RF/IF Terminology and Specs

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Terminology

- LNA - Low-Noise Amplifier. A specialized amplifier to boost the very small received signal, usually 10-20 dB of gain, while adding as little noise as possible
- Mixer - performs frequency conversion. For example, a mixer in a receiver might move a 900 MHz signal to a lower frequency such as 70 MHz, where additional gain and filtering can be applied.
- Modulator - applies desired modulation to RF or IF carrier wave
- Demodulator - extracts the original modulation from the RF or IF

Terminology

- Logarithmic Amplifier: Device which measures signal strength over a large dynamic range (typ 60-100dB)
- Direct Conversion Receiver: A receiver in which much of the gain in the signal path occurs at baseband (DC).
- Superheterodyne Receiver: A receiver in which much of the gain in the signal path occurs at one or more Intermediate Frequencies (IFs). The number of “conversions” represents the number of intermediate frequencies. Single- and dual-conversion architectures are commonly used.

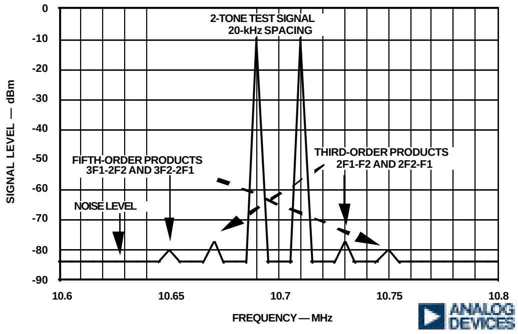
Terminology

- 1-dB compression (P1dB) - the amplitude at which a device's output no longer increases by 1 dB for each 1 dB increase in input signal.
- VCO - voltage-controlled oscillator, used with PLL
- LO - Local Oscillator - what the VCO is used for
- PLL - Phased Locked Loop. Key specs are phase noise (measured with VCO), frequency range, and division ratios.

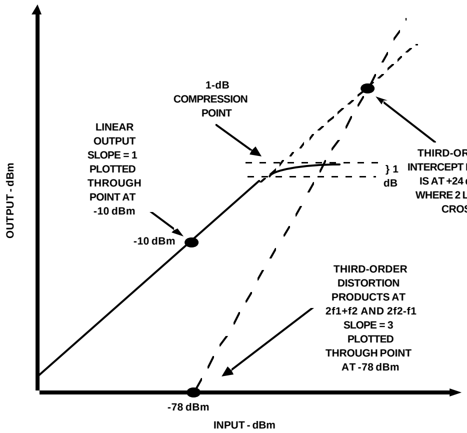
Third-Order Intercept Point (IP3)

- The Third-Order Intercept Point is the theoretical amplitude at which the mixer's third-order distortion products are equal in amplitude to the mixer's linear IF output point. The third-order intercept is measured using a two-tone RF test signal that mixes with the LO input to produce the desired mixing products f1±f2 and undesired distortion products of the form nf1±mf2. When n+m=3, these are called Third-Order Distortion Products. Because these products are close to the desired signal, they are the products most likely to interfere with the desired signal, so it's important that the mixer have as high a third-order intercept point as possible to minimize these distortion products.

Spectrum Analyzer display showing 2-tone test signal, Third-Order Distortion Products, and Fifth-Order Distortion Products. This is the test signal used to characterize the AD831. The 10.7 MHz center frequency is the desired IF



Third-Order Intercept Point: Graphical Solution



- When you plot the amplitude of the two-tone test signal at -10 dBm and the Third-Order Distortion Products at -78 dBm and draw lines through them with slopes of one and three, respectively, the lines cross at the Third Order Intercept Point.

Noise Factor and Noise Figure

- Noise Figure is a figure-of-merit used to determine how a device degrades the signal-to-noise ratio of its input. Note: S/N is a power ratio below!
  - Noise Factor (F), is defined as

$$F = \frac{SNR_{In}}{SNR_{Out}}$$

  - Noise Figure (NF) is defined in dB as

$$NF = 10 \log_{10} \frac{S_I/N_I}{S_O/N_O} = 10 \log F$$

Cascaded Noise Figure

- Noise figure is a figure of merit used to describe how much noise is added to a signal in the receive chain of a radio. Usually, it is specified in dB although in the computation of noise figure, the numerical ratio (non-log) is used. The non-log is called Noise factor and is usually defined as shown below.

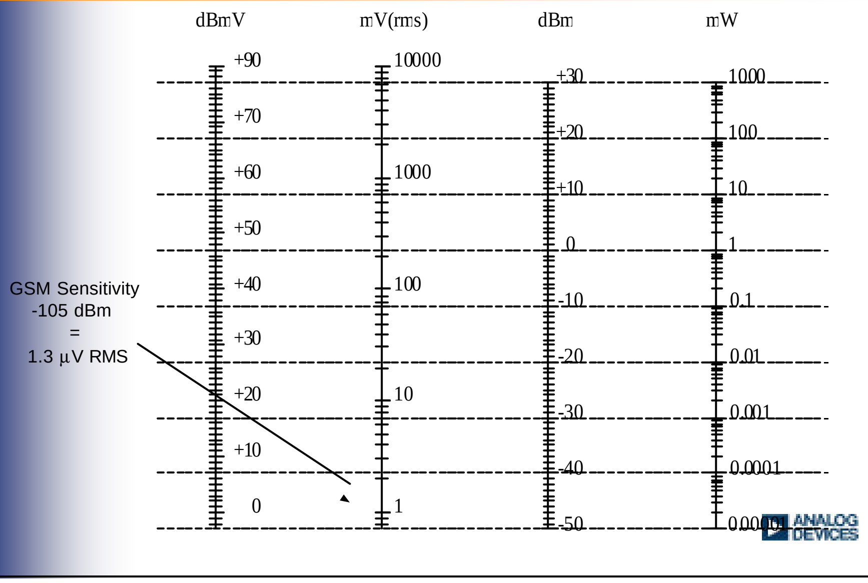
$$F_{total} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \frac{F_4 - 1}{G_1 G_2 G_3} + \ldots$$

- where F_N and G_N are the noise factor and gain, respectively, of the Nth stage in the receiver. This is called the Friis equation.

Specs and Figures of Merit

- Noise Figure (dB): lower is better
- Third-order Intercept (dBm): higher is better
- 1-dB Compression point (dBm): higher is better
- Dynamic range (dB): more is (usually) better
- Phase Noise (dBc/Hz): less is better
- Power (mW): less is better
- Cost ($): depends

Specs - Know Your dBm (50Ω system)



GSM Sensitivity
-105 dBm
=
1.3 µV RMS

Specs - Converting between Volts and dBm

$$dBm = 10\log\left[\frac{\frac{Vrms^2}{R}}{1mW}\right] = 20\log\left[\frac{Vrms}{\sqrt{R\cdot 1mW}}\right]$$

$$Vrms = \sqrt{0.001W \times 50\Omega \times \log^{-1}\left(\frac{dBm}{10}\right)}$$

For example

0dBm = 223.6 mVrms (50 Ohm)

20dBm = 2.236 Vrms (50 Ohm)

- Note that dBm is used to express *absolute* power levels (e.g. a base station transmits +50dBm) while dB is used to express power or signal level *differences* (e.g. the distortion is 50dB below the carrier; 50dBc is also used to express dBs relative to the *carrier*).

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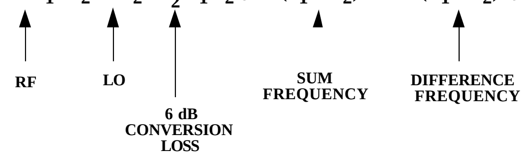
The Mixing Process

- Given two input signals, where $A_1\cos\omega_1 t$ is the RF input and $A_2\cos\omega_2 t$ is the LO input, an ideal multiplier performs the linear multiplication

$$A_1\cos w_1 t\, A_2\cos w_2 t = \frac{1}{2} A_1 A_2 \{\cos(w_1 + w_2)t + \cos(w_1 - w_2)t\} \quad \text{Eq. (1)}$$



RF

LO

6 dB CONVERSION LOSS

SUM FREQUENCY

DIFFERENCE FREQUENCY

- But a mixer is ***normally*** not a linear multiplier — it multiplies the RF input by the SIGN of the LO input - a square wave at the LO frequency. Several pages of math later we have the sum and difference frequencies (higher ordered terms are not shown):

$$IF = \frac{1}{2}\frac{4}{\pi} A_1(\cos(\omega_1 + \omega_2)t + \cos(\omega_1 - \omega_2)t)$$

$$IF = \frac{2}{\pi} A_1(\cos(\omega_1 + \omega_2)t + \cos(\omega_1 - \omega_2)t)$$

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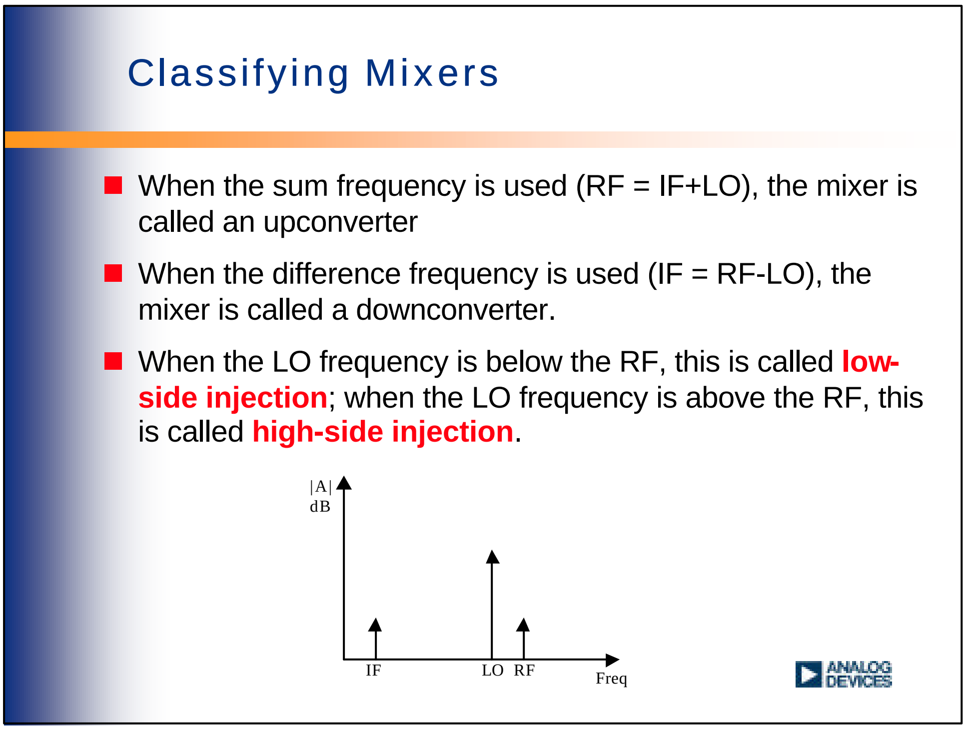
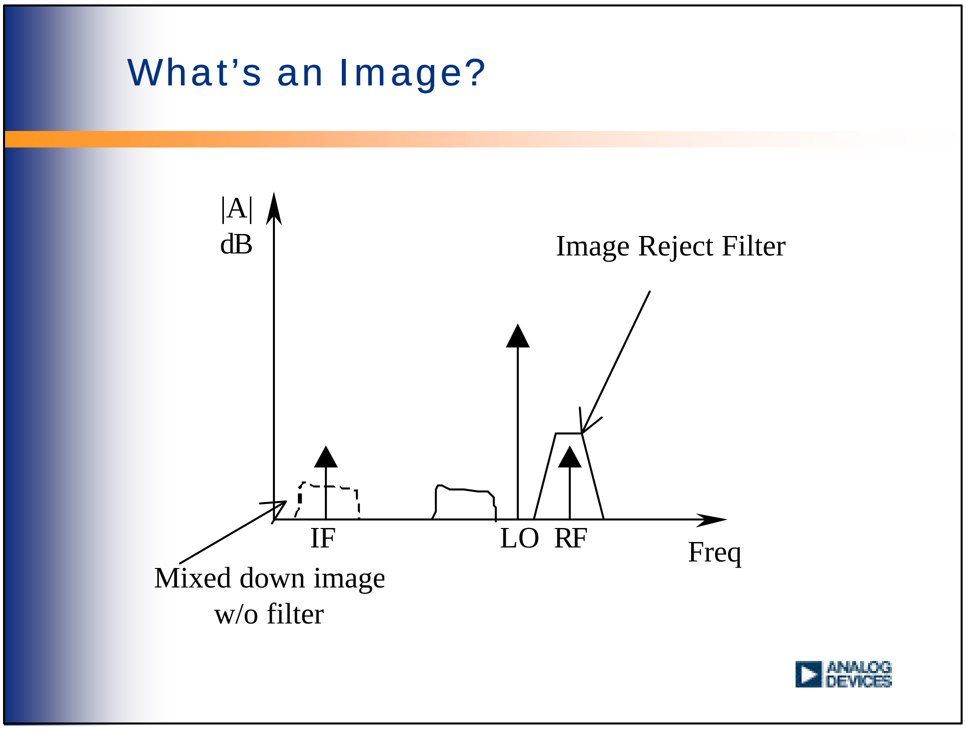


Classifying Mixers

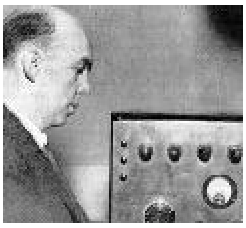
- When the sum frequency is used (RF = IF+LO), the mixer is called an upconverter
- When the difference frequency is used (IF = RF-LO), the mixer is called a downconverter.
- When the LO frequency is below the RF, this is called **low-side injection**; when the LO frequency is above the RF, this is called **high-side injection**.



What's an Image?

Major Edwin H. Armstrong and the Superheterodyne Receiver

- In the early days of radio, tubes had poor high-frequency response - a few MHz at best. Receivers consisted of tuned RF amplifiers, a detector, and audio gain. This was the homodyne (direct conversion) receiver.
- In 1917, in order to get more gain, Major Edwin H. Armstrong decided to convert (mix) the radio frequency (RF) signal to a lower, fixed intermediate frequency (IF), where tubes had lots of gain. He named his invention the "super-heterodyne" receiver.



Major Edwin H. Armstrong

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Why Superheterodyne Receivers are Good

- It is much easier to have all the gain and selectivity of a receiver at a single frequency than to have the gain and frequency-selective circuits "tune" over a band of frequencies.
- Fixed-frequency filters are easier and cheaper to make than mechanically-tuned tracking filters.
- The input bandpass filter rejects the image frequency - “image rejection”.
- In receivers with linear signal chains, AGC keeps the amplitude of the output signal constant at the input of the ADC (or audio amplifier!)

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Why is there more than one receiver architecture?

- Homodyne: Direct-to-baseband conversion. No IF and no images.
- Super Heterodyne Receivers:
  - Single Conversion: Uses one mixer and one IF. Requires high IF for good image rejection but getting gain and especially selectivity at too high an IF can be difficult. Used in CDMA
  - Dual Conversion: Uses a "high" IF for image rejection and a low IF for high gain and narrow filters. Used in IS136.
  - Triple Conversion: Used in communications receivers. First IF is higher than RF input to avoid "tuning through the IF". Second IF is for image rejection and third IF for gain and selectivity.

Direct Conversion Architecture - Problems and Solutions

- Homodyne transmitter has problems due to interactions of PA and VCO. (e.g., transmitter affects VCO, changes phase trajectory)
  - Don't run the VCO at the transmit frequency
- Receive to LO (VCO) isolation causes problems such as self detection for blocking signals
  - LO to Receive isolation. LO is now in band and results in DC offsets at base band, which change on a channel to channel and burst to burst basis
  - Frequency planning, avoiding VCO or multiples to overlap RF, and high resolution. ADC
- All selectivity occurs at base band implying high dynamic range base band filters
  - Replace analog filters with high resolution ADCs and digital filtering
- AM Suppression. 2nd order non-linearity in mixer will cause the envelope of adjacent channel (or other AM interferers) to be detected at base band. This is covered by specific tests within GSM 5-05. GSM requires 80dB AM rejection
  - Appropriate mixer design

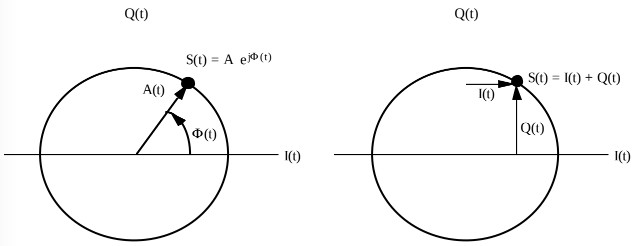
What is an IF Strip?

- Both transmitters and receivers have an "IF Strip". This name originates from the days when the IF section of a transmitter or receiver consisted of a "strip" of amplifiers, each with a tuned input and output circuit, all in a row.
- The IF strip is where the bulk of the gain and selectivity occur. In a high-performance receiver design, the IF strip has about 130 dB of gain-control range. GSM handhelds require 65 dB.

Types of IF Strips

- Limiting IF Strip (log amp)
  - high, fixed gain provides limited (clipped) output
  - nonlinear amplifier retains phase information at output
  - received signal strength indication (RSSI) output
  - often incorporates phase demodulator
- Linear IF Strip (variable gain amplifier)
  - low distortion
  - linear-in-dB variable gain
  - linear amplifier retains amplitude information
  - automatic gain control (AGC) provides constant signal level at output (not clipped)
  - often incorporates a demodulator

Any signal can be represented in either Polar (left) or rectangular (right) form



- Polar Coordinates
  - ☐ limiting IF
  - ☐ IS136 and AMPS
- Rectangular Coordinates
  - ☐ linear IF
  - ☐ IS136 and IS95

Demodulating I/Q signals in DSP

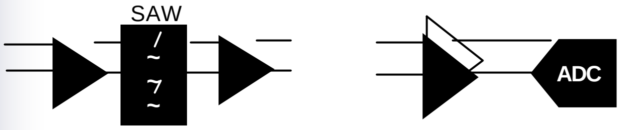
- AM: S(t) = sqrt (I^2 +Q^2)
- FM: S(t) = arctan (I/Q)
- 4-state digital encoding (4QAM):

Data	**I**	**Q**
00	0	0
01	0	1
10	1	0
11	1	1

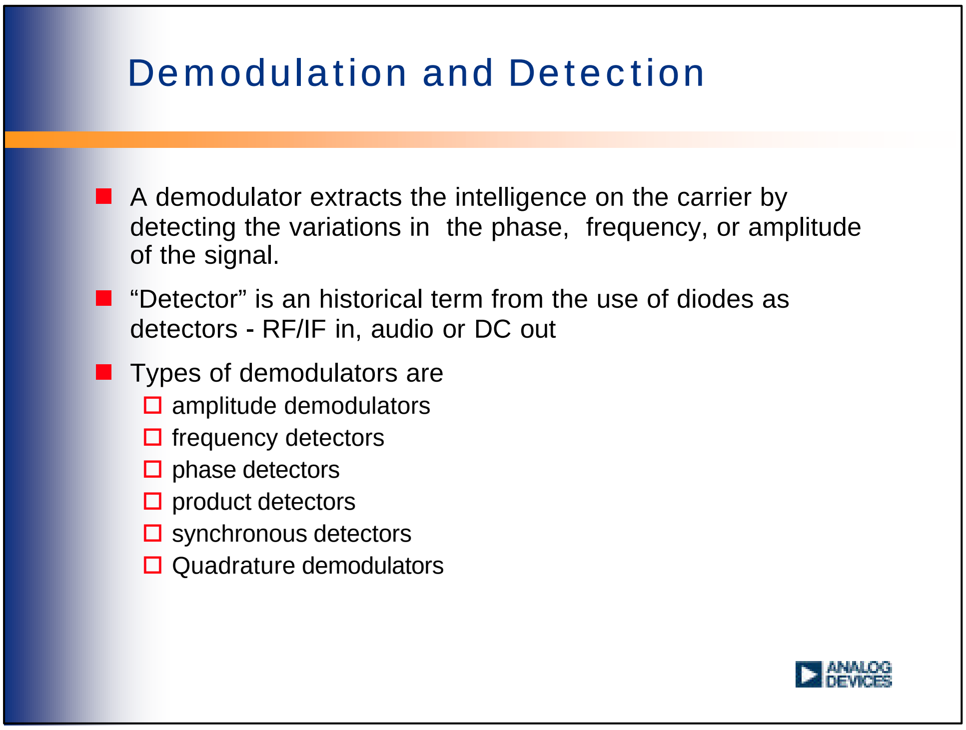
Bandpass Filter Types and Costs vs Frequency

- RC: Cheapest, used at baseband. Broadband. Noisy.
- LC: Simple ones are low cost. Narrowband. Ideally noiseless.
- Ceramic: Cheap (35¢ in 1000s). Common at 455 kHz and 10.7 MHz IFs (AM and FM broadcast band receivers, respectively).
- SAW: $1-$3 in volume. Size and price decrease as frequency increases.
- Crystal: Cheap crystal filters are used in land-mobile radio and pagers at IFs~45 MHz.
- Mechanical: Used in high performance communications receivers.

Stand Alone IF Amplifiers for Base Stations (AD8350, AD8138, AD6630)

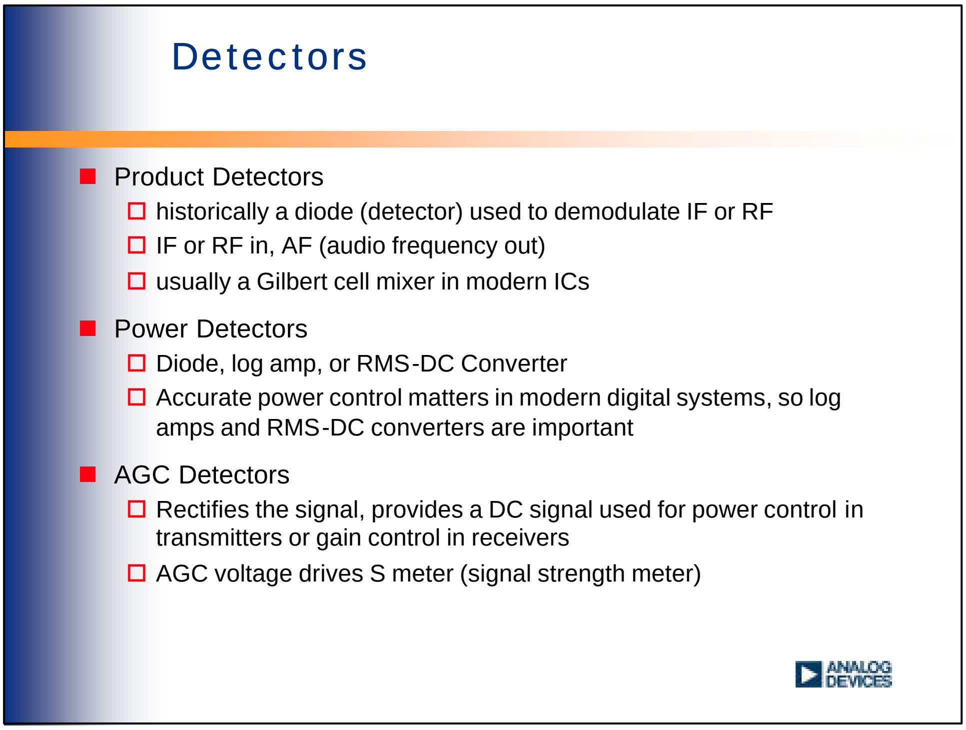


- IF Amp has multiple functions
- Received Signal fundamentally needs gain
- SAW Buffer. SAWs have typically 20dB insertion loss. Signal needs to be restored to original amplitude
- Noise Figure is critical if signal is small. NF becomes less critical as you get further away from the antenna
- Why go Differential at IF Frequencies?
  - Higher CMRR
  - Lower Distortion (lower 2nd order harmonics)
  - SAWs and IF ADCs are differential



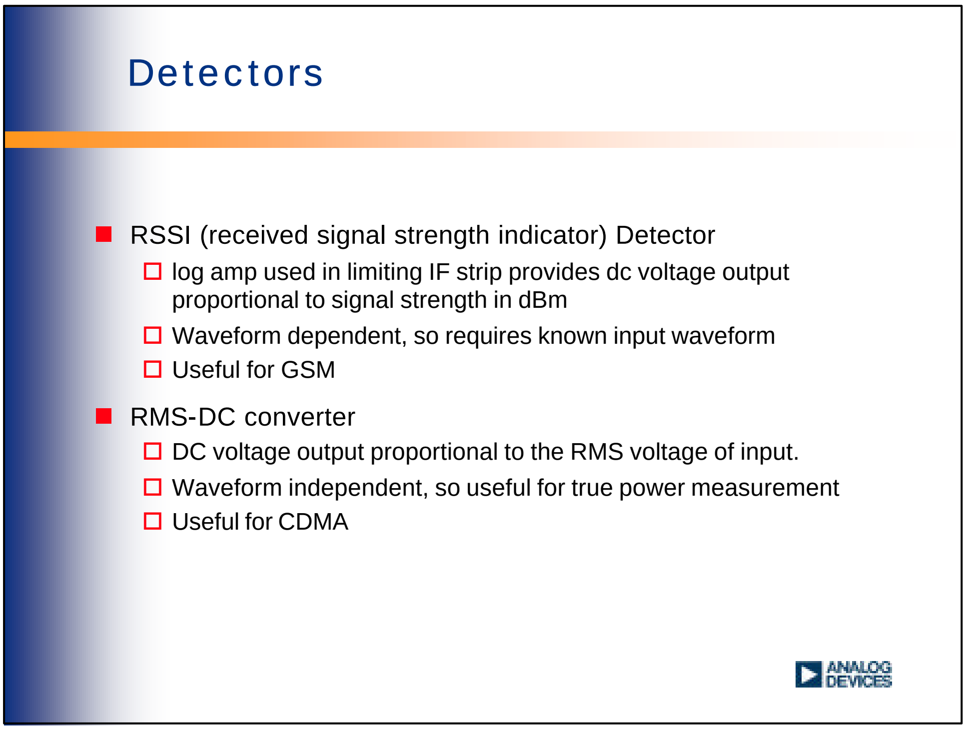
Demodulation and Detection

- A demodulator extracts the intelligence on the carrier by detecting the variations in the phase, frequency, or amplitude of the signal.
- “Detector” is an historical term from the use of diodes as detectors - RF/IF in, audio or DC out
- Types of demodulators are
  - amplitude demodulators
  - frequency detectors
  - phase detectors
  - product detectors
  - synchronous detectors
  - Quadrature demodulators



Detectors

- Product Detectors
  - historically a diode (detector) used to demodulate IF or RF
  - IF or RF in, AF (audio frequency out)
  - usually a Gilbert cell mixer in modern ICs
- Power Detectors
  - Diode, log amp, or RMS-DC Converter
  - Accurate power control matters in modern digital systems, so log amps and RMS-DC converters are important
- AGC Detectors
  - Rectifies the signal, provides a DC signal used for power control in transmitters or gain control in receivers
  - AGC voltage drives S meter (signal strength meter)



Detectors

- RSSI (received signal strength indicator) Detector
  - log amp used in limiting IF strip provides dc voltage output proportional to signal strength in dBm
  - Waveform dependent, so requires known input waveform
  - Useful for GSM
- RMS-DC converter
  - DC voltage output proportional to the RMS voltage of input.
  - Waveform independent, so useful for true power measurement
  - Useful for CDMA

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