RF Receiver Hardware Design

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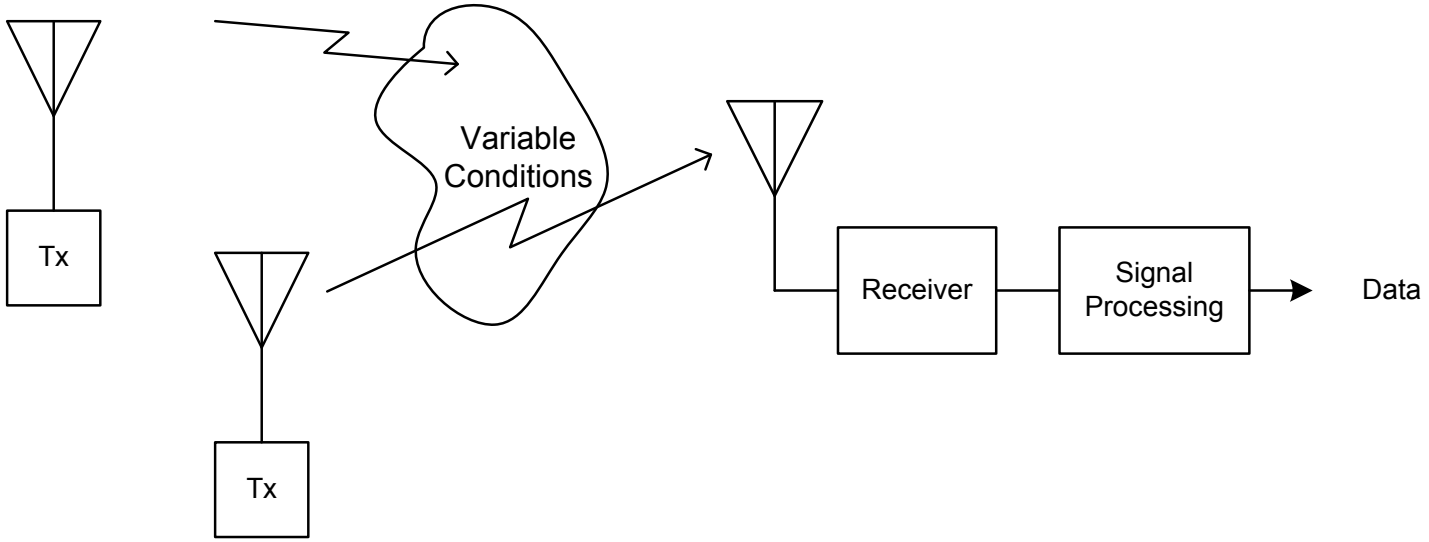
Topics

- Customer Requirements
- Communication link environment
- Performance Parameters/Metrics
- Frequency Conversion Architectures
- I/Q Demodulation Architectures
- Example Design Based on a Real Product
- Receiver RF Modeling
- My career history

Customer Requirements

- Who was my customer?
  - My employer
  - Various groups with *similar* but slightly *different* applications
- Requirements
  - 70 MHz input center frequency
  - Industry standard cPCI form factor
  - Detailed RF requirements coming up
- Internally generated requirements are often vague
- Ill-defined requirements can easily lead to schedule slips and cost over-runs

Communication Link Environment



- Wireless (RF) link between transmitter and receiver
- Input signal to receiver may vary in amplitude
- Interference may be present
- RF spectrum is crowded (adjacent channel interference)
- Desire low Bit Error Rate (BER) at high data rates
- Design goal: Optimize receiver performance under variable conditions (in this presentation under variable signal amplitude only)

Receiver Performance

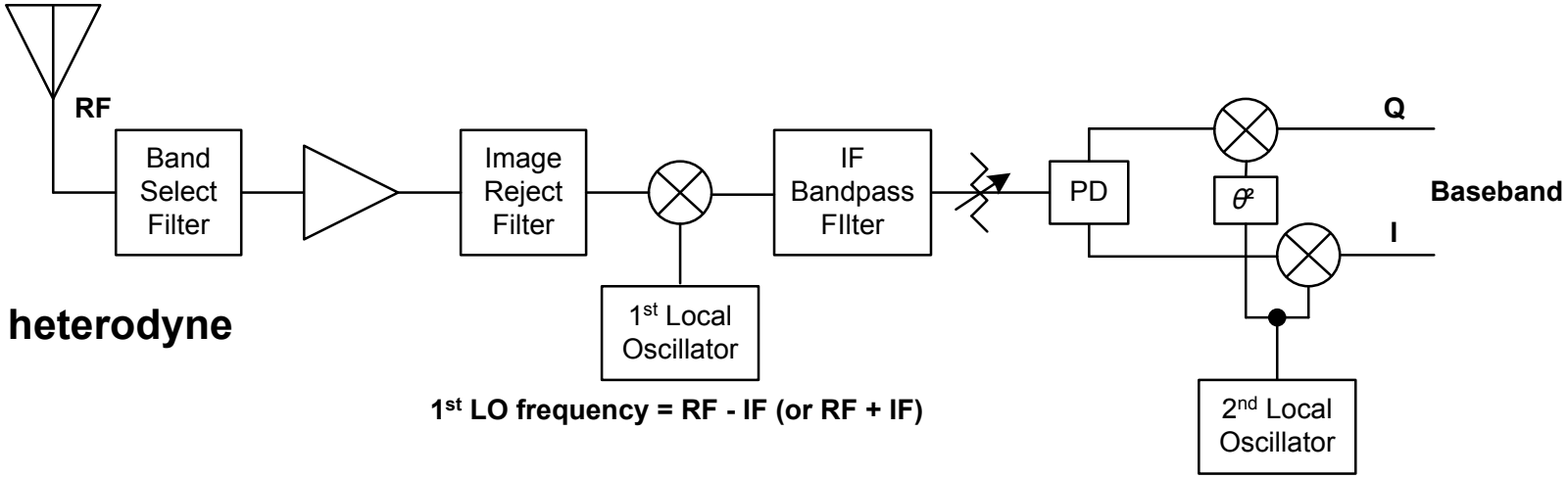
- Receiver Performance Dependent on Signal Strength

- Small signal performance generally dictated by AWGN (w/o fading)
  - Noise Bandwidth
  - Noise Figure
  - Signal-to-Noise ratio (SNR), Signal-to-Noise Density ratio (S/No)
  - Eb/No

- Large signal performance generally dictated by receiver linearity
  - Intermodulation Distortion
    - Spectral spreading, re-growth, etc
    - 3rd Order Intercept Point
  - Harmonic Distortion
  - Amplitude Compression

- Receiver design can be optimized for
  - Small signal performance
  - Large signal performance
  - A combination/balance of small and large signal performance

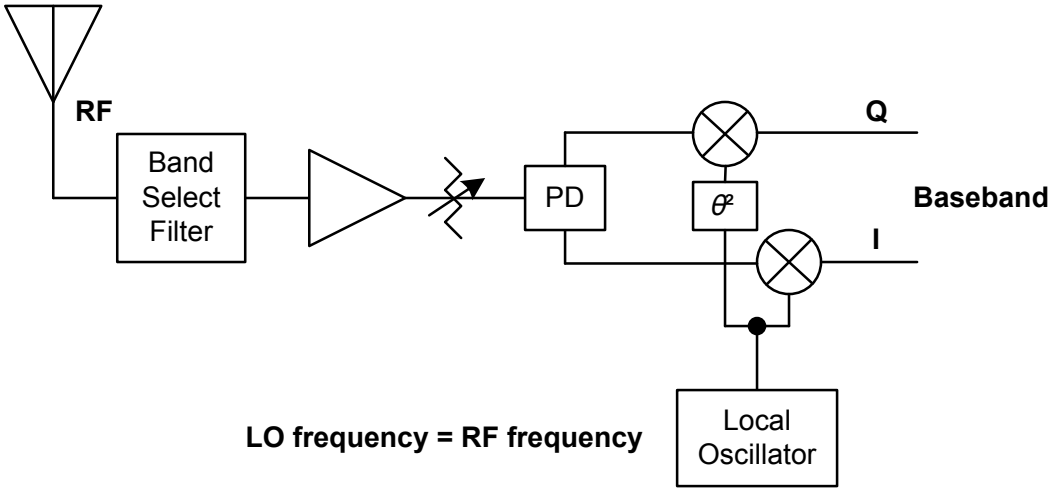
Frequency Conversion Architectures



Super heterodyne

1st LO frequency = RF - IF (or RF + IF)

2nd LO frequency = IF frequency



Direct Conversion

LO frequency = RF frequency

Frequency Conversion Trade-offs

- Super heterodyne
  - – High performance, high cost
  - – Distributed frequency plan allows distributed filtering and gain
- Direct Conversion Benefits
  - – Fewer parts
    - Image reject filter
    - IF bandpass filter
    - 1st Local Oscillator
  - – Smaller and lower cost
- Direct Conversion Issues
  - – DC offsets
  - – LO leakage
  - – 2nd order distortion
  - – 1/f noise (flicker noise)

Direct Conversion Issues

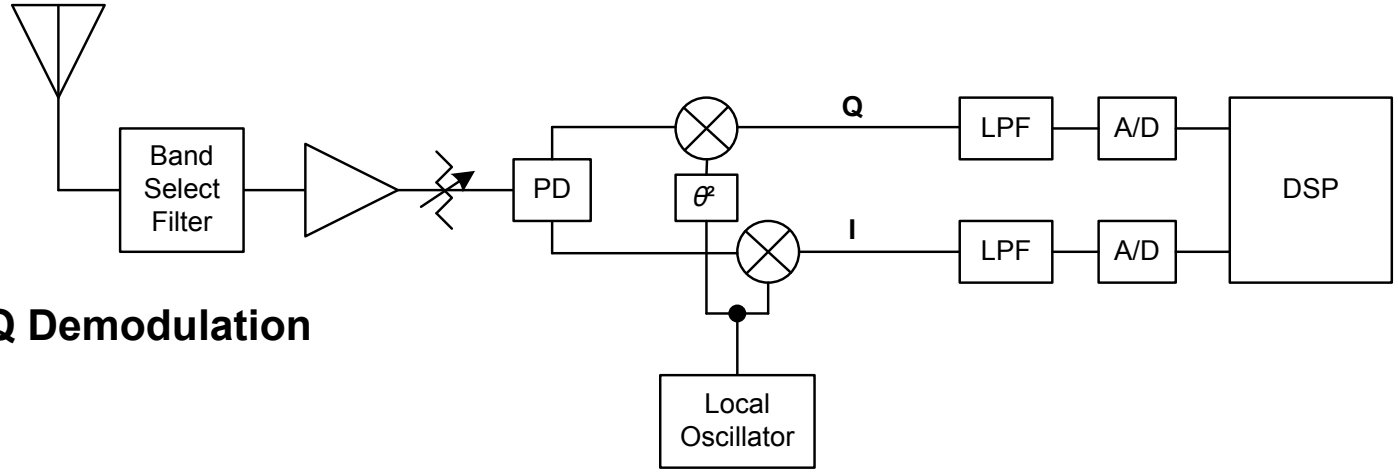
- DC Offsets in baseband I/Q signals
  - Caused by LO self-mixing and baseband circuitry
  - Offset amplitude varies with RF frequency and antenna effects
  - Mitigated by compensation/calibration, near-zero IF, AC coupling, etc

- LO Leakage Out of Receiver
  - LO is at RF frequency and cannot be filtered
  - Leakage amplitude dependent upon isolation of components

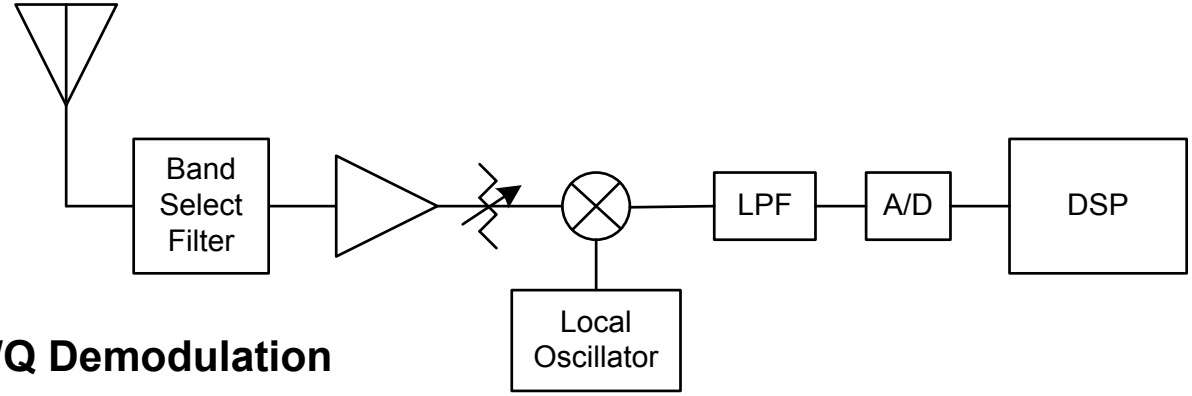
- 2^{nd} Order Distortion with two input signals at frequencies f_1 and f_2
  - 2^{nd} order distortion is at $|f_1-f_2|$ and f_1+f_2
  - $|f_1 - f_2|$ problematic when f_1 and f_2 are in-band and close in frequency
    - Distortion is near DC and interferes with desired I/Q baseband signals

- 1/f Noise (flicker noise) is intrinsic in semiconductor devices
  - Coupling of 1/f noise with desired signal is predominately at baseband
  - Direct conversion has smaller signals (and more gain) at baseband
  - SNR degradation is more pronounced as compared with super heterodyne

I/Q Demodulation Architectures



Analog I/Q Demodulation

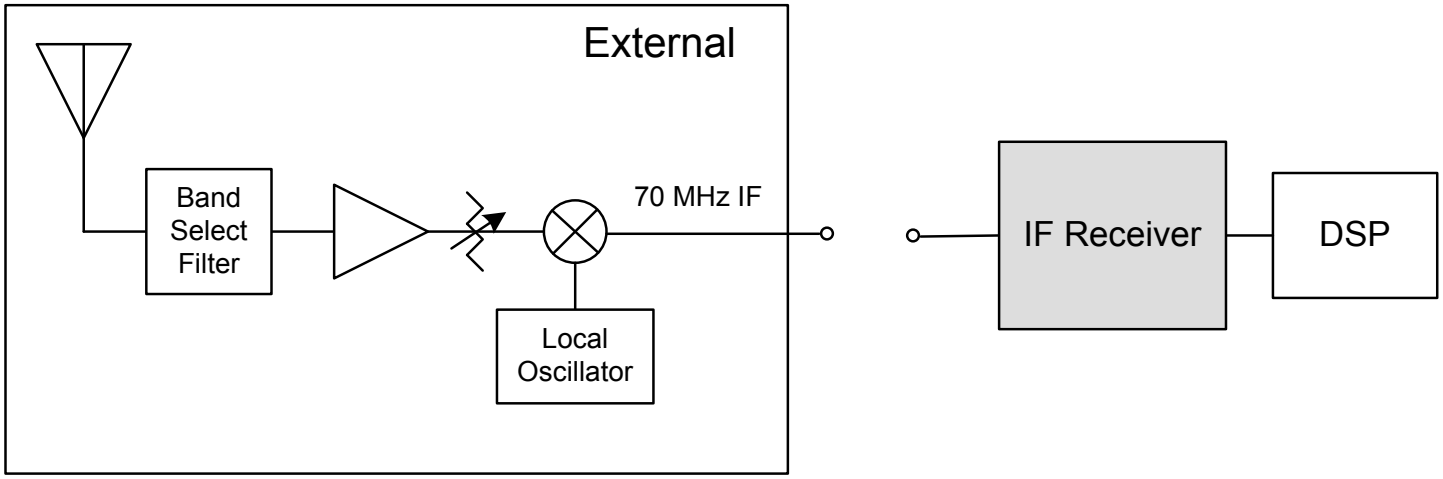


Digital (DSP) I/Q Demodulation

I/Q Demodulation Trade-offs

- Digital I/Q Demodulation
  - I/Q gains are exactly equal and phase is exactly quadrature
  - Requires A/D sample rate at least 2x modulation bandwidth
- Analog I/Q Demodulation
  - I/Q gain and phase are not perfectly balanced
  - Imbalances create distortion
  - Requires A/D sample rate at least 1x modulation bandwidth
- For a given A/D converter capability, analog I/Q demodulation provides twice the modulation bandwidth at the expense of more hardware and higher distortion

IF Receiver Example: Requirements



- Input frequency is 70 MHz
- Modulation bandwidth up to 40 MHz (various data rates & modulation)
- Input signal amplitude -75 dBm to 0 dBm
- Input noise floor -150 dBm/Hz to -135 dBm/Hz (Not just thermal noise)
- Intermodulation distortion
  - -60 dBc for signal inputs up to -10 dBm
  - -50 dBc for signal inputs from -10 dBm to 0 dBm

IF Receiver Example: Architecture Selection

- Commercial A/D Converter technology provides 12 bits at 210 Msps
  - – Meets Nyquist criteria of greater than 2x the modulation BW (80 MHz)
  - – Digital I/Q demodulation architecture avoids imbalance distortion issues
  - – Over-sampling provides at least 5 samples per bit for high performance data demodulation and bit synchronization
- 75 dB of signal amplitude variation requires analog gain control
- Gain required for adequate signal amplitude into A/D converter
- Consider input noise floor
  - – 40 MHz noise bandwidth => 76 dB-Hz
  - – Input noise density of -135 dBm/Hz is -59 dBm (over 40 MHz)
  - – Receiver automatic gain control (AGC) operates on S+N
  - – Input SNR can be negative

IF Receiver Example: Critical Trade-offs

- Receiver must provide the necessary gain to bring the input signal to the optimum level into the A/D converter

- Too little gain => inadequate signal level into A/D
  - – Instantaneous dynamic range limited by A/D quantization noise floor

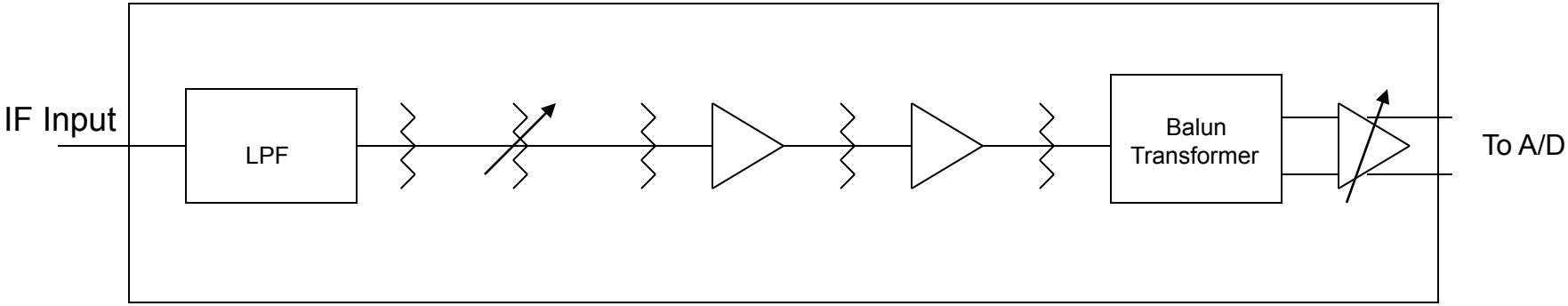
- Too much gain => excessive signal level into A/D
  - – With low SNRs, the A/D can saturate on noise “spikes”
  - – Increased intermodulation distortion

- Optimum level into A/D dependent upon SNR, noise statistics, signal characteristics, and number of bits in the A/D
  - – For small SNRs, Gaussian noise, sinewave input, and 12 bit A/Ds, the optimum amplitude into the A/D is about 14 dB below A/D fullscale*

* “High Speed Analog-to-Digital Converters in Communication Systems: Terminology, Architecture, Theory, and Performance”, TRW Corporation paper

IF Receiver Example: Design Approach

- IF Receiver product for a multitude of satellite communication applications
- Generic architecture consists of filters, amplifiers, variable attenuators, etc



- Model the cascade of receiver components to predict performance
- Follow signal, noise, and distortion levels through each component in the receiver chain
- Calculate receiver performance metrics such as noise figure and input intercept point

IF Receiver Example: Cascaded Metrics

- Noise Figure describes the SNR degradation caused by noise generated internally within the receiver

- Cascaded Noise Figure
  - $NF_{total} = NF_1 + (NF_2 - 1)/G_1 + (NF_3 - 1)/(G_1 * G_2) + \ldots$

- In this example design, the system noise performance is dictated by external noise floor over most of the input signal amplitude range

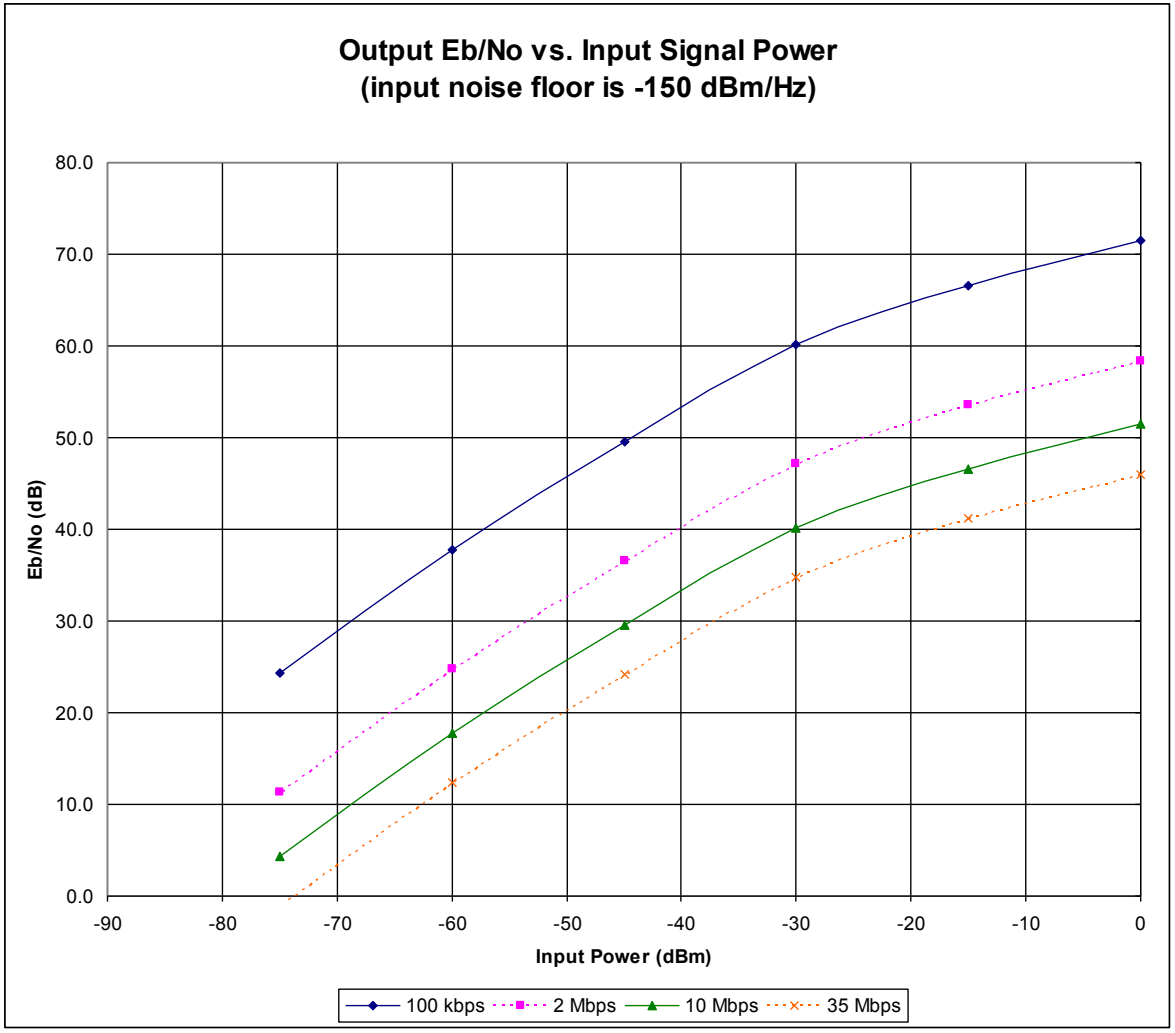
- Third Order Intercept Point quantifies the intermodulation distortion created within the receiver

- Cascaded Third Order Input Intercept Point
  - $IIP3_{total} = 1 / \{ (1/IP3_1) + (G_1/IP3_2) + ((G1 * G_2)/IP3_3) + \ldots$

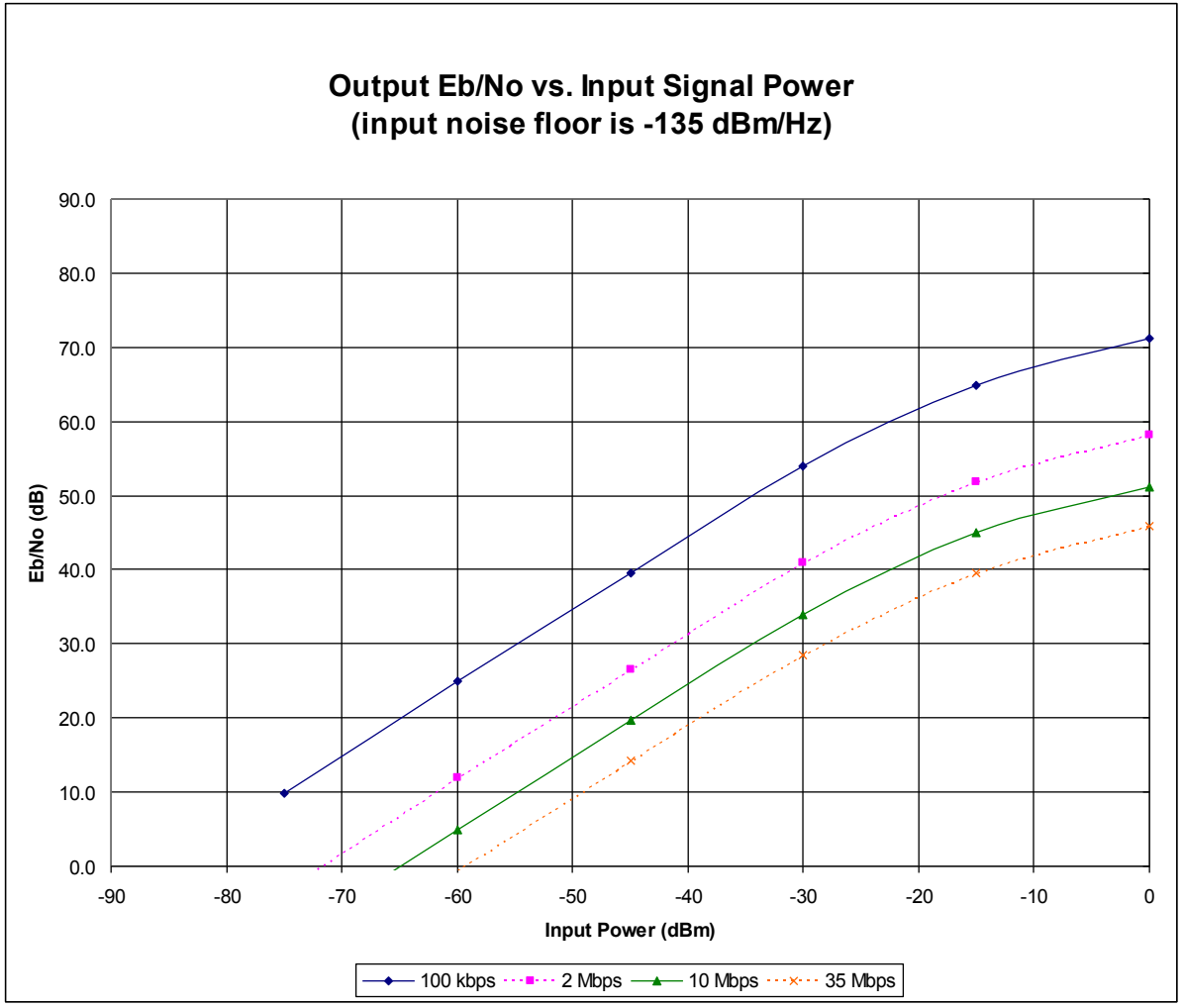
IF Receiver Example: Cascaded Model

Input signal power:	-75	**dBm**		-75 to 0 dBm input signal													
Input noise density:	-150	**dBm/Hz**															
Input SNR:	-1.0	**dB (in 40 MHz bandwidth)**															
			Input	**Input**	**Input**	**Output**	**Output**	**Output**	**Output**	**Output**							
			Signal	**Comp**	**3rd Order**	**Signal**	**Comp**	**3rd Order**	**3rd Order**	**Noise**	**Noise**	**Output**	**Output**	**Output**			**Cascaded**
	Gain	**NF**	**Power**	**Point**	**ICP**	**Power**	**Point**	**ICP**	**Distortion**	**Density**	**Bandwidth**	**Noise Pwr**	**SNR**	**SFDR**	**Linear**	**Linear**	**IIP3**
Component	**(dB)**	**(dB)**	**(dBm)**	**(dBm)**	**(dBm)**	**(dBm)**	**(dBm)**	**(dBm)**	**(dBm)**	**(dBm/Hz)**	**(MHz)**	**(dBm)**	**(dB)**	**(dB)**	**Gain**	**IIP3**	**(dBm)**
Lowpass filter	-2.7	2.7	-75		75	-77.7		72.3		-152.7					0.54	3.16E+07	-37.7
Fixed Atten	-2	2	-77.7			-79.7				-154.6	40	-78.6	-1.1		0.63	1.00	
Step atten	-3	3	-79.7	22	37	-82.7	19	34	-316.1	-157.5	40	-81.5	-1.2	233.4	0.50	5.01E+03	
Fixed Atten	-2	2	-82.7			-84.7				-159.4	40	-83.3	-1.4		0.63	1.00	
Amplifier	15.4	3.7	-84.7	-4.9	9.6	-69.3	10.5	25	-257.9	-143.6	40	-67.6	-1.7	188.6	34.67	9.12	
Fixed Atten	-3	3	-69.3			-72.3				-146.6	40	-70.6	-1.7		0.50	1.00	
	0	0	-72.3			-72.3				-146.6	40	-70.6	-1.7		1.00	1.00E+00	
	0	0	-72.3			-72.3				-146.6	40	-70.6	-1.7		1.00	1.00	
Amplifier	28	2.5	-72.3	-7	3	-44.3	21	31	-194.9	-118.6	40	-42.6	-1.7	150.6	630.96	2.00	
Fixed Atten	-3	3	-44.3			-47.3				-121.6	40	-45.6	-1.7		0.50	1.00	
Transformer	-0.5	0.5	-47.3			-47.8				-122.1	40	-46.1	-1.7		0.89	1.00	
Variable Gain Amp	32	7	-47.8		-10.5	-15.8		21.5	-90.4	-90.1	40	-14.1	-1.7	74.6	1584.89	0.09	
						ADFS:	1.536	V	assumed to be pk-pk								
						14 dB backoff:	0.199526	linear									
Cascaded NF:	**13.54**	**dB**				set point:	0.306472	V	assumed to be pk-pk								
Output power:	**-15.80**	**dBm**															
ADC input load impedance:	**200.0**	**ohms**			**S+N:**	**-11.84**	**dBm**		1st stage NF:	13.4	dB	2nd stage NF:		5.50	dB		
I/Q voltage:	**0.073**	**Vrms**			**S+N voltage:**	**0.114**	**Vrms**		1st stage NF:	21.9	linear	1st stage gain:		5.70	dB		
I/Q voltage:	**0.205**	**Vpk-pk**			**S+N voltage:**	**0.324**	**Vpk-pk**					2nd stage NF:		3.55	linear		
Output SNR:	**-1.7**	**dB**										1st stage gain:		3.72	linear		
Total gain:	**59.2**	**dB**										2nd stage contribution:		6.86E-01	linear		
Total SFDR:	**74.6**	**dB**	based only on 3rd order distortion						cascaded:	2.257E+01	linear	3rd stage NF:		10.50	dB		

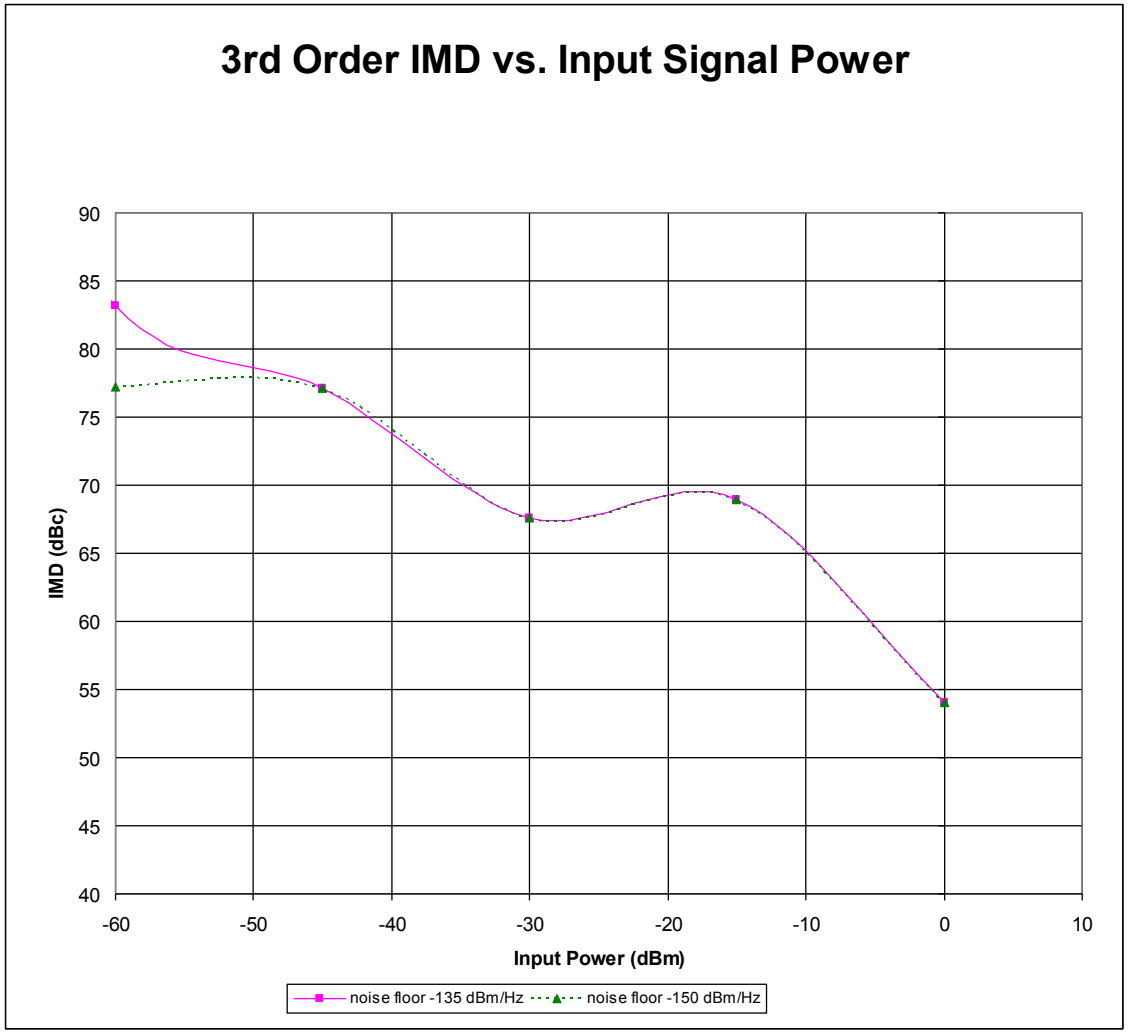
IF Receiver Example: Modeled Eb/No Performance



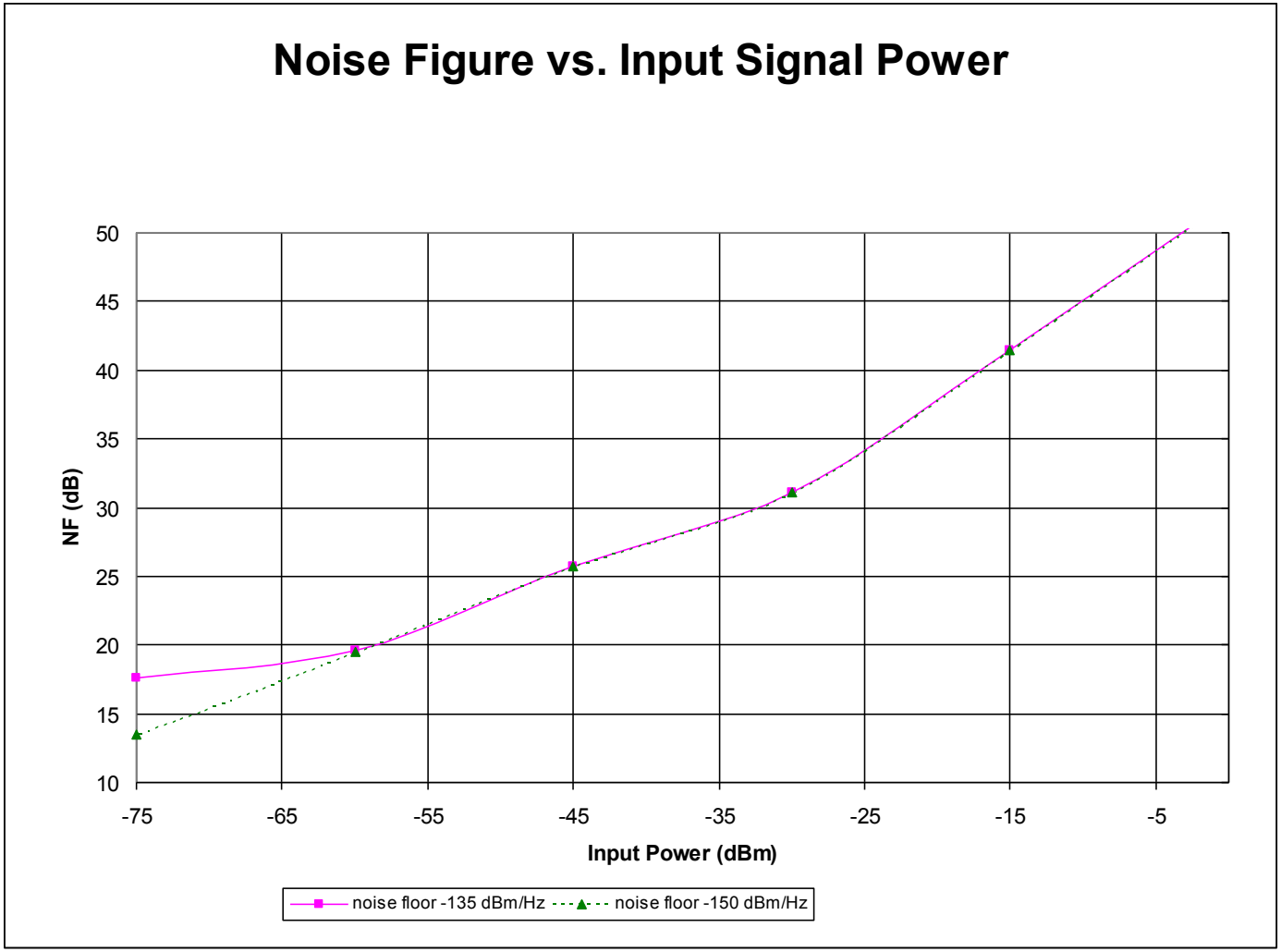
IF Receiver Example: Modeled Eb/No Performance (con't)



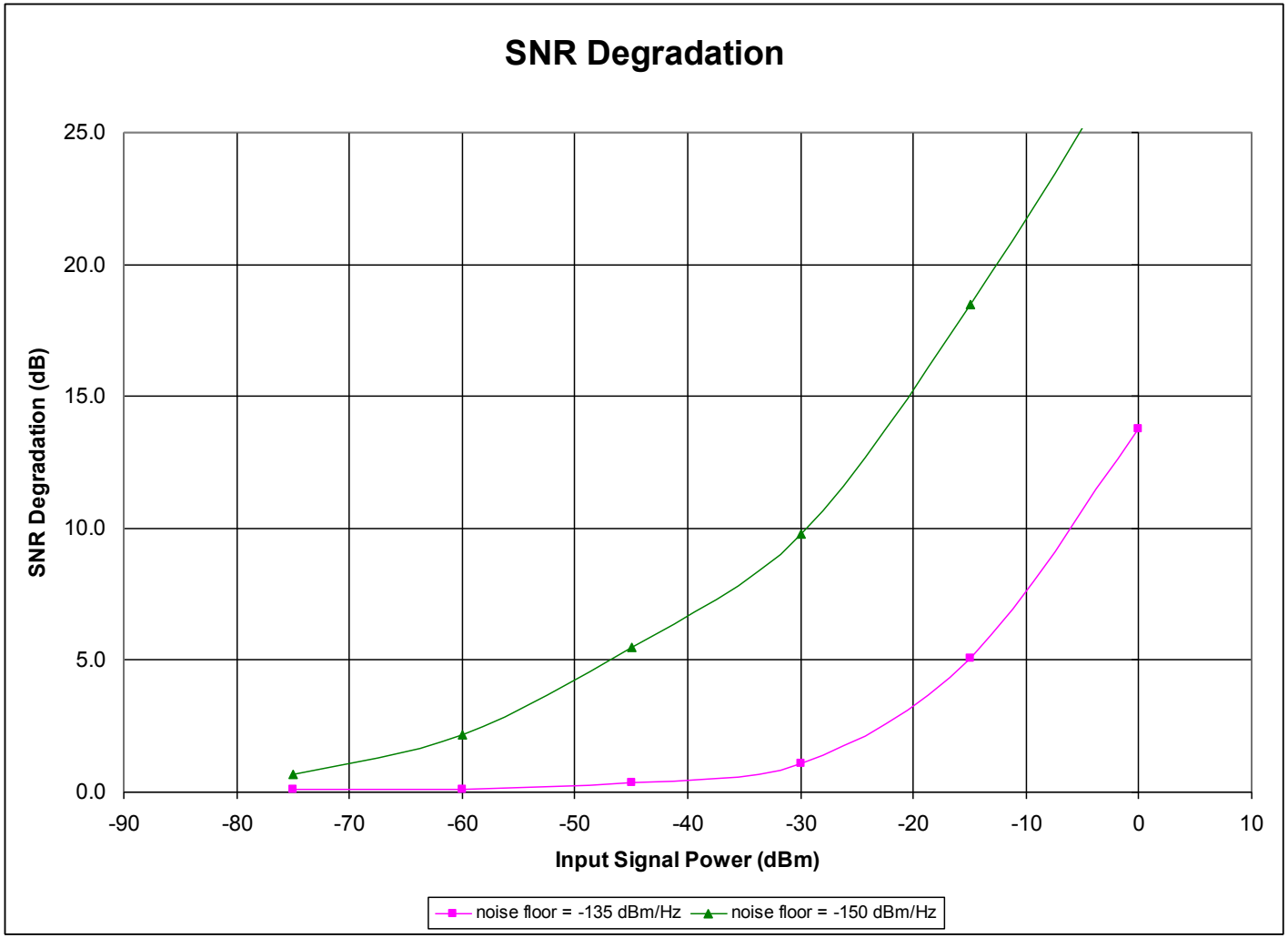
IF Receiver Example: Modeled 3rd Order Intermodulation Distortion Performance



IF Receiver Example: Modeled Noise Figure Performance



IF Receiver Example: Modeled SNR Degradation Performance



Questions

My Engineering Career

- BSEE 1983 from Iowa State University
  - Analog and communications focus
- 1982 to 1989: Hughes Aircraft Company, Los Angeles
  - Radar systems engineer primarily for RF and IF receivers
- 1989 to 1990: Research & Development Laboratories , Los Angeles
  - Radar and RF engineer for receiver design
- 1990 to 1994: NAVSYS, Monument, CO
  - GPS and RF engineer, project management, engineering management
- 1994 to 1996: XEL Communications, Aurora, CO
  - CATV data modem design
- 1996 to 2001: Mission Research Corporation, Colorado Springs
  - Fading channel emulators, military communications and radar systems, mgmt
- 2001 to 2003: Xircom/ Intel, Colorado Springs
  - Commercial wireless modems, mgmt
- 2003 to present: RT Logic, Colorado Springs
  - Satellite communications, RF data links, radar, mgmt

MSEE from UCCS 1991-1996

MBA classes from UCCS 2009-present

Career Dialog

- What's it like to be an engineer?
- Do I really need to remember all that calculus stuff?
- What career paths are available?
- What's important and what's not?
  - Salary
  - Challenge
  - Title
  - Writing
  - Math
  - Speaking
  - Company culture
  - Co-workers
  - Type of work
- In hindsight, would I do anything different?
- What if I don't like engineering once I start working?
- How do I get, and hold, an engineering job?