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DRS TECHNOLOGIES

Basic Receiver Fundamentals and Design

Presented by,
Clark Pope

Bio- Clark Pope

- MSEE University of Illinois, 1994
- 13 years at DRS Signal Solutions
- Work History
  - DSP coding for HF product Line
  - Digital Engineer section head
  - System engineer (VXI, slot zero, Pentek DSP)
  - Architect Sunrise SDR
  - Several years on digital demodulators (Qam, Psk, Fsk, etc. Reed-Solomon, Viterbi, BCH. etc.)
  - Architect Pico SDR (FPGA SOC, USB2.0 OTG, Embedded Linux)

Outline

- Receiver Fundamentals
  - Definition of a Receiver
  - Basic Block Diagram
  - Building Blocks
  - Superheterodyne Receiver
  - Direct Conversion Receiver
  - Digital Backends and the Software Definable Radio
- Real World Datasheet
- Working as a Radio Engineer
- Questions

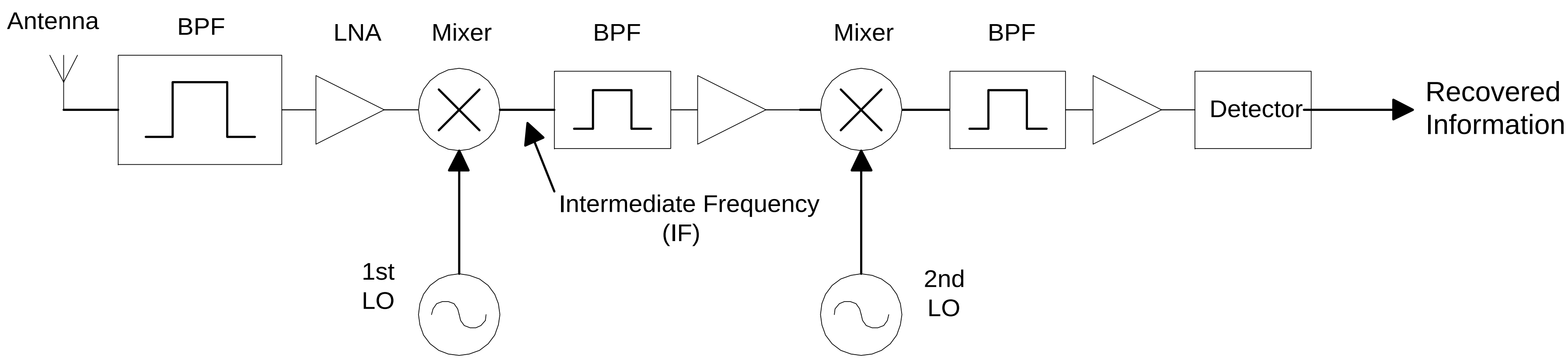
What is a receiver?

What does an FM Radio do??

It recovers the transmitted stereo music.

More generally a receiver performs the task of extracting the source information from a transmitted modulated signal that has been corrupted by noise.

Basic Receiver Block Diagram



BPF == Band Pass Filter

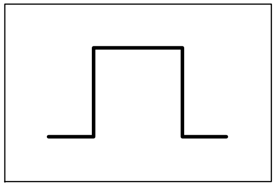
LNA == Low Noise Amplifier

LO == Local Oscillator

Building Blocks

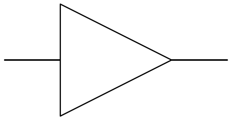
Filters

BPF



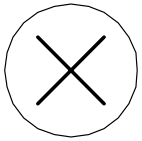
Amplifiers

LNA



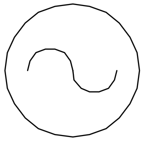
Mixers

Mixer



Oscillators

LO



Filters

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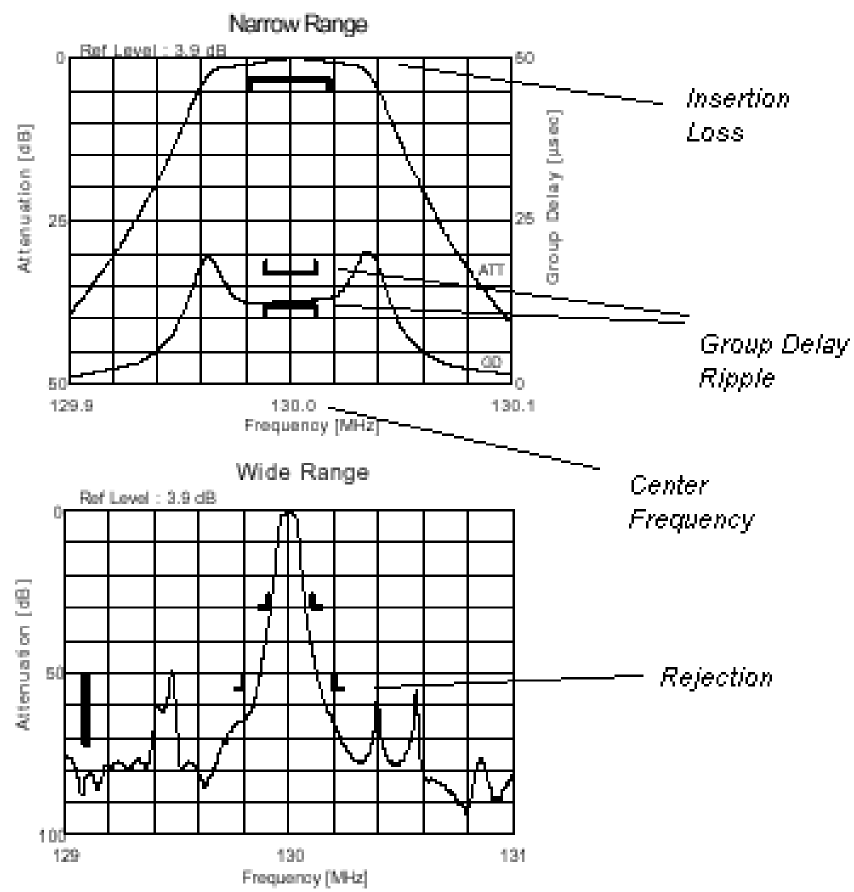
- Pass desired signals and reject undesired signals.
- Important Characteristics
  - Center Frequency fo
  - Bandwidth BW
  - Transition Bandwidth BT
  - Insertion Loss IL
  - Rejection REJ
  - Amplitude Ripple AR
  - Phase Ripple
  - Group Delay Ripple GDR



Amplifiers

•A device to amplify signals in the signal path in the forward direction.

•Supply reverse isolation to prevent signals from propagating back through a system.

•Important Characteristics

- •Gain - G, in dB: G = 10log(Pout/Pin) = 20log(Vout/Vin)
- •Noise Figure- NF, in dB: NF = 10log(S/N in)/(S/N out)
- •1 dB Compression point: P1

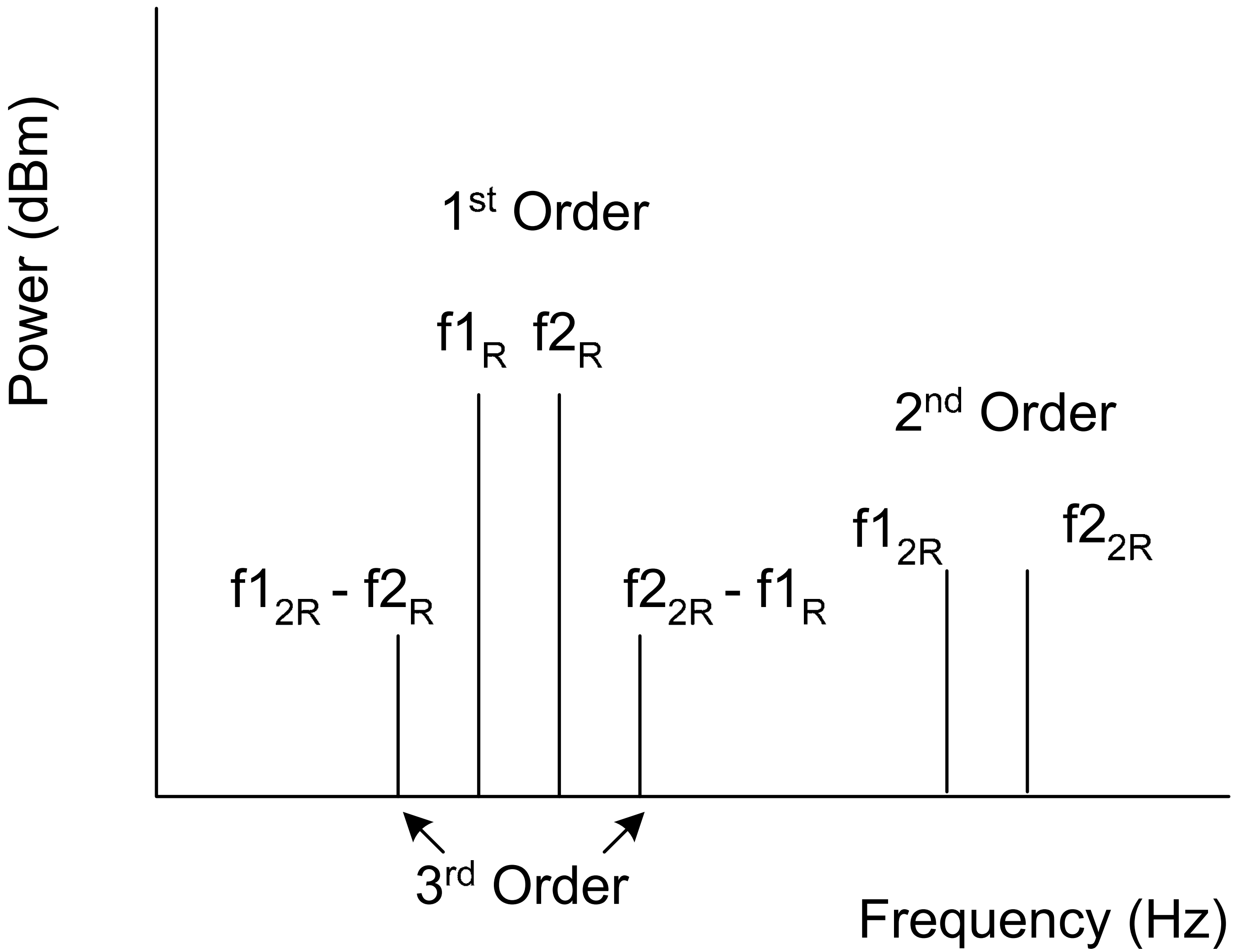
  The output power at which the gain of the amplifier has decreased by 1 dB.

  This is a measure of the signal handling and linearity of an amplifier.
- •Output Third Order Intercept Point: OIP3 = P1 + 10 dB (approximately)

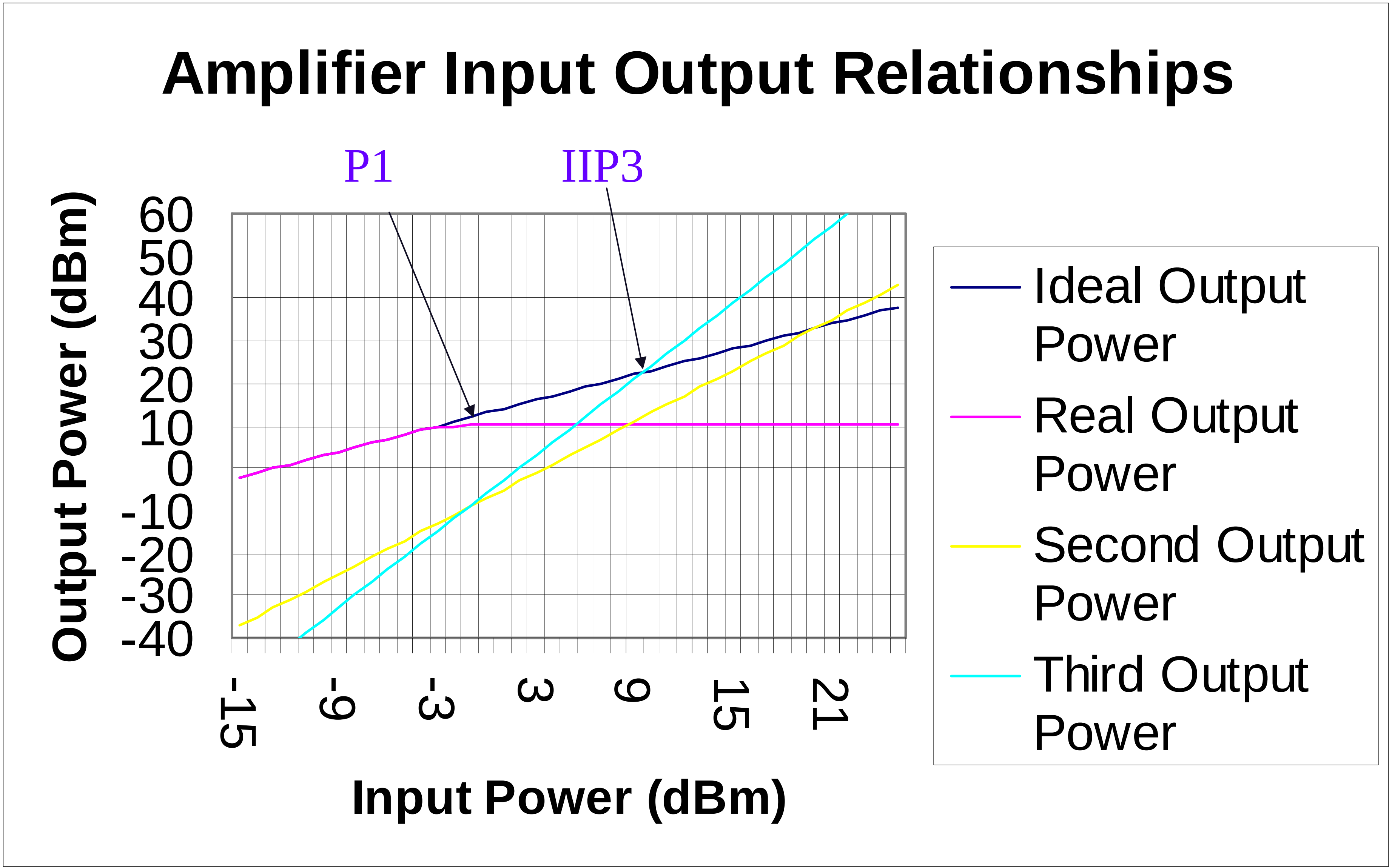
  The theoretical output power where the 3rd order product would equal
  the fundamental output power.
- •Input Third Order Intercept Point: IIP3 = OIP3 - G

  The Output third order intercept point reflected to the input of the amplifier.

Nth Order Products



Gain Compression



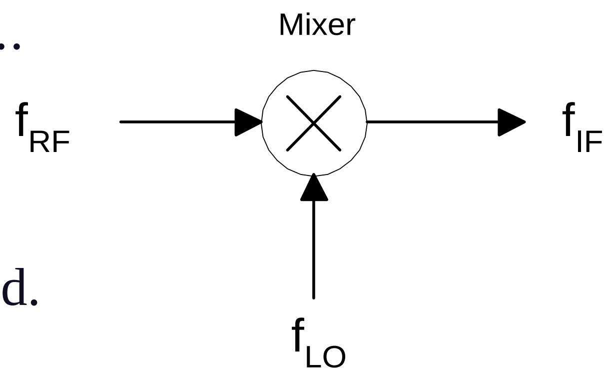
Mixers

- Mixer is a three port devices used for frequency translation.
  - f_{RF} is the RF frequency input. (RF is Radio Frequency)
  - f_{IF} is the IF frequency output. (IF is Intermediate Frequency)
  - f_{LO} is the LO frequency input. (LO is the Local Oscillator Frequency)

$$f_{IF} = \pm m\, f_{RF} \pm n\, f_{LO} \quad m \text{ and } n = 0,1,2,3,4\ldots.$$

Usually want $m = n = 1$:

$$f_{IF} = f_{RF} \pm f_{LO} \quad \text{low side LO}$$
$$f_{IF} = f_{LO} \pm f_{RF} \quad \text{high side LO}$$



- Higher order terms are unwanted and should be avoided.
- Important Characteristics
  - Conversion Loss: (the gain of the mixer) Mixing generally causes the signal level to drop by 6 to 8 dB.
  - Noise Figure- NF, in dB: Usually equal to the conversion loss unless an active mixer is used.
  - Intercept Points: The same as for an amplifier.

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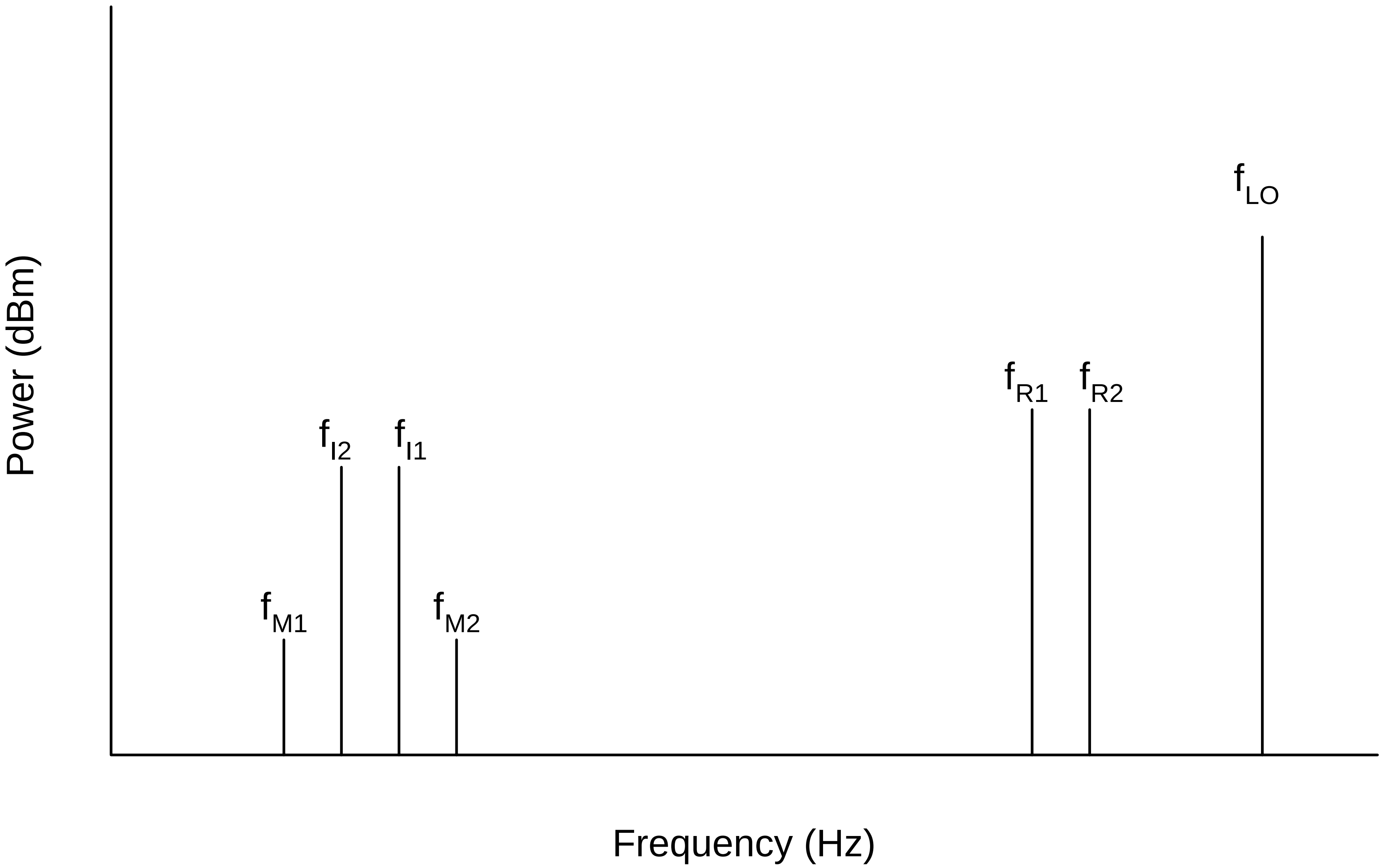
Mixing Products

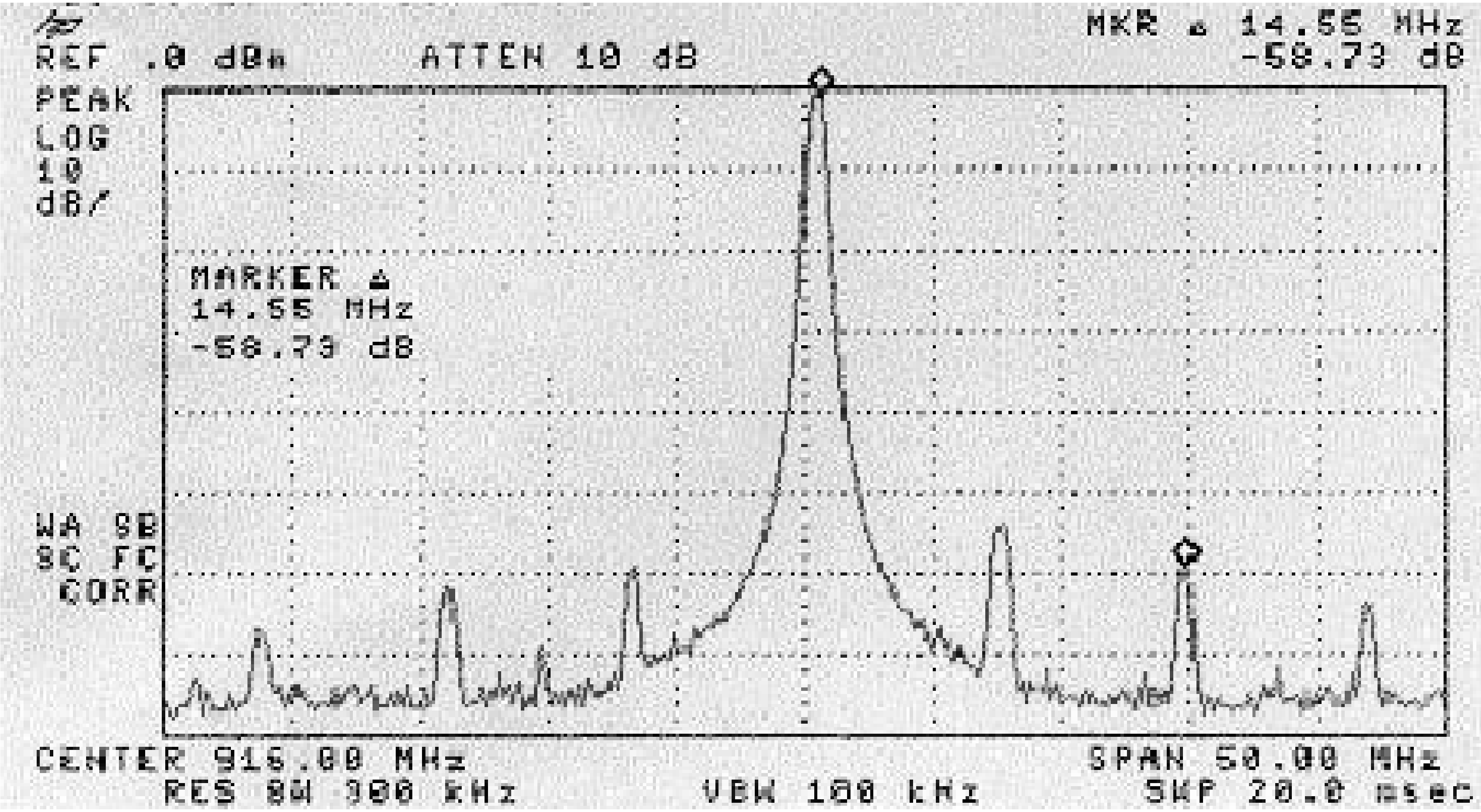


Oscillators

- An oscillator is an electrical device that produces a sinusoid at a specified frequency
- Used in the mixing process.
- Usually phase locked to a very stable and clean crystal reference oscillator
- Important Characteristics
  - Frequency of oscillation.
  - Jitter – short term variation in frequency
  - Tuning characteristics: MHz/V
  - Output Power
  - Phase Noise

    The phase noise of an oscillator is a measure of the amount of power contained in 1 Hz bandwidth, relative to the carrier power
    at increasing offsets from the desired carrier frequency. (dBc/Hz)

Oscillators(2)



How does a receiver design start?

First a frequency plan is established.

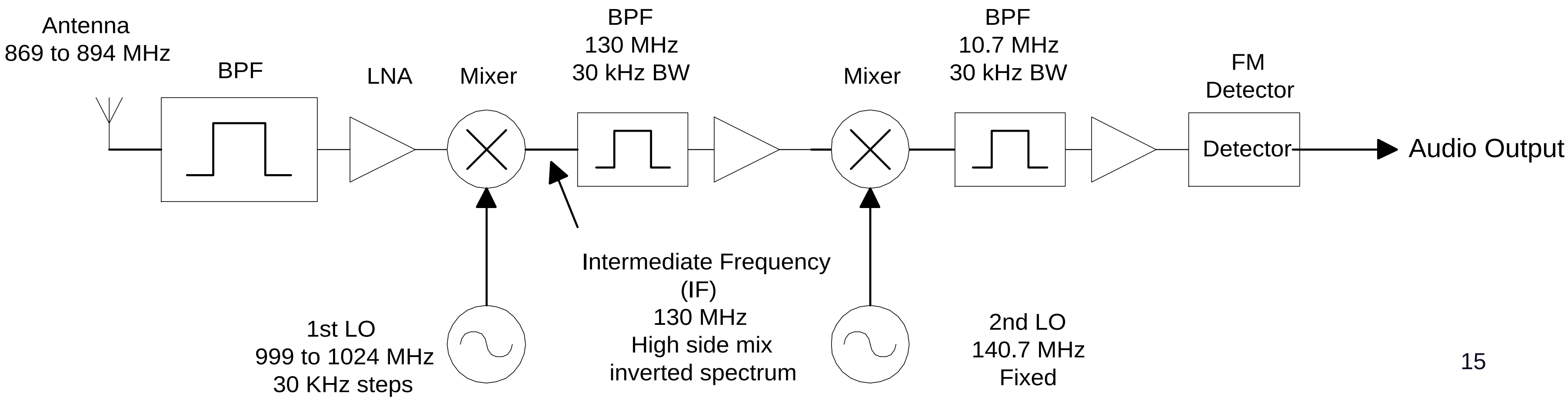
What are the input frequencies of interest?

What first IF will be used to avoid any mixer spurious products?

What final IF will be used?

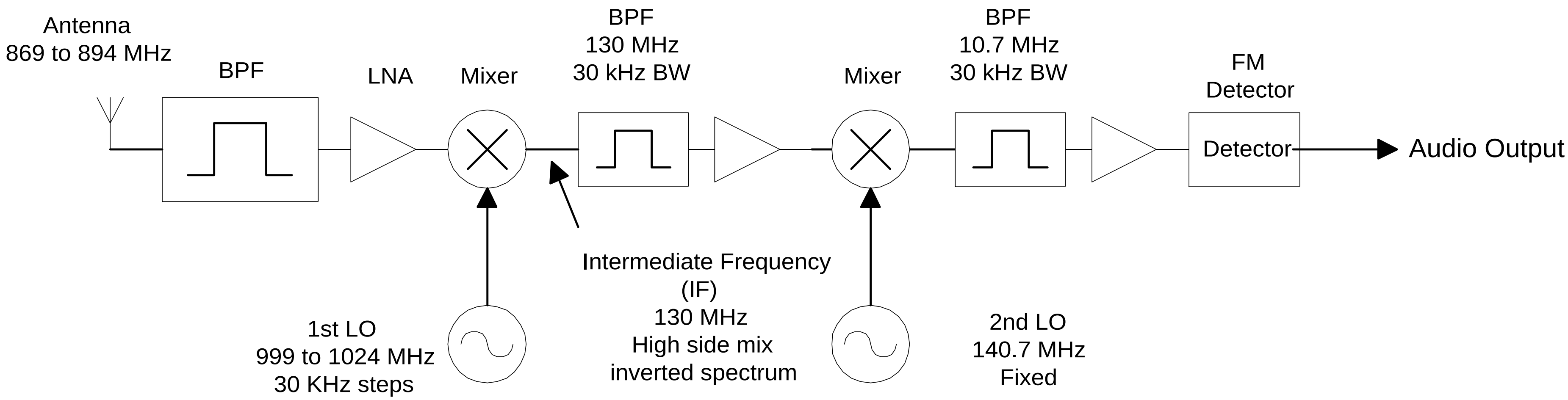
Next the input signal level is defined so that the noise figure and amplifier signal handling capabilities can be defined.

Finally a demodulation type is chosen (given) and audio levels established.



Superheterodyne Receiver

This type of receiver is the most common today. In this receiver the input signal is either up converted or down converted to an intermediate frequency (IF). The information is then extracted by a demodulator.



System Level Equations

- Gain: $G_t = G1 * G2 * G3....$

  $G_t(dB) = G1(dB) + G2(dB) + G3(dB).....$
- Noise Figure:

  $NF = NF1 + (NF2 - 1)/(G1) + (NF3 - 1)/(G1 * G2) + \ldots$

  $(NFn - 1)/(G1*G2*\ldots\ldots Gn-1)$
- Output Intercept Point

  $1/OIP3 = 1/OIP3(1) + 1/(OIP3(2))*G1 + 1/(OIP3(3))*G1*G2\ldots$
- Noise Floor --- kTB -- Thermal Noise power in a 1 Hz bandwidth.

  At room temperature this is -174 dBm.
- Minimum Detectable Signal -- Defined as the signal level that is twice as strong as the noise power.

  $MDS = -174 + 3 + NF + 10\log(BW)$
- Equivalent Input Level of Intermodulation Product

  $IM = 3*Pin - 2*(IIP3)$
- Define the Spur Free Dynamic Range (SFDR) as the range from the noise floor to the input power where the spurious products (third order products) equal the noise floor.

  $SFDR = 2/3*(IIP3 - NF - 10\log(BW) + 174 - 3)$

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Superheterodyne Receiver Example

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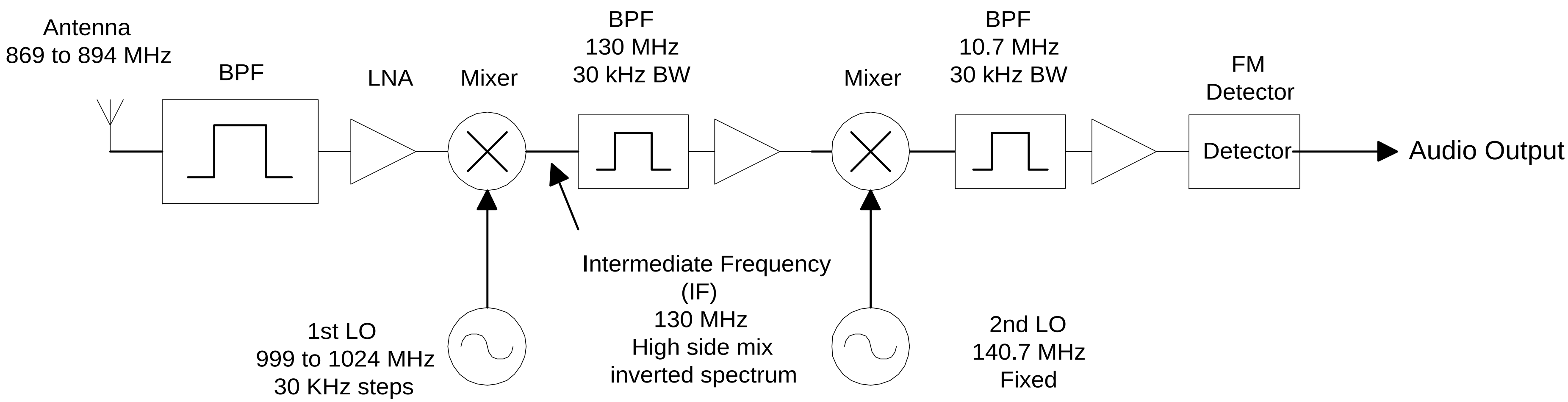
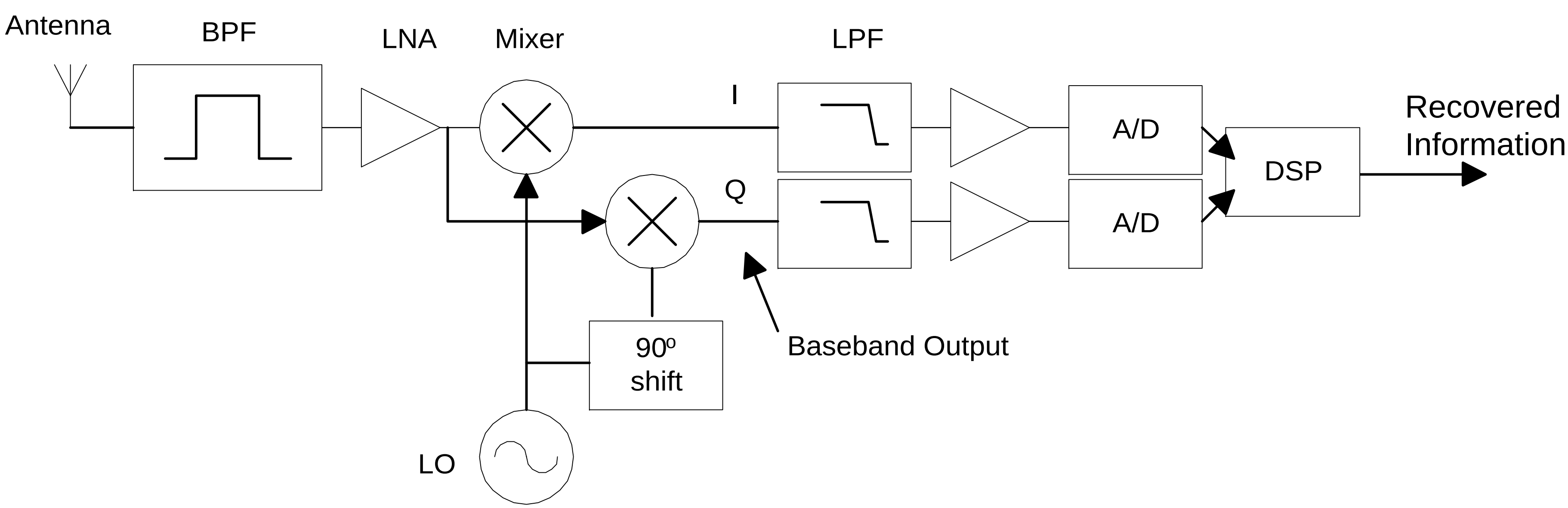


	04:14 PM									Pin (dBm)		
			Stage				Cumulative			-116		
		Gain	NF	IIP3	IIP2	Gain	NF	IIP3	IIP2	Pout		SFDR
NO.	Stage Type	(dB)	(dB)	(dBm)	(dBm)	(dB)	(dB)	(dBm)	(dBm)	(dBm)	IIP3-NF	(dB)
1	Connector	-1.0	1.0	40.0	999.0	-1.0	1.0	40.0	999.0	-117.0	39	112.16
2	Duplexer	-4.0	4.0	99.0	999.0	-5.0	5.0	40.0	993.5	-121.0	34.999996	109.49
3	Amplifier	18.0	1.7	15.0	999.0	13.0	6.7	20.0	991.2	-103.0	13.256786	95.00
4	Filter	-3.0	3.0	99.0	999.0	10.0	6.7	20.0	982.2	-106.0	13.210715	94.97
5	Mixer	-7.0	7.0	22.0	999.0	3.0	7.1	11.4	978.9	-113.0	4.2553063	89.00
6	SAW FILTER 130 MHz+15KHz	-5.0	5.0	99.0	999.0	-2.0	7.9	11.4	977.8	-118.0	3.4227396	88.44
7	Amplifier	32.0	3.0	5.0	999.0	30.0	8.9	5.6	982.8	-86.0	-3.2723028	83.98
8	Mixer	-7.0	7.0	22.0	999.0	23.0	8.9	-8.2	967.4	-93.0	-17.101111	74.76
9	Crystal Filter 10.7 MHz	-5.0	5.0	99.0	999.0	18.0	8.9	-8.2	964.6	-98.0	-17.107146	74.75
10	Demodulator	43.0	5.0	-40.0	999.0	61.0	8.9	-58.0	963.4	-55.0	-66.942446	41.53

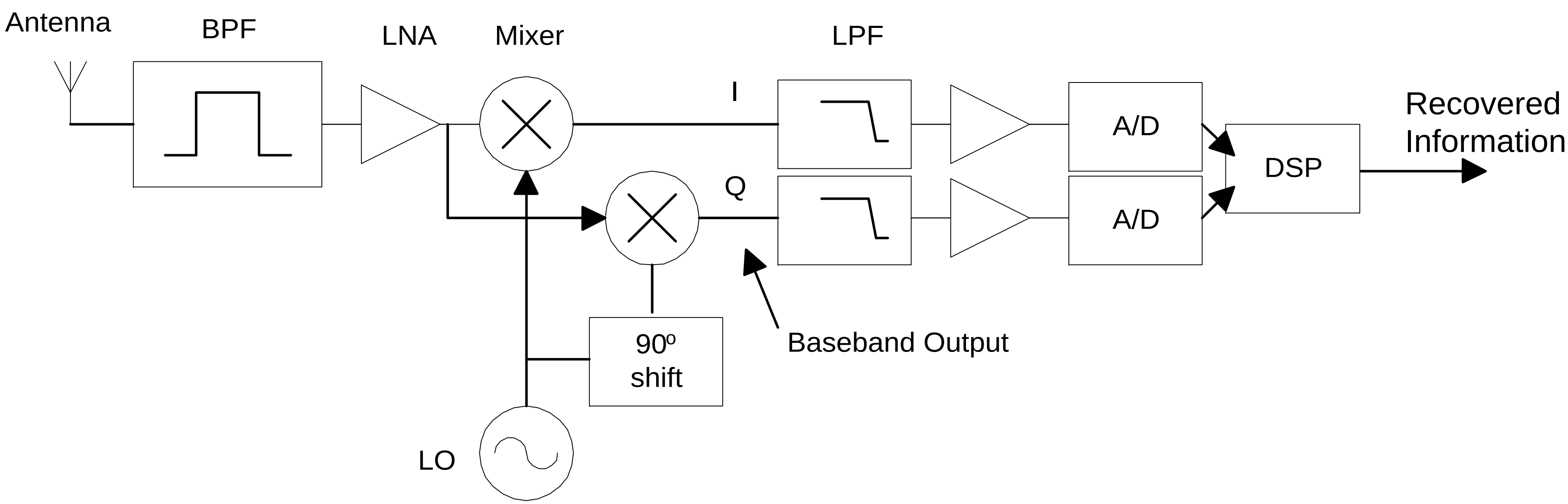
Direct Conversion Receiver

This type of receiver is now used in some GSM handsets. It requires less hardware than the Superheterodyne receiver, most notably the IF filter is removed. In this receiver the input signal is mixed with an LO at the same frequency as the RF carrier. This is then low pass filtered and the information is then extracted by a demodulator.



Digital Backends and the Software Definable Radio

In the GSM example the baseband I and Q signals are being sampled by an A/D converter. These samples are then used for FM demodulation and subsequent audio generation. This is the earliest type of digital demodulation.



What is an A/D Converter?

An A/D converter is an Analog to Digital converter. An input analog signal is sampled at a constant rate and the digital word corresponding to the signal level at that instant is sent out in a digital word.

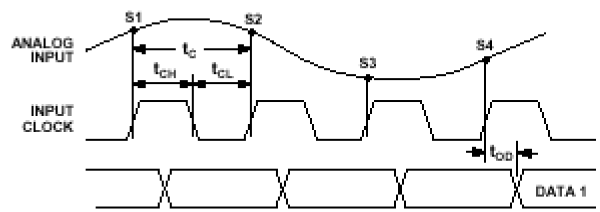


Figure 1. Timing Diagra

Table IV. Output Data Format

Input (V)	Condition (V)	Digital Output	OTR
VINA –VINB	< – VREF	0000 0000 0000	1
VINA –VINB	= – VREF	0000 0000 0000	0
VINA –VINB	= 0	1000 0000 0000	0
VINA –VINB	= + VREF – 1 LSB	1111 1111 1111	0
VINA –VINB	≥ + VREF	1111 1111 1111	1

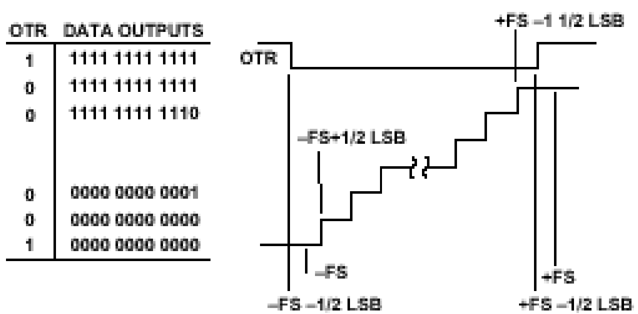


Figure 53. Output Data Format

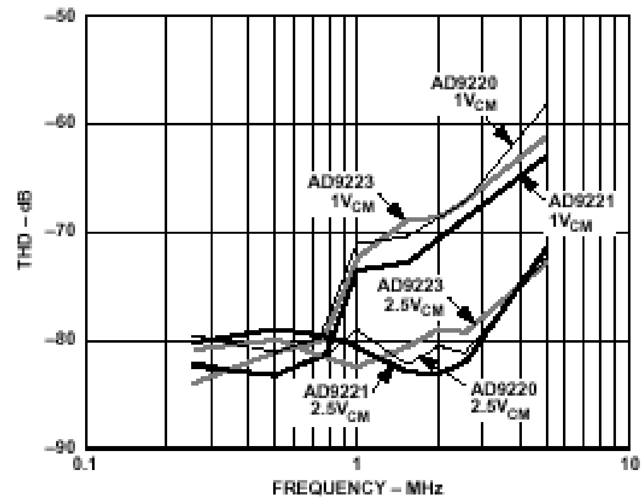
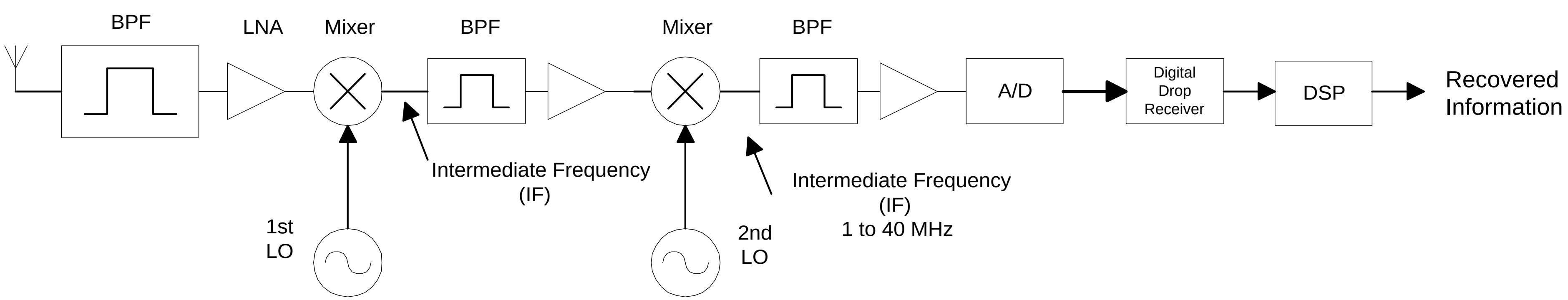


Figure 32a. AD9221/AD9223/AD9220 THD vs. Frequency for V_{CM} = 2.5 V and 1.0 V (A_{IN} = –0.5 dB, Input Span = 2.0 V p-p)

Digital Backends and the Software Definable Radio

Newer Software Definable Radio's are sampling large bandwidths of spectrum near baseband. This 1 MHz to 40 MHz band is sampled at 80 MHz and then a single channel of information is extracted with a digital drop receiver (DDR). The digital drop receiver is controlled by a digital signal processor (DSP) and the DSP is also processing the single channel output of the DDR.



Digital Backend (Detail)

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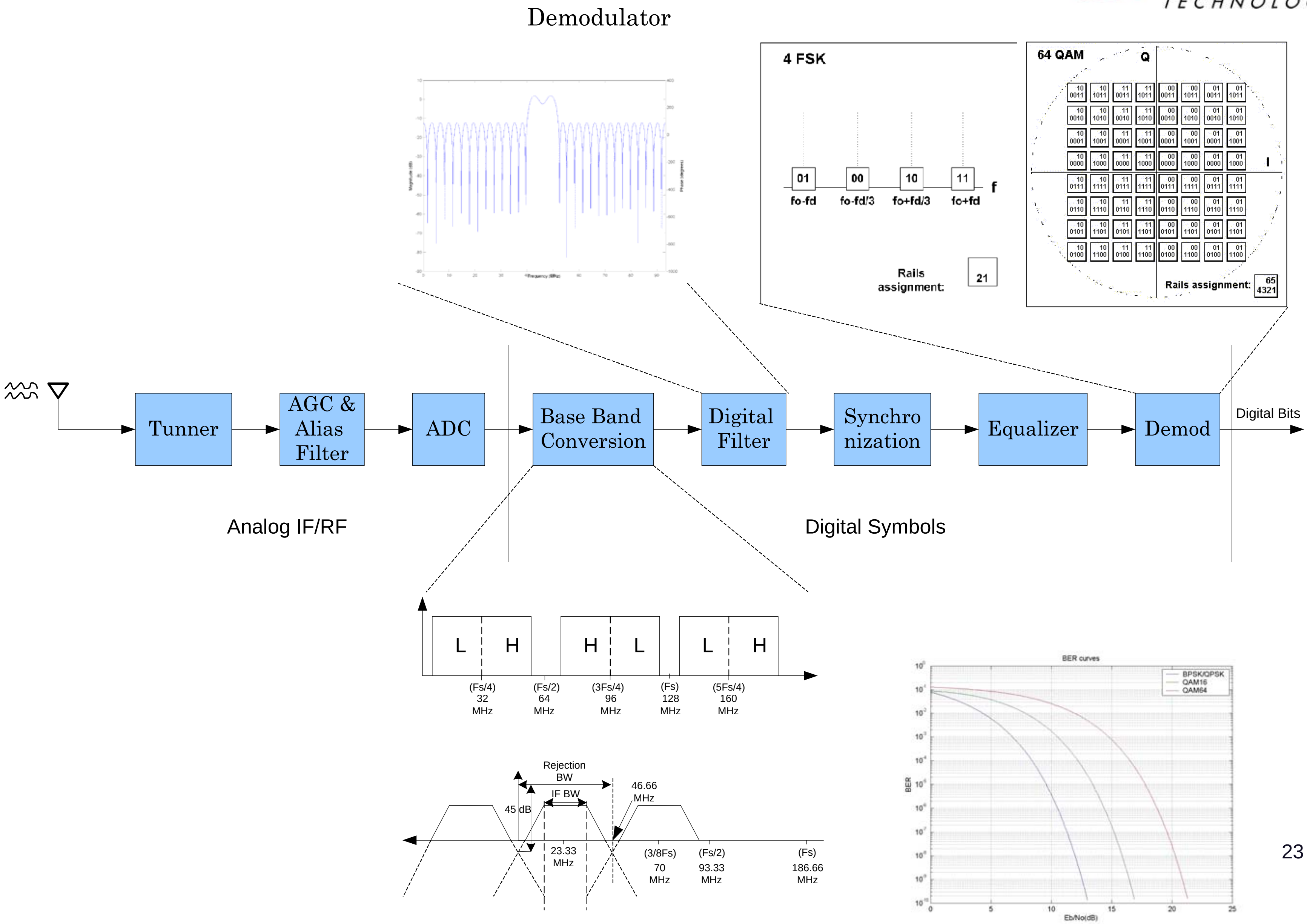
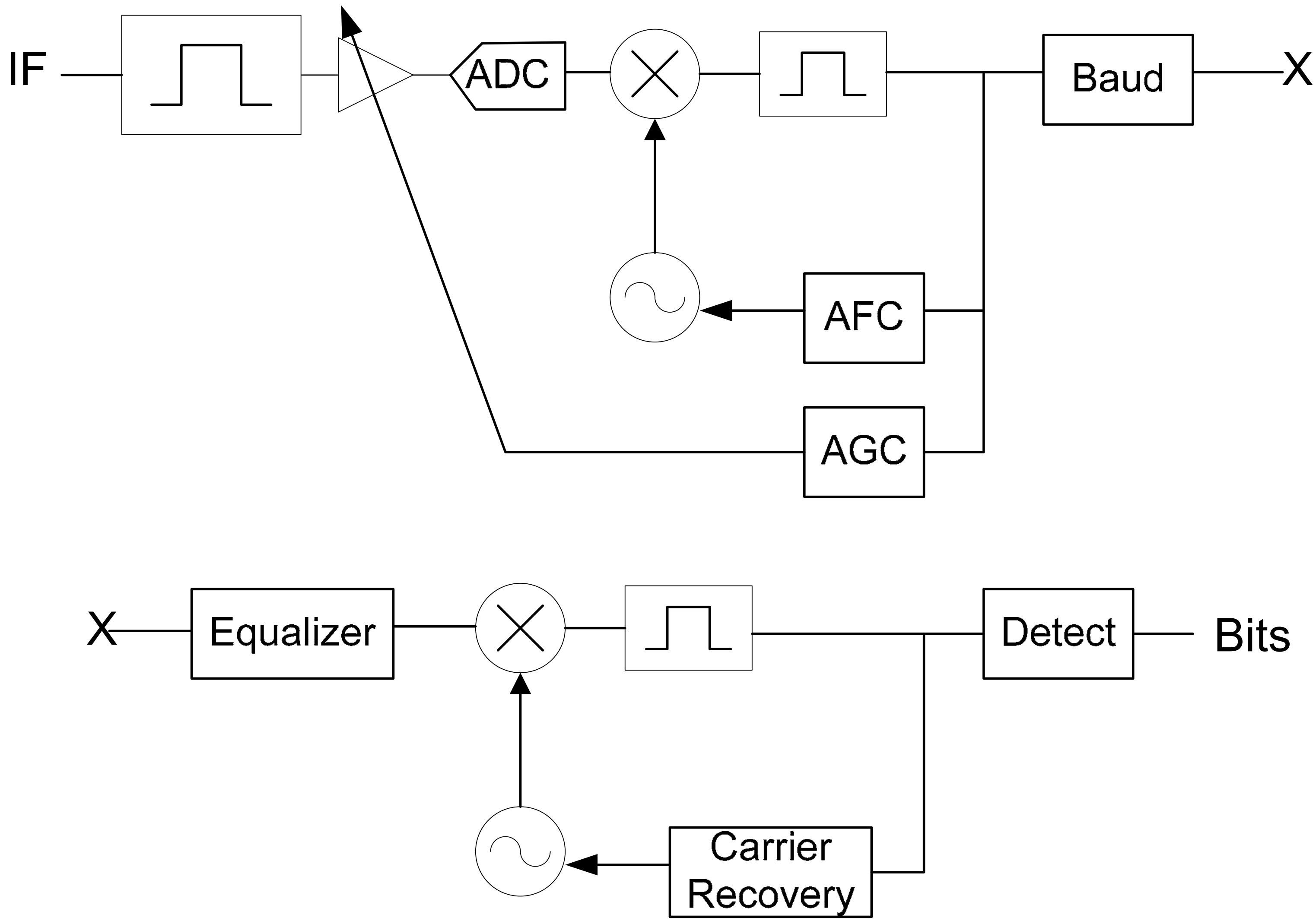


Processes


IF
ADC
Baud
X
AFC
AGC
X
Equalizer
Detect
Bits
Carrier
Recovery

Processes (2)

- There are several control loops in a receiver
  - Automatic Gain Control (AGC) = adjusts the gain stages throughout the receiver for best SNR and to prevent clipping (remember that NF depends on where the gain is applied)
  - Automatic Frequency Control (AFC) = adjusts the tuning to center the signal in the filter
  - Baud Synchronization = resamples the signal at 2x or 4x the baud rate with the samples at “optimal” places in the symbol
  - Equalization = adapts the response of the system to match the response of the channel
  - Carrier Tracking = in digital demodulation, tracks the phase of the signal to keep the constellation upright
  - Channel Scanning = tunes the radio, checks signal strength, if above COR level, dwells for a period, before moving to the next frequency

HF-1000/WJ-8711A Datasheet (Handout)

- Tip: If you can explain the specifications on an interviewer's product, you'll probably get a job offer.

- Specifications fall in to broad categories
  - Functional = what the product does
  - Performance = how well the product works
  - Environmental = mechanical configuration and the conditions it operates in

Functional Specifications

Features

- Frequency coverage from 5 kHz to 30 MHz in 1-Hz steps
- High dynamic range: +30 dBm third-order intercept typical
- Digital filtering provides 66 IF bandwidths up to 16 kHz with exceptional shape factors
- AM, SAM, FM, CW, USB, LSB and ISB detection mModes Standard
- Fast, flexible scanning with 100 memory channels
- Large readable LED displays and user-friendly controls
- Three variable AGC decay settings
- Noise blanking and passband tuning
- Tunable IF notch filter
- Internal switchable preamplifier and attenuator
- Standard remote interface (optional Multidrop RS-232, RS-485, RS-422, CSMA or IEEE-488)
- Built-in self test
- Optional suboctave preselector
- Optional digital data output

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- Systems Engineers compete on functionality and capability. Trying to cram more into the same size, weight, and power (SWAP)

Performance

- Design Engineers compete on performance (tune speed, intermod performance, noise figure)

Frequency range	5 kHz to 30 MHz (tunable to 0 Hz, degraded performance below 500 kHz)
Tuning resolution	1 Hz
Internal reference stability	>0.7 PPM (0 to 50ºC)
	>0.2 PPM (0 to 50ºC) with REF option
External reference rrequency	Accepts 1, 2, 5 or 10 MHz (±1 PPM or better, 200 mVrms into high impedance load); automatically switches to external reference upon application of signal
Synthesizer lock time	<10 ms, typical
Antenna input	
Impedance	50 ohms, nominal
VSWR	2:1, maximum at receiver's tuned frequency
Maximum input signal	+30 dBm
Connector	BNC, female
Third-order intercept point	+30 dBm, typical
	+ 25 dBm, minimum (for signals separated by 50 kHz, minimum)
Second-order Intercept Point	+60 dBm, typical
Noise figure	14 dB, maximum (11 dB, maximum with preamplifier engaged)

Lesser Known Performance Specs

First image rejection	90 dB, minimum
IF rejection	85 dB, minimum (>90 dB, typical)
LO phase noise	-110 dBc at 1-kHz offset, typical
Reciprocal mixing	With a desired signal of 25 mV in the 3.2-kHz IFBW, the desired signal-to-noise ratio (SNR) is >20 dB, when an undesired signal 70 dB higher in amplitude and 35 kHz removed in frequency is present.
Cross modulation	With a desired signal of 10 mV, an undesired signal 86 dB higher, 30% AM modulated produces <10% cross modulation for frequency separation of >50 kHz in the 1-kHz IFBW.
Internal spurious	<-114 dBm referred to the RF input
Blocking	An unwanted 1 mV signal separated 20 kHz from a desired signal of 1 mV will not cause the IF output to fall by more than 3 dB.

Environmental

Operating temperature	0 to +50°C
Storage temperature	-40 to +70°C
Humidity	10 cyclic days (240 hours); Procedure III for continuous exposure to 95% RH
Altitude	50,000 ft (15,240 meters) non-operating 24,000 ft (7,315 meters) operating
Vibration	
A. Basic transporation (secure cargo) category 1	Random vibration 1.04Gs non-operating (2 hours)
B. Ground mobile (wheeled or tracked vehicle) category 8	Random vibration 6.0Gs operating (15 minutes)
C. Marine (shipboard vessel not specified) category 9	Random vibration 1.0Gs operating (2 hours)
D. Environmental stress (NAVMAT-P-9492)	Random vibration 6.0Gs operating (15 minutes for design qualifications) 3.06Gs nonoperating [10 minutes for production screening (ESS)]
Shock	Bench handling (field service) eight drops total onto a horizontal hard wooden surface, operating
MTBF	In excess of 10,000 hours; estimated in accordance with MIL-HDBK 217E for Ground Fixed; +40°C environment
EMC	EN50081-1 (radiated and conducted emissions to EN55022, class B) EN50082-1 (including IEC 801-2:1984, IEC 801-3:1984 and IEC 801-4:1988) EN55020 (immunity for receivers)
Safety	IEC 1010-1:1990+A1/EN61010:1993
Power requirements	97 to 253 Vac (47 to 440 Hz) auto switching
Power consumption	35 W, typical with options

Working in Radio Industry (1)

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- General
  - The main markets for radio engineering are:
    - Consumer
      - Examples: bluetooth, wifi, cable modem, am/fm radio
      - Usually a specific band of interest
      - Goal is a low cost integrated solution with acceptable performance
    - Telecom/Professional
      - Ex: cellular networks, point to point microwave, satellite communications
      - Moderately expensive, higher performance systems
      - Business use this technology to make money so performance is often more important than cost since it gets spread over many customers
    - Test and Measurement
      - Ex: signal generators, test radios, production testers
      - Highest performance (standard that the rest are measured against)
      - Very Expensive
    - Military/Government
      - Ex: SIGINT, ELINT, COMINT
      - High Performance
      - Often most expensive because of quantities and mechanical/environmental challenges
      - Most challenging for the engineer
      - All modulations, all frequencies, all bandwidths!

Working in Industry(2)

- Analog Engineers
  - RF = lower frequencies < 1 GHz
  - Microwave = > 1 GHz
  - Toolsets and design methodologies are very different
  - Manufacturing and shielding become major efforts
  - Specialties
    - Synthesizer design (higher frequencies, wider coverage, better phase noise)
    - RF chain design (mixers, amplifiers, filters, better GNFIP, lower cost, fewer spurs)

Working in Industry(3)

- Digital Engineers
  - PCB/HW Engineers
    - Design circuit boards and do general digital design of PLDs and FPGAs
    - Focus on high frequency digital design where the circuits are essentially microwave because of the clock edges
    - PCB signal analysis tools employed heavily
    - Generally cutting edge CPU clocking, DDR2 memories, and so on
  - DSP Engineers
    - Focus on the signal processing algorithms
    - Simulate in matlab
    - Implement in either DSP chip (TI, Freescale, Analog Devices) or FPGA (Xilinx or Altera, usually VHDL)
    - Though technology changes regularly the basic math stays the same

Working in Industry (4)

- Software Engineers
- GUI/System engineers generally write software that integrates several pieces of equipment into a framework that gets presented to the user
  - Use tools like Qt
  - Web based
  - Databases
- Embedded SW engineers work on small microprocessers inside the equipment
  - Mostly C and assembler code
  - Limited OS if any
  - Often develop usng a debugger/emulator
  - Work closely with the DSP engineer

Advice

- Subscribe to EE Times and at least one specialty magazine like RF&Microwave
- Team work is over emphasized in school. Often you'll be the only person in your technical area on the project, don't expect a lot of help.
- Learn continuously. Half life of your degree is ~5 years.
- Engineering is more than technical knowledge
  - Time management
  - Communications
  - People skills
  - Attitude
- What you don't realize yet: Engineers create paper, that's all. Schematics, test procedures, program listings, datasheets, etc.

Questions?

- Please see me after class if interested in DRS employment.