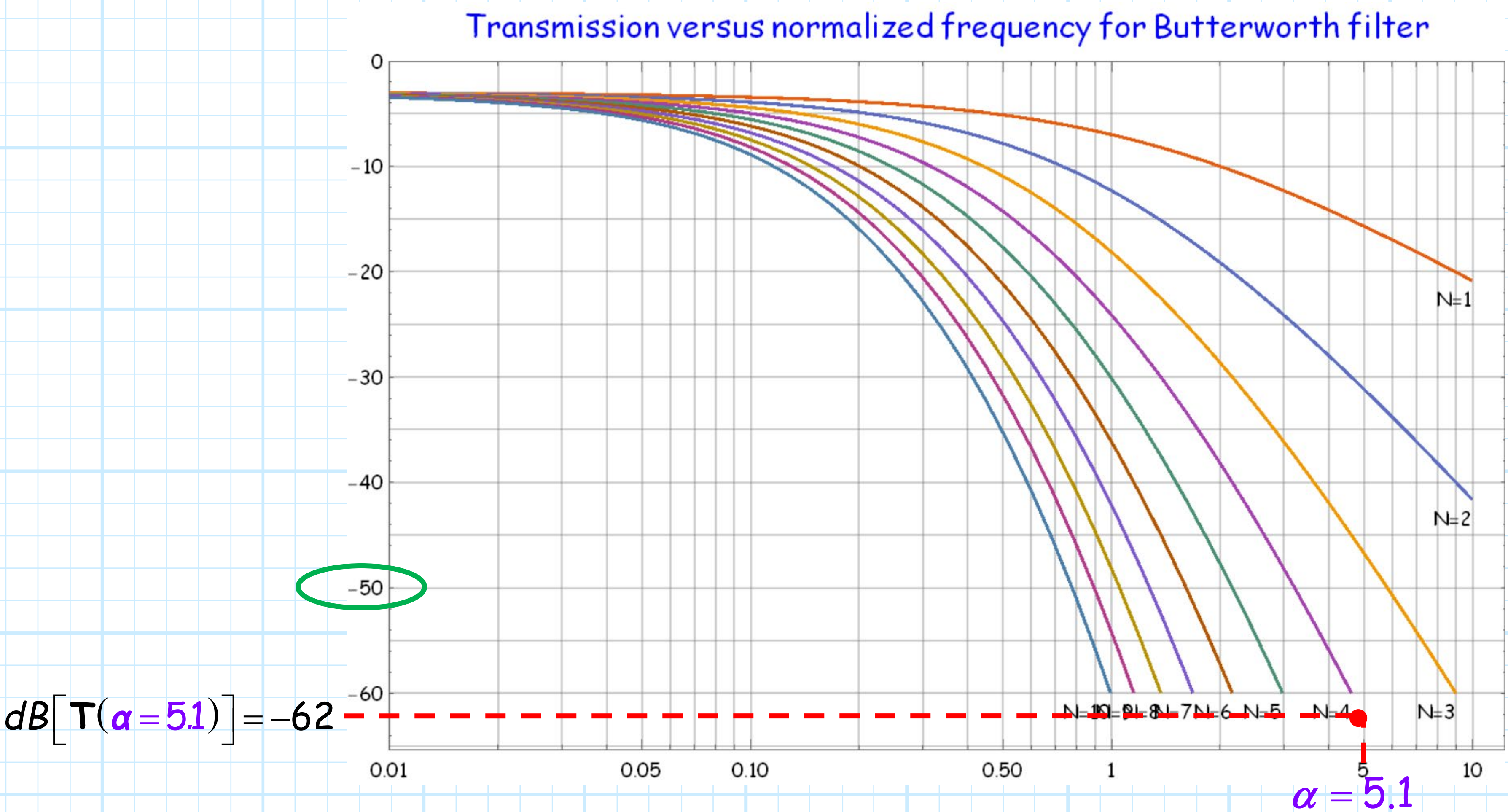
$\alpha = 5.1$

Although $47dB$ is **close** to $50dB$, it is does **not** exceed $50dB$!

Thus, a 3rd-order Butterworth filter is **entirely insufficient**.

The other hand holds 62 dB

On the **other** hand, a $\mathbf{4^{th}}$**-order** filter will provide about **62dB** of attenuation at $\alpha = 5.18$—this **does** exceed $50dB$ (by a whopping **12dB**).



A $\mathbf{4^{th}}$**-order** Butterworth filter is necessary to achieve the required Selectivity for this FM radio design!

It is what it is!!!!

Q: *So, do I proudly state that the Selectivity of this receiver design is* ***more than 50dB****?*

A: NO!!!

Since your 4th-order IF filter attenuates the lower channel by 62 *dB*, we say that **the selectivity of the receiver is 62 *dB***!

I believe it has something to do with phase delay

Q: *Couldn't we further increase the receiver selectivity by using a **Chebyshev** filter (**instead** of a Butterworth)?*

A: Because of the **faster roll-off** of Chebychev filter, this would **indeed** increase the receiver selectivity (**or**, we could get by with **just** a 3rd-order filter).

But remember, an **IF filter** is a **narrowband filter** (i.e., the **signal** bandwidth and the **filter** bandwidth are approximately **equal**).

Thus, using a Chebychev **IF** filter is a **very bad** idea!

Do **you** remember why?