Mega Hertz, Mega Samples, Mega bits, Mega Confusing

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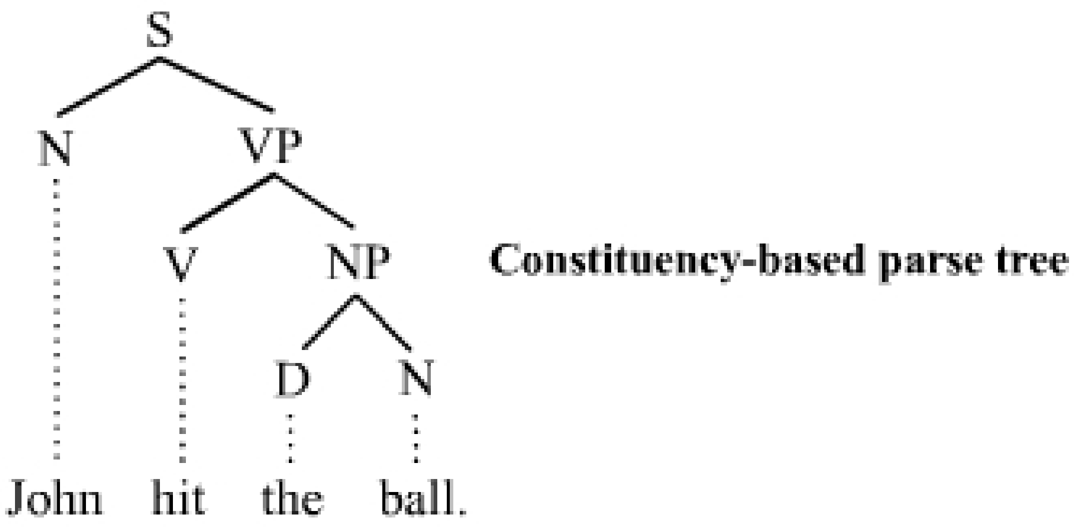
AHEAD OF WHAT'S POSSIBLE™

THE FREE & OPEN SOFTWARE RADIO ECOSYSTEM

Focus of this talk

- Grammar
  - grammar is the set of structural rules governing the composition of clauses, phrases and words in a natural language.
  - https://en.wikipedia.org/wiki/Grammar



Tjo3ya - Own work, CC BY-SA 3.0

- Numbers
  - A number is a mathematical object used to count, measure, and label.
    - https://en.wikipedia.org/wiki/Number
  - Numbers in Science
  - Numbers in Mathematics

Back to basics

https://www.umass.edu/pvnet/imagery_files/TeacherProjectsAug/kittredge.ppt

Back to basics

https://www.umass.edu/pvnet/imagery_files/TeacherProjectsAug/kittredge.ppt

Back to basics

The ADALM-PLUTO has a maximum sample rate of

$$\frac{1}{61{,}440{,}000}\ \text{Hz}$$

Michelle Getz, a 6th grade teacher

Back to basics

Numbers in Science vs. Numbers in M

This lesson is designed to help provi
numbers are used in science. This c
way you are used to thinking about
example, while every digit that com
important in mathematics, it is almo
every digit that comes from your ca
class.

Numbers in Science
Have Units (Often)
Have an Associated Uncertainty (Have Significant Figures)
Derive from a Measurement

Making a Measurement

The key to understanding numbers in science i
is a fundamental difference between numbers
counting or calculation and the numbers we d
world.

The reason for this is that ***no measurement is***
estimation involved in making a measurement

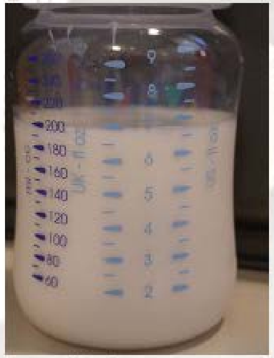


Photo from Wikipedia user MilCdetroit, Creative Commons

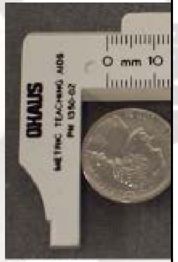


Photo by SKMay

Reporting a Measurement

To be truly scientific, every measurement
uncertainty associated with it. That is, m
uncertainty. The uncertainty is a measure

For example, on the previous slide, we mi
199 ± 1 mL 21.0 ±

Because we encounter numbers all the tin
include only the measurement, we should

The number of digits reported in any meas
upon by all scientists: exactly one estimat
exactly one estimated digit is reported.

While it is preferable to record actual unc
implicit rule is that your uncertainty is ± p

Therefore, a mass of 68.5 kg is implicitly 6

Significant Figures

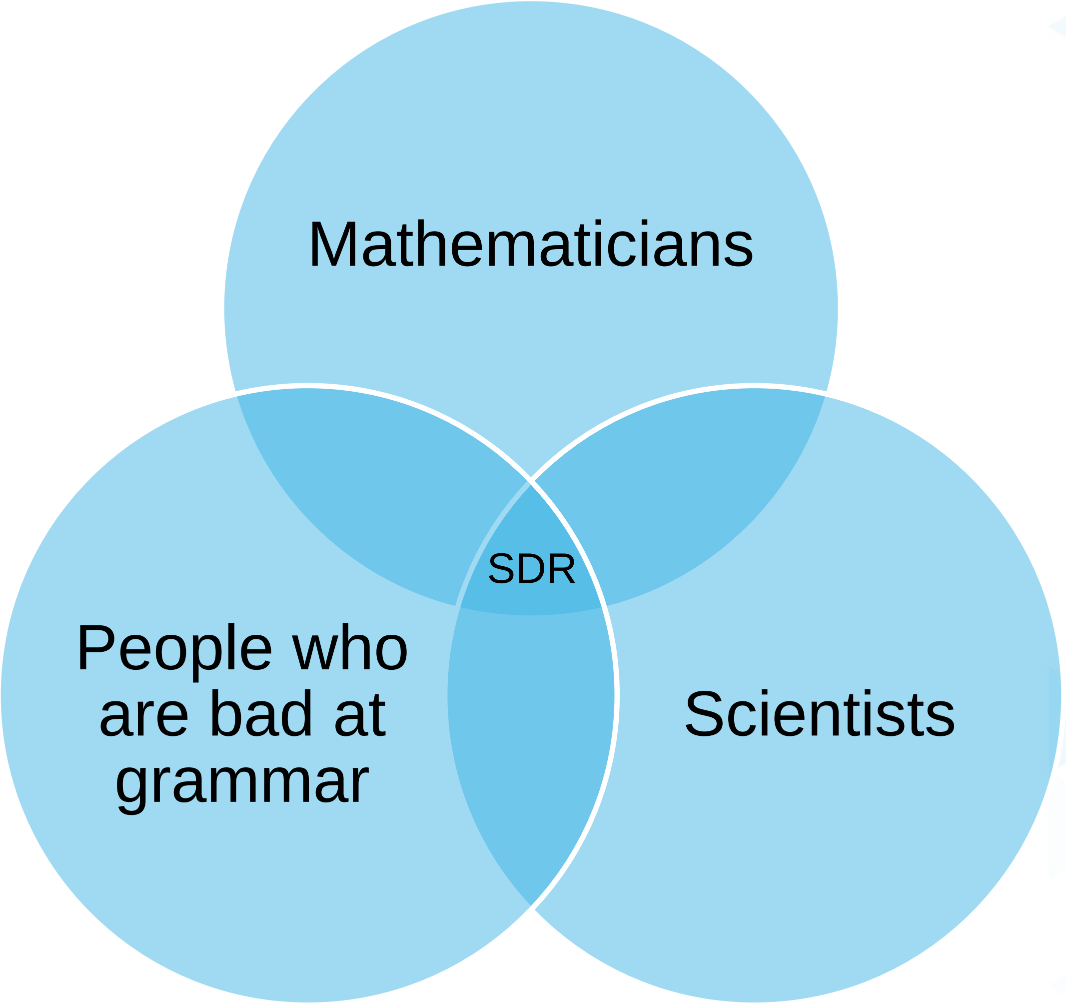
Because scientists have agreed on a convention that *exactly one estimated digit is significant*, one can assume that the smallest recorded digit corresponds to the estimate.

Consider the following examples:

Measurement	Estimated Digit	Implied Uncertainty	# of Sig Figs
2.0×10^{30} kg	0 in the 10^{29} kg place	$2.0 \pm 0.1 \times 10^{29}$ kg	2
384,400 km	4 in 100 km place	384,400 ± 100 km	4
13 billion years	3 in the billion years place	13 ± 1 billion years	2
3.00×10^{8} m/s	0 in the 10^{6} m/s place	$3.00 \pm 0.01 \times 10^{8}$ m/s	3
8 planets in SS	None	None	Unlimited
365.242199 days	9 in the 10^{-6} days place	365.242199 ± 0.000001 days	9

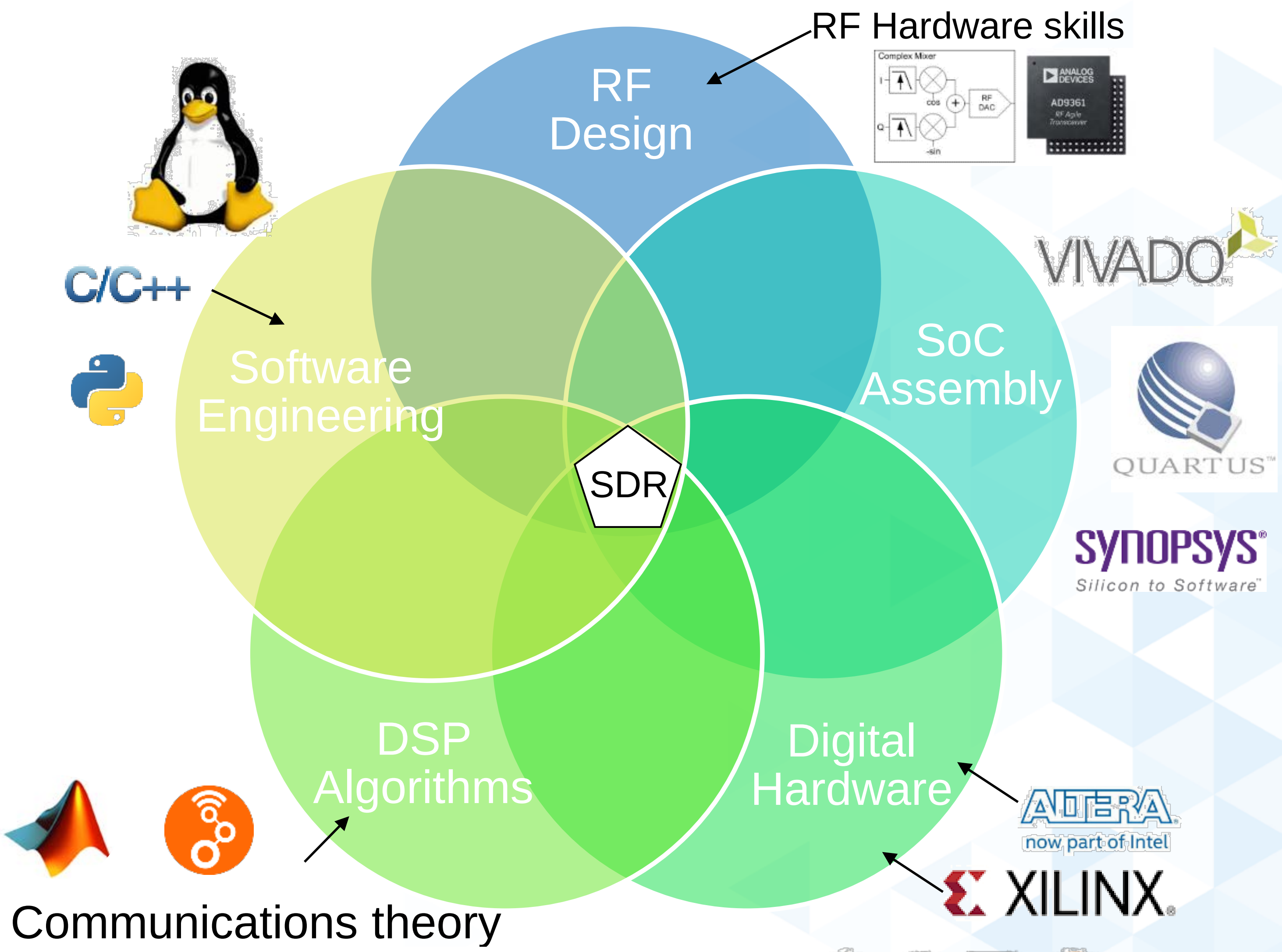
https://www.haystack.mit.edu/edu/pcr/physics_mosaic/Data,%20Measurement,%20Uncertainty/Numbers%20in%20Science.pptx

Software Defined Radio Audience



Software Defined Radio mix of Math & Science

- Communications Theory is:
  - largely mathematics and statistics
  - everything is a float
    - infinite precision
  - Everything is exact, no units
- Digital Hardware
  - everything is fixed int
    - 18-bit numbers, fixed point fractional
  - Everything is exact, no errors in clocks
- RF Hardware
  - makes up units
    - dB is relative to what?
  - Doesn't want to say how bad the hardware is, so leaves out uncertainty
- Software
  - Everything is a buffer/vector
- Each discipline feels their work is obvious, and doesn't use units



$$s[2\ell N + n] = \frac{1}{2N} \sum_{k=0}^{2N-1} p_k[\ell] e^{j(2\pi nk/2N)},$$

RF to Antenna

What does Bandwidth mean?

Bandwidth

- Bandwidth is the difference between the upper and lower frequencies in a continuous band of frequencies. It is typically measured in hertz, and depending on context, may specifically refer to passband bandwidth or baseband bandwidth.
  - https://en.wikipedia.org/wiki/Bandwidth_(signal_processing)

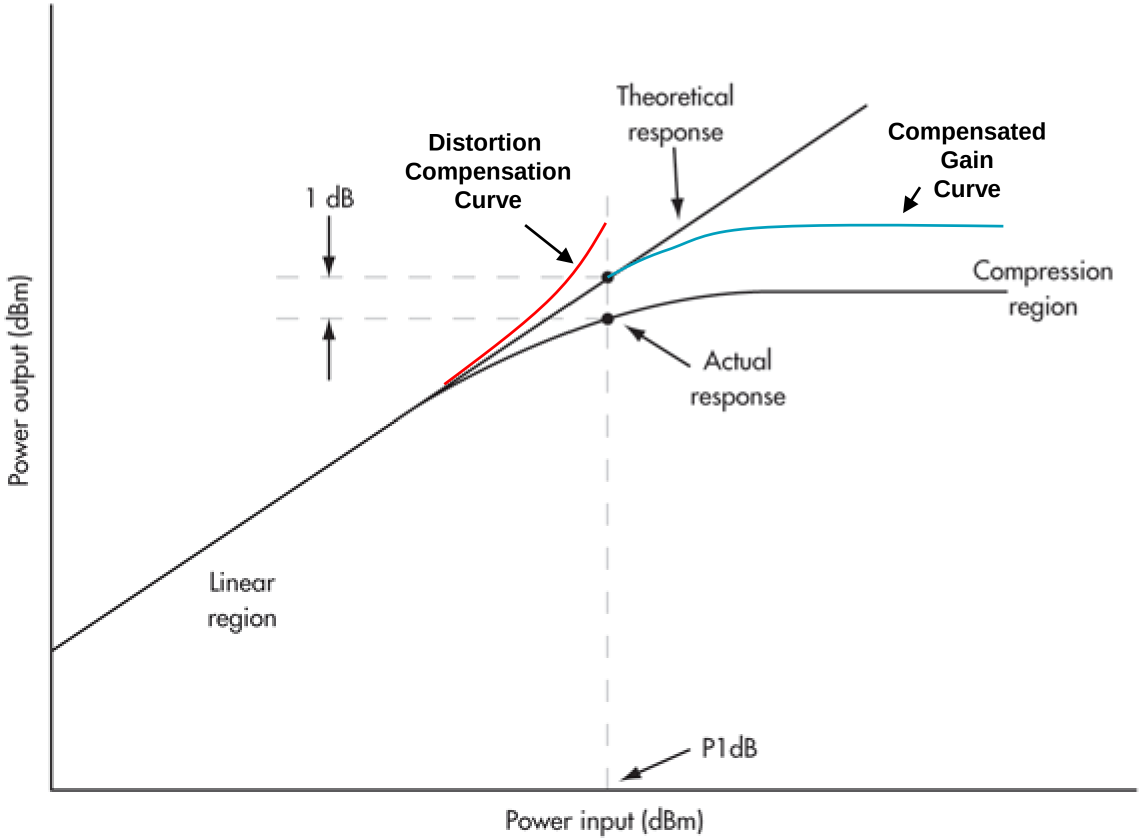
- The frequency range or bandwidth over which an antenna functions well can be very wide

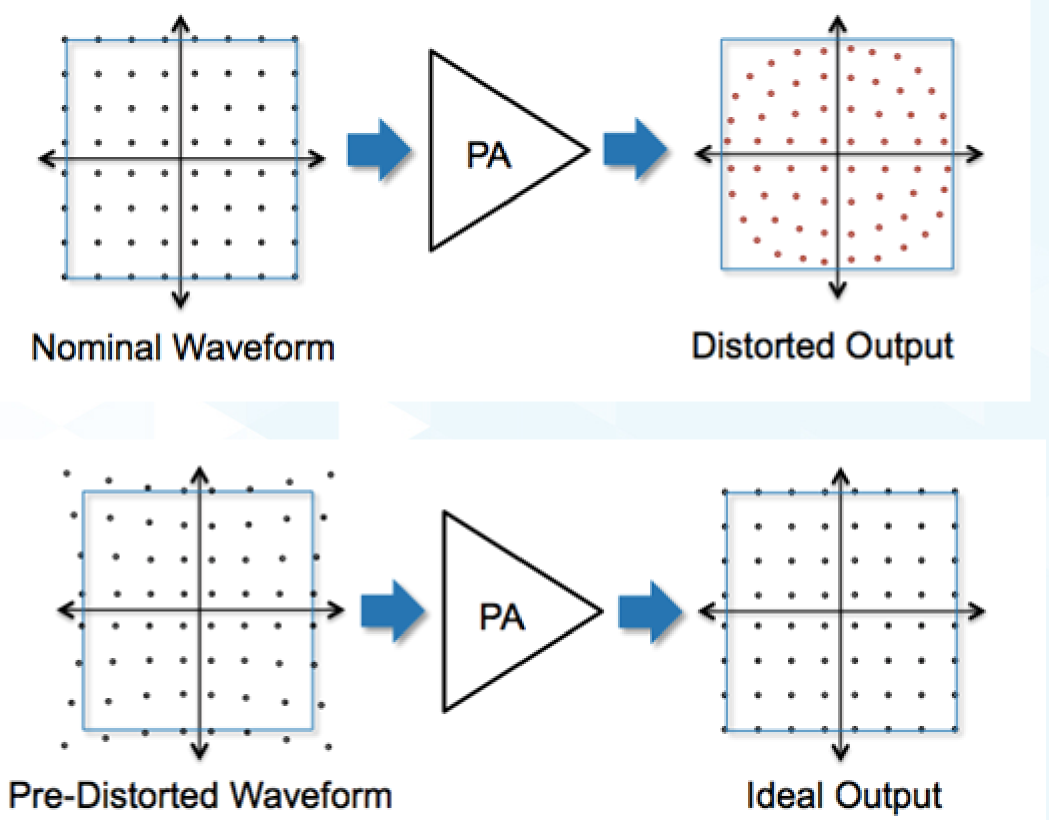
Jinchang Electron Global Service

SPECIFICATIONS

Item		Specifications
Antenna	Frequency Range	824~894/1710~2170MHz or 880~960/1710~2170MHz
	Polarization	Linear
	Gain	2dBi（Zenith）
	V.S.W.R（min）	＜2.5
	Impendance	50 Ω
	Connector	SMA right Male
Environmental	Operating Temperature	-40℃~+85℃
	Vibration	10 to 55Hz with 1.5mm amplitude 2hours
	Environmentally Friendly	ROHS Compliant

What is Digital PreDistortion?



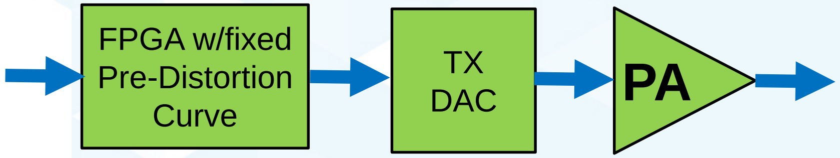


http://www.ni.com/newsletter/52238/en/

11

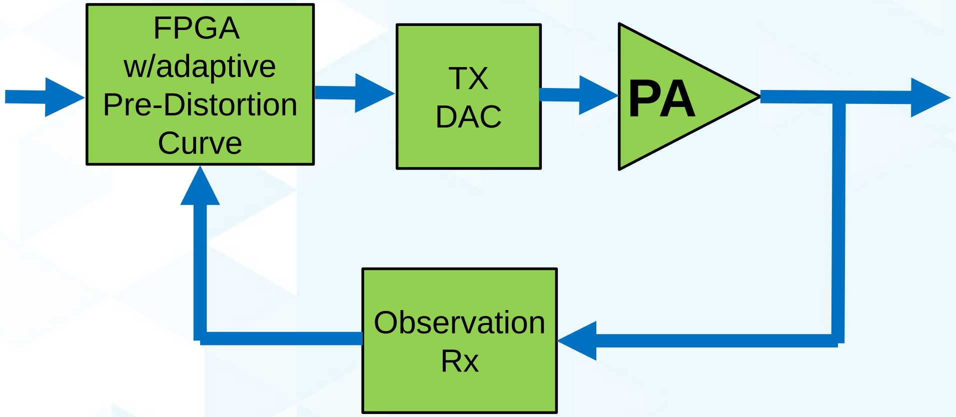
DPD - Digital Pre-Distortion

- Feed-forward approach
  - Simpler
  - Does not account for part-to-part or temp variation



Feed Forward

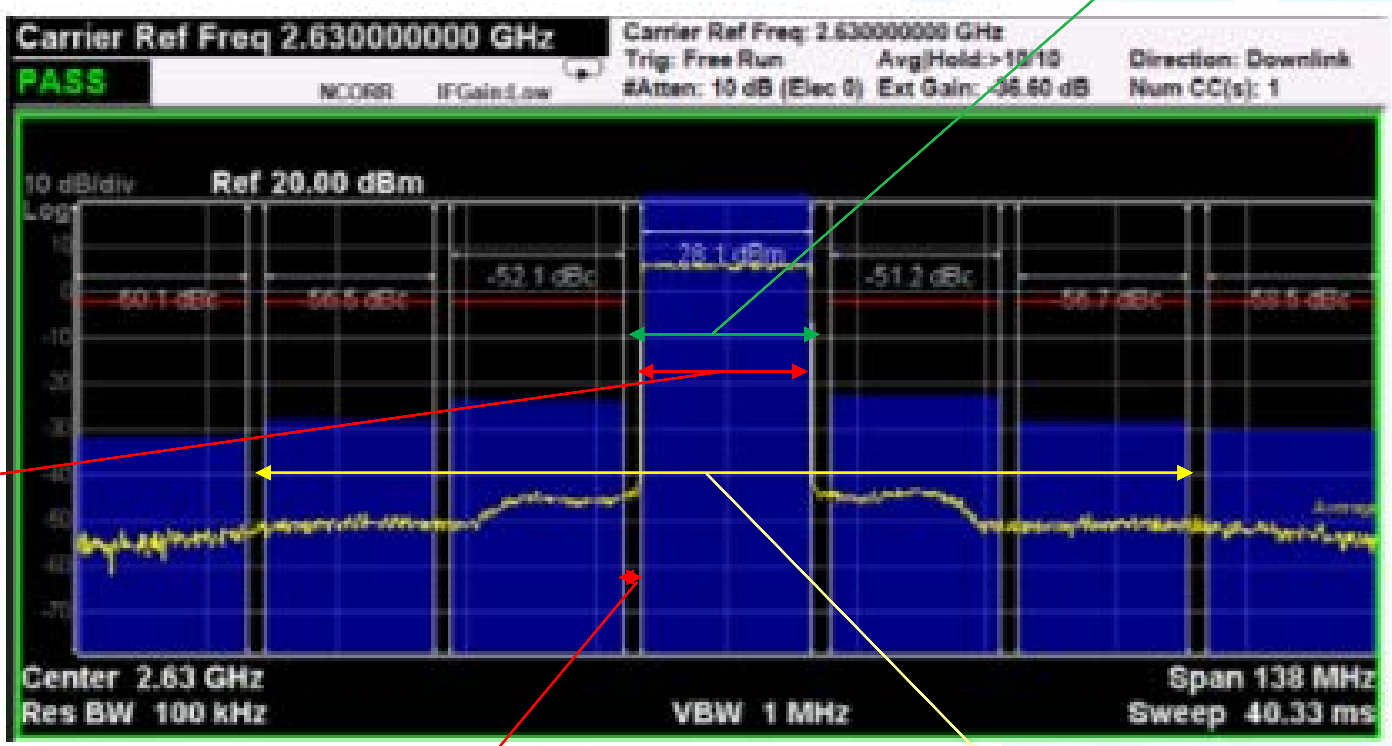
- Feed-back approach
  - More complicated
  - Adapts to changing conditions
  - Typically requires 5x signal bandwidth observation Rx



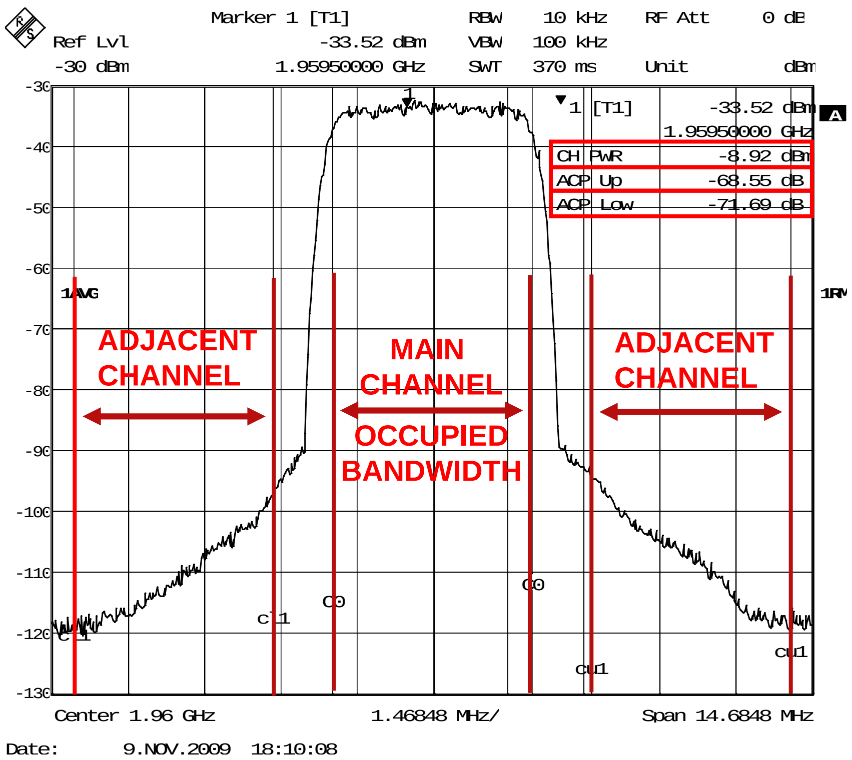
Feed Back

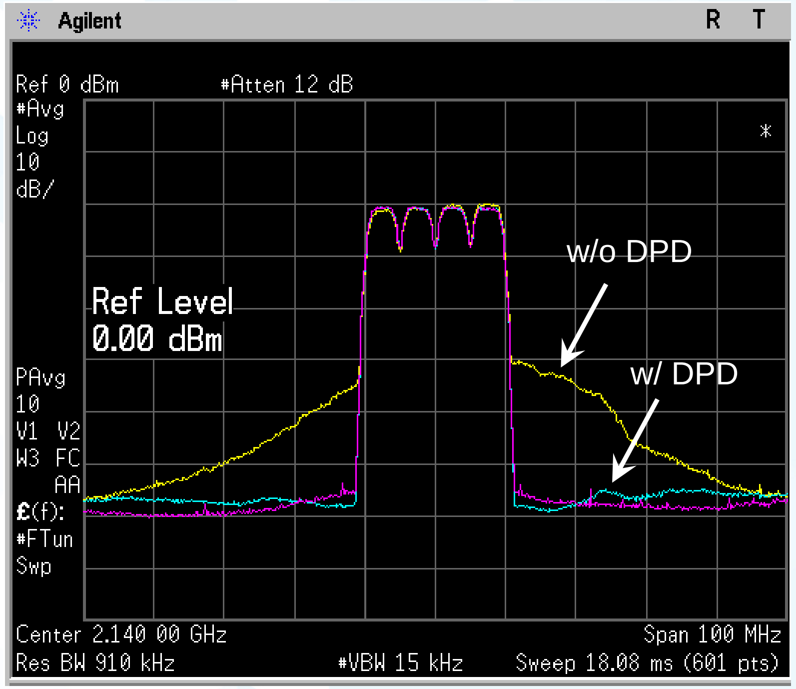
Air Interface

LTE Bandwidth Set	Occupied RF Bandwidth
MHz	MHz
1.4	1.08
3	2.7
5	4.5
10	9
15	13.5
20	18



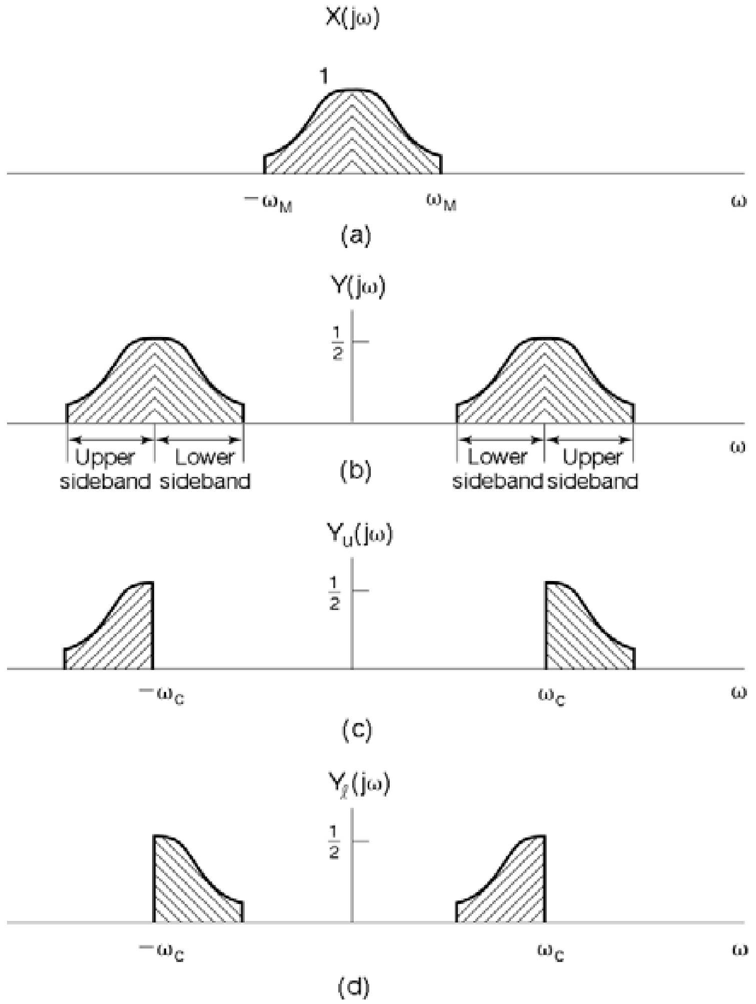
ACLR - Adjacent Channel Leakage Ratio





- ACLR is the ratio of the mean Tx channel power to the mean adjacent or alternate channel power (ACP)
- Power Amplifier is primary source of ACP due to its nonlinearities
- Signal pre-distortion techniques are employed to reduce the ACP
- 3GPP LTE Spec: 45 dB

Analog Signals



- **Double-sideband (DSB) occupies** *2M* **bandwidth in** $\omega > 0$**, even though** ***all*** **the information is contained in** *M***.**

- **Single-sideband (SSB) occupies** *M* **bandwidth in** $\omega > 0$**.**

http://stellar.mit.edu/S/course/6/sp08/6.003/courseMaterial/topics/topic1/lectureNotes/Lecture__15/Lecture__15.pdf

Antenna to Interface

SDR Hardware

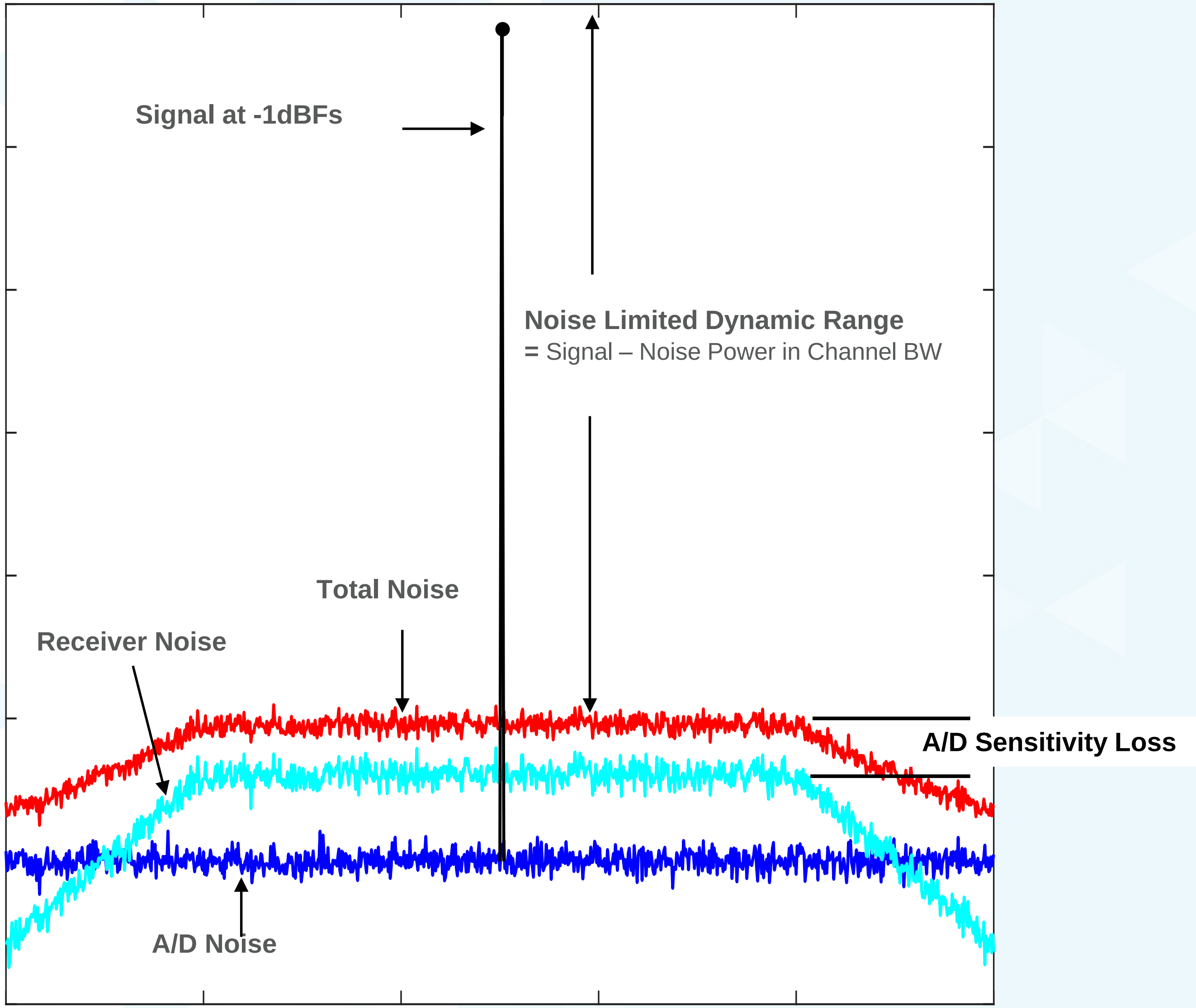
Receiver Noise

- Receiver Total Noise
  - Combination of RF section and A/D
  - RF section shaped by anti-aliasing filter
  - A/D noise typically flat
- Calculation Method
  - Convert to common units
  - Noise added in units of power
- Noise Limited Dynamic Range
  - Signal – Noise Power in Channel BW

$$\text{A/D Noise}(dBm/Hz) = \text{A/D Full Scale}\,(dBm) + \text{A/D NoiseDensity}(dBFs/Hz)$$

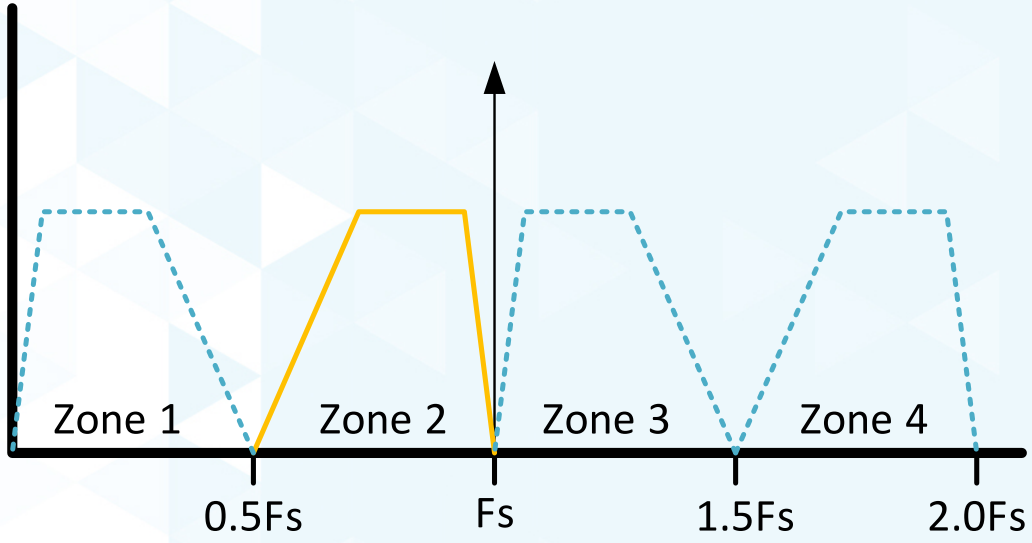
$$\text{Total Noise}(dBm/Hz) = 10\log_{10}\left(10^{\frac{\text{Receiver Noise}(dBm/Hz)}{10}} + 10^{\frac{\text{A/D Noise}(dBm/Hz)}{10}}\right)$$

$$\text{A/D Sensitivity Loss (dB)} = \text{Total Noise}(dBm/Hz) - \text{Receiver Noise}(dBm/Hz)$$



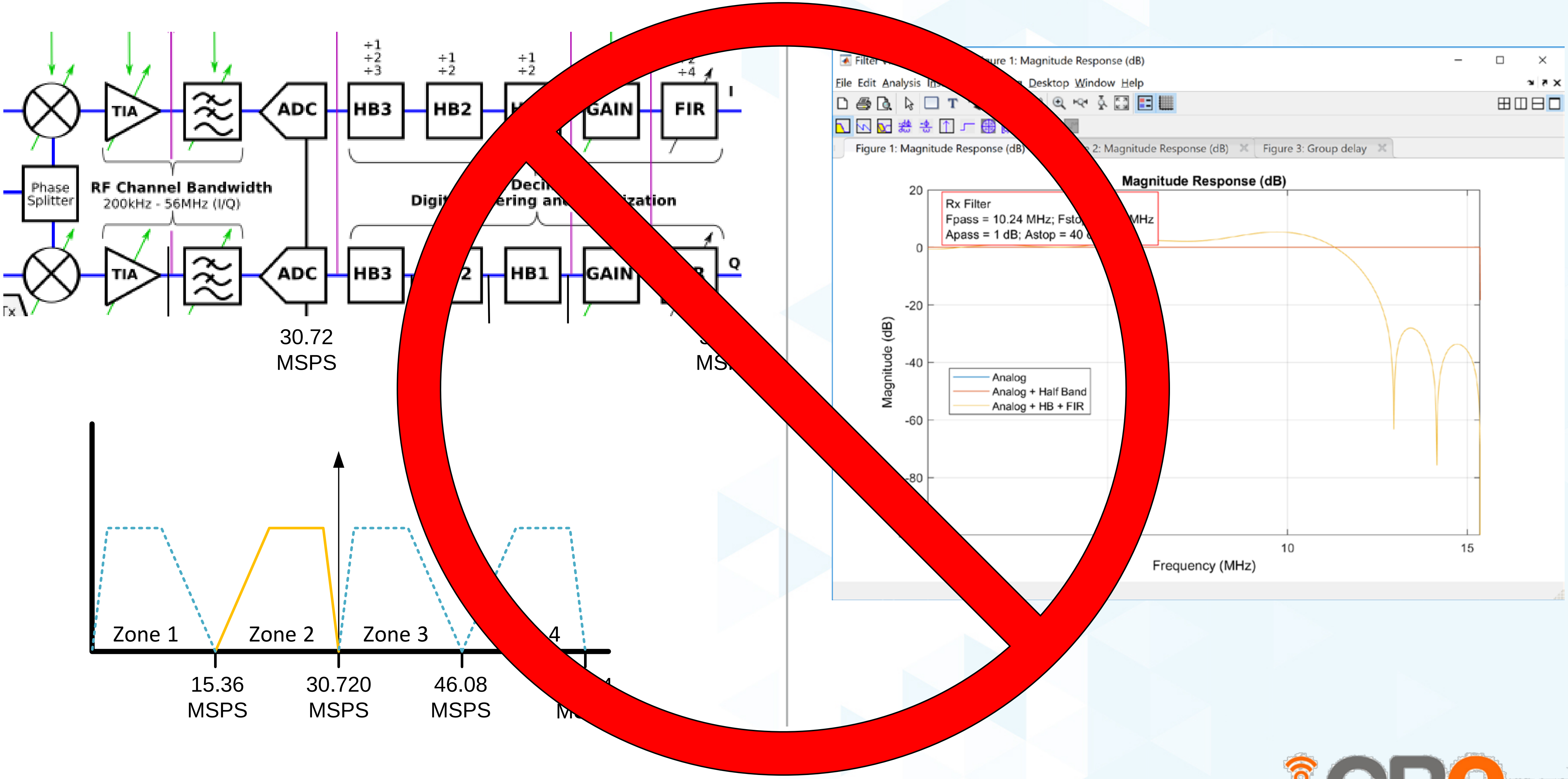
Receiver Specs – Bandwidth / Frequency Range

- Bandwidth
  - Can refer to
    - Amount of spectrum that can be used at any instant (Instantaneous BW)
    - Channelized BW – BW passed through digital filtering
    - Frequency range that can be received
  - More instantaneous bandwidth allows
    - more users/channels
    - faster sweep times (fewer steps)
  - More instantaneous BW means more potential interference
    - Sometimes leads to selectable BW
  - Higher BW requires higher sample rate on ADC
    - Ex: To achieve 1GHz BW, sample ADC at >2GSPS

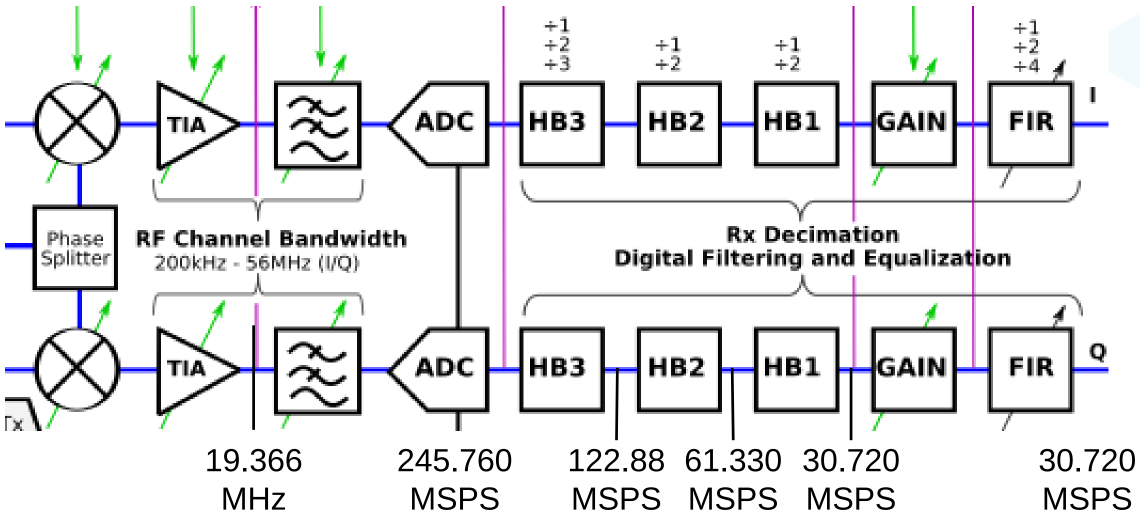


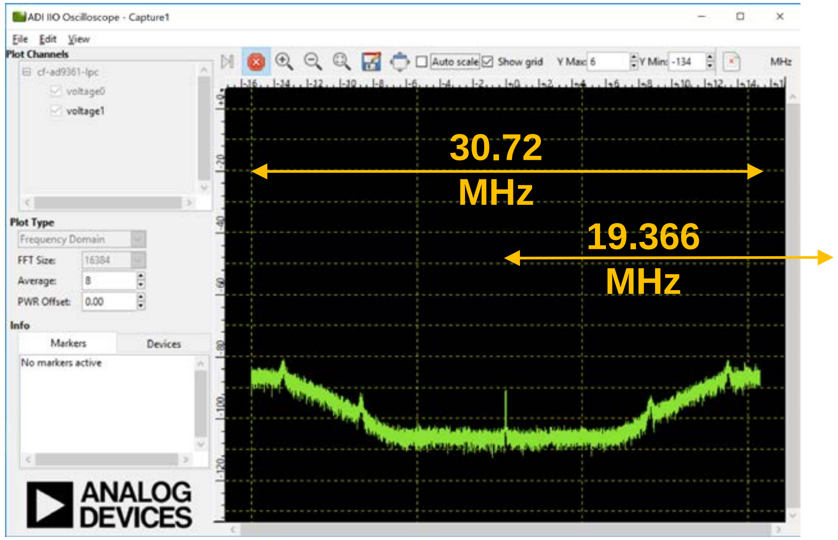
Simply stated, the Nyquist criterion requires that the sampling frequency be at least twice the highest frequency contained in the signal, or information about the signal will be lost. Harry Nyquist's classic Bell System Technical Journal article of 1924. (He was 35)

SDR Σ-Δ ADC clocking



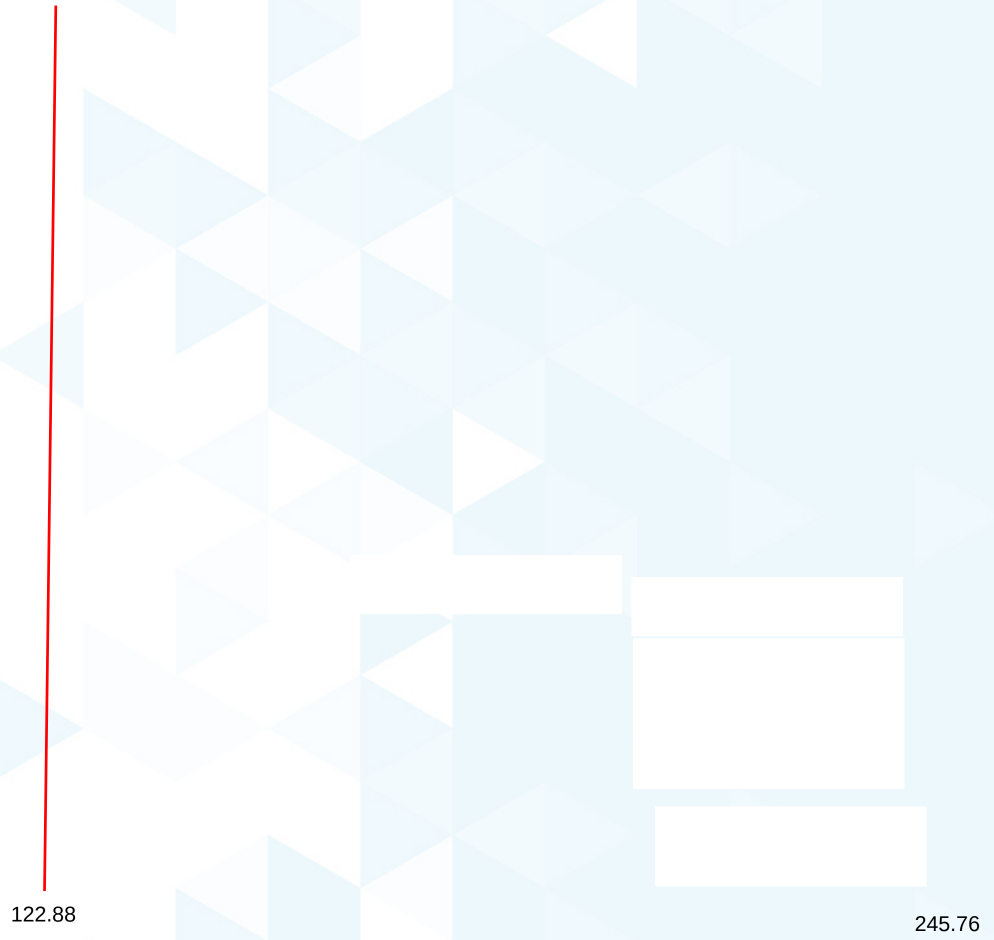
SDR Σ-Δ ADC noise shaping



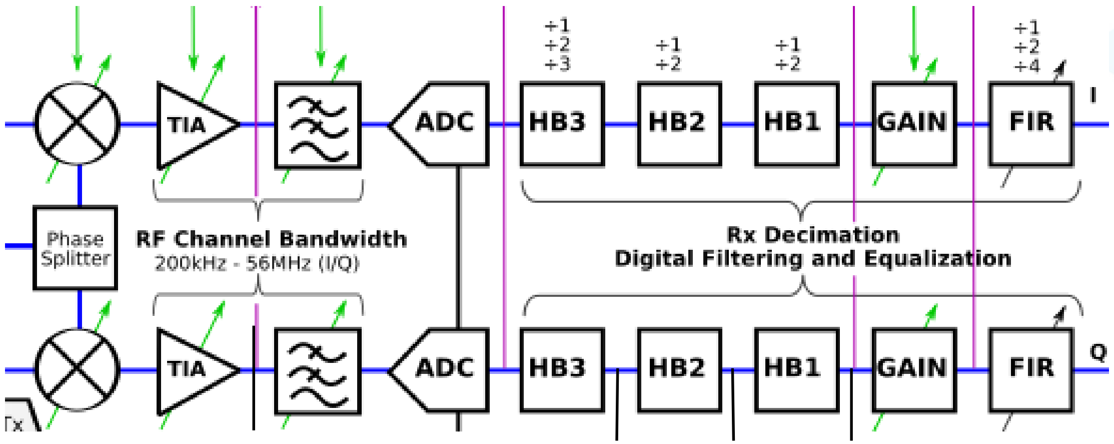


$$\frac{30.72}{2} x\, 1.25 \approx \mathbf{19.366}$$

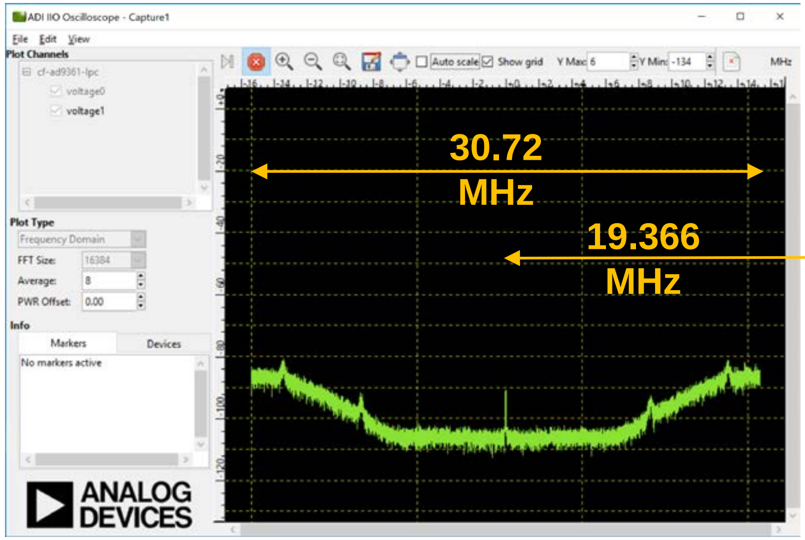
Analog filtering is easier with higher sample rates



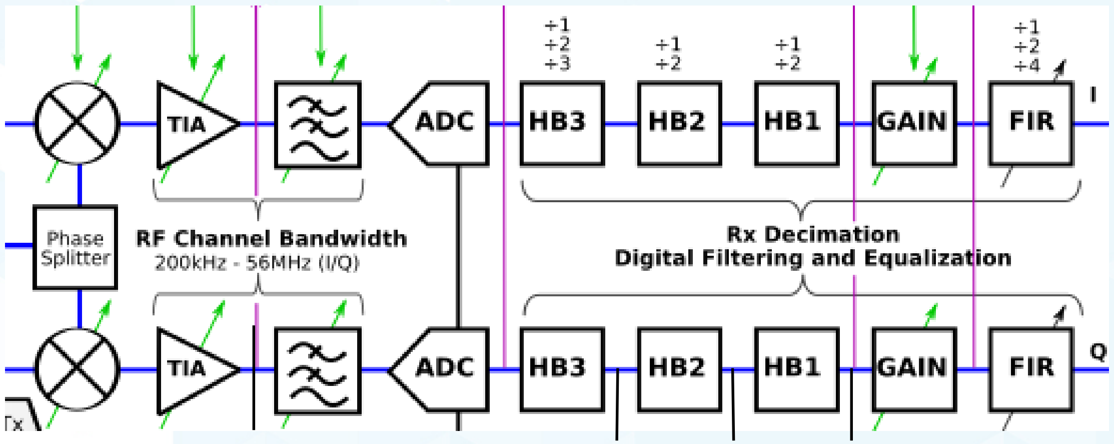
SDR Σ-Δ ADC noise shaping



19.366 MHz | 245.760 MSPS | 122.88 MSPS | 61.330 MSPS | 30.720 MSPS | 30.720 MSPS

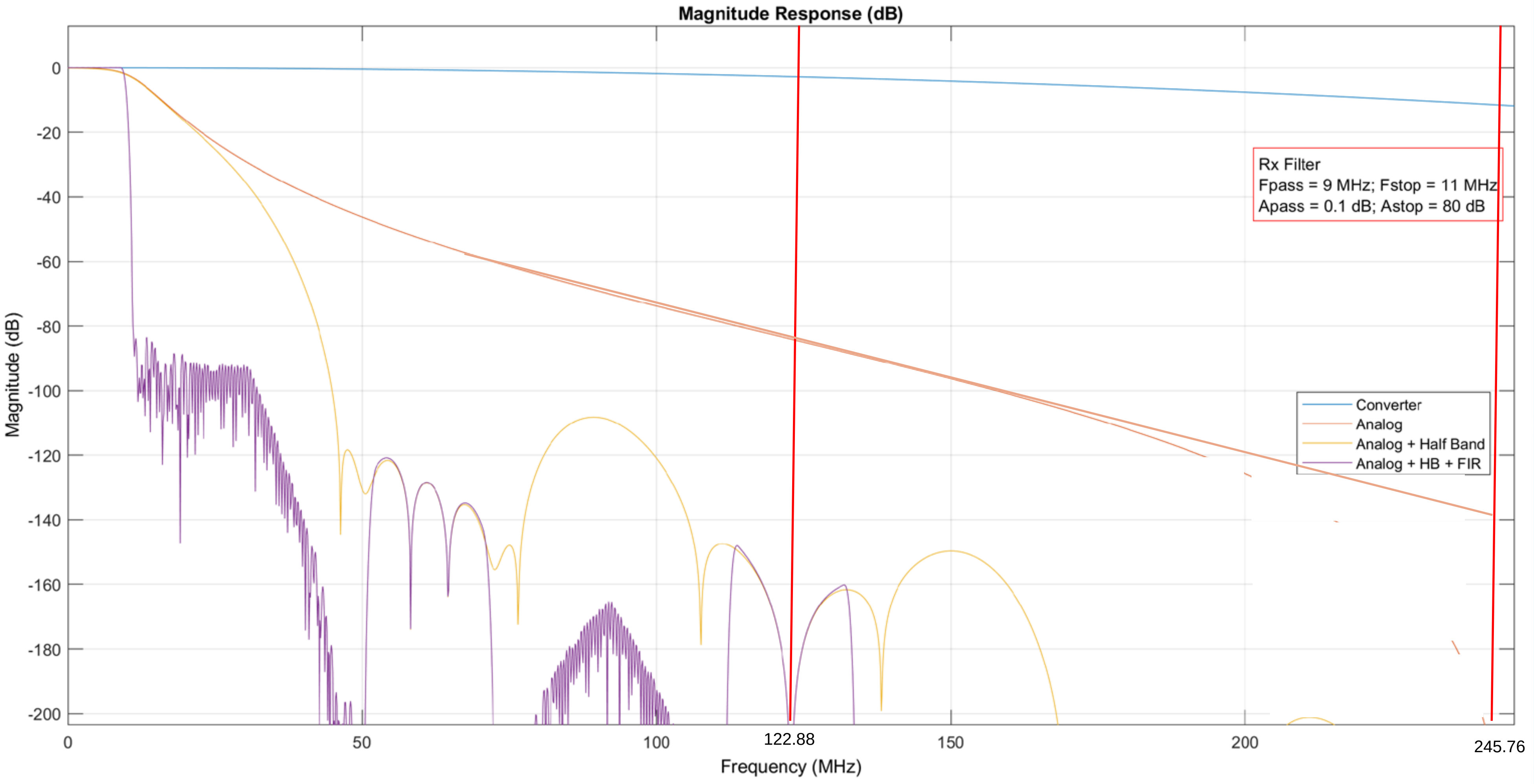


$$\frac{30.72}{2} x\,1.25 \approx 19.366$$

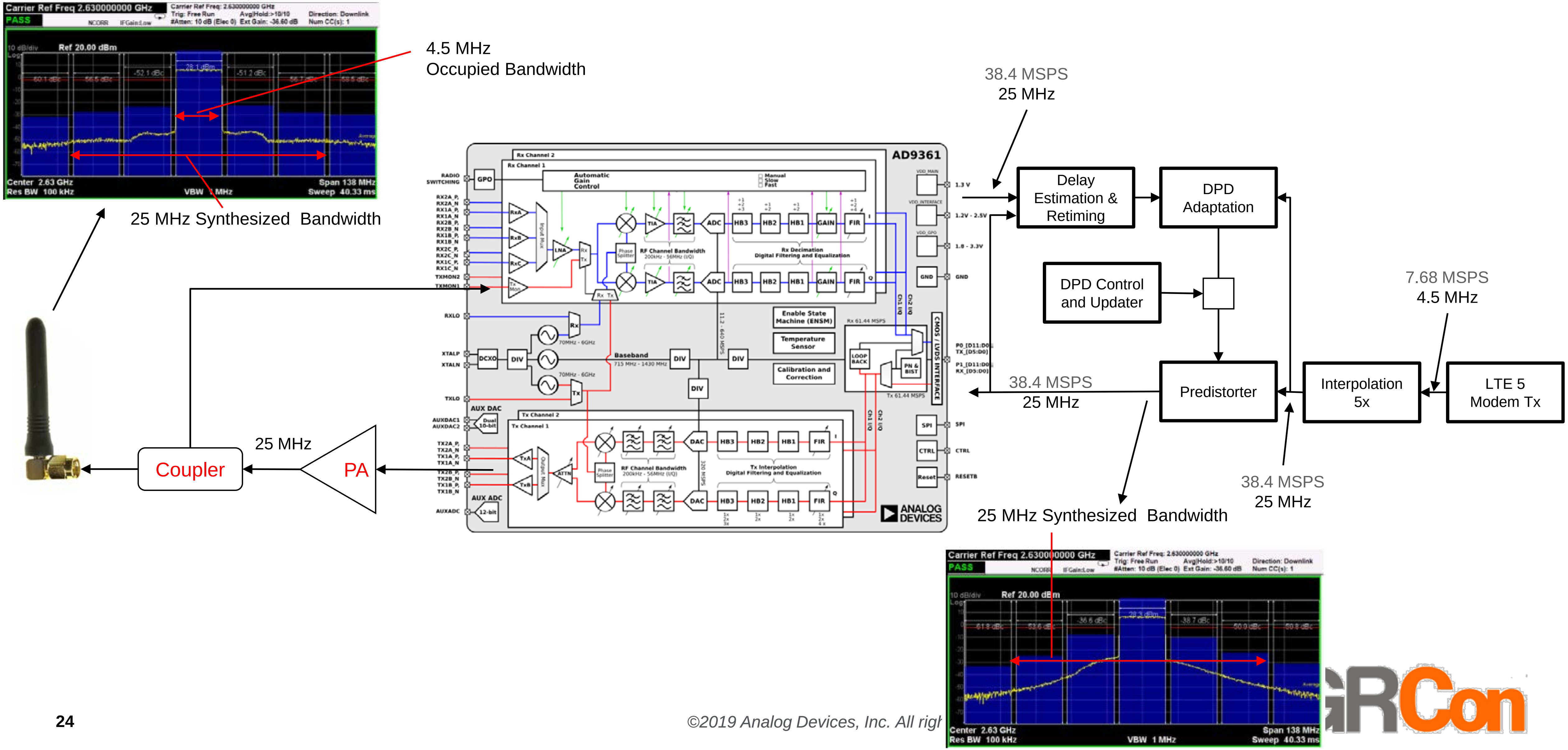


19.366 MHz | 491.520 MSPS | 245.760 MSPS | 122.880 MSPS | 61.440 MSPS | 30.720 MSPS

Analog filtering is easier with higher sample rates



Basic DPD System

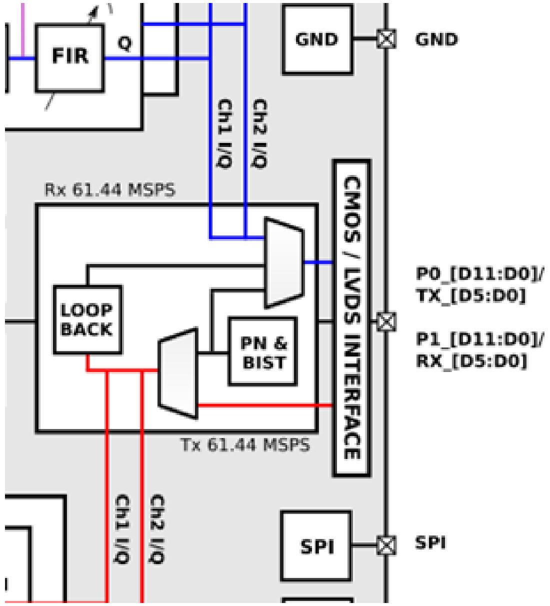


LTE Specifications

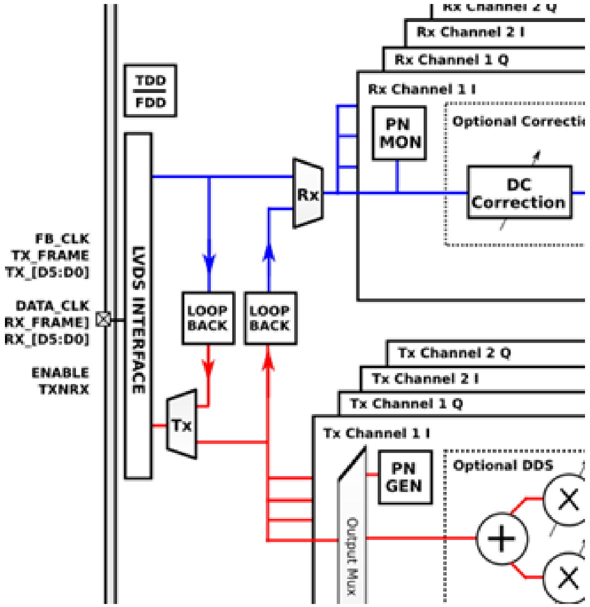
Channel Bandwidth MHz	Occupied Bandwidth MHz	MSPS
1.4	1.08	1.92
3	2.7	3.84
5	4.5	7.68
10	9	15.36
15	13.5	23.04
20	18	30.72

Interface : CMOS or LVDS

Transceiver

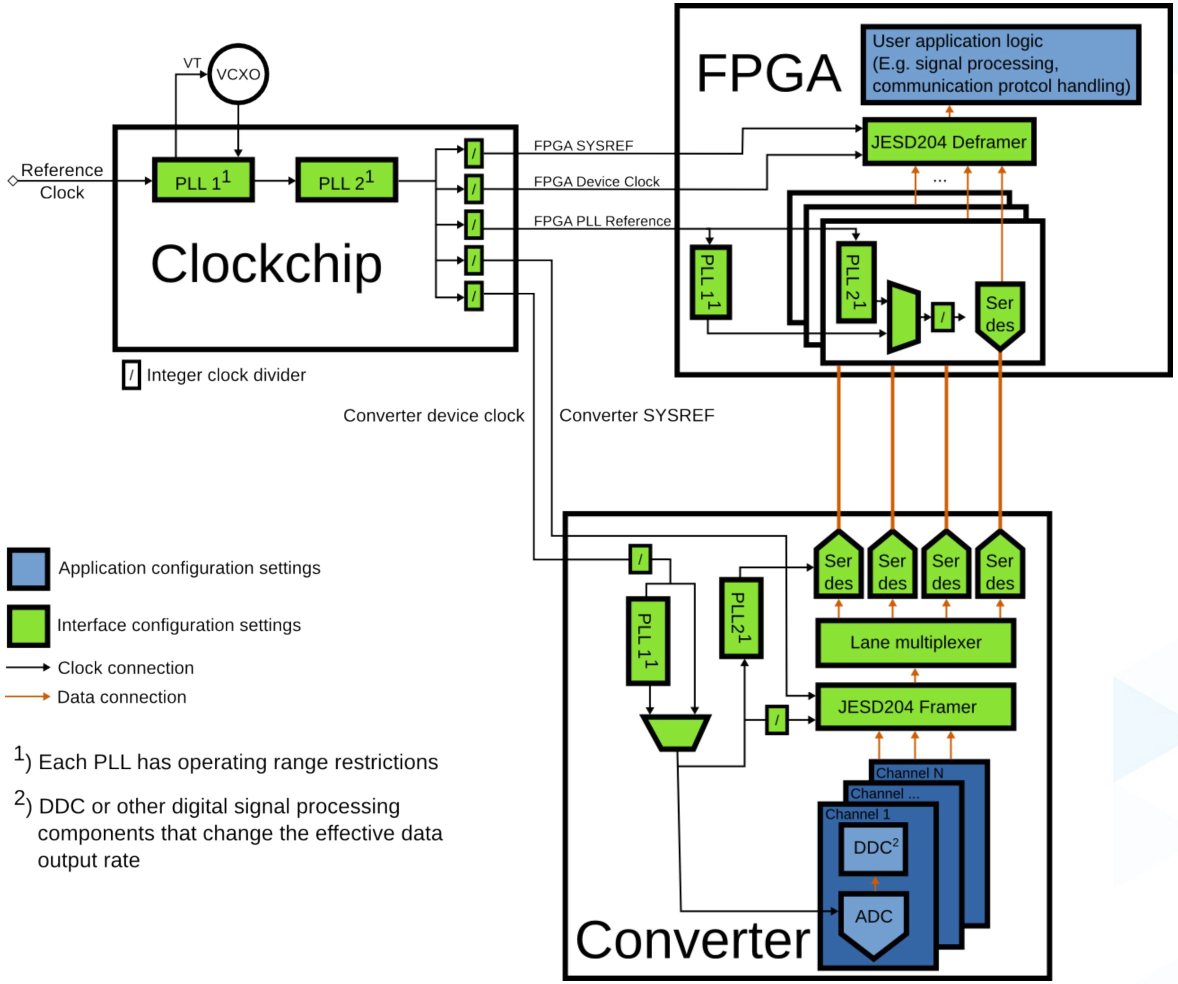


FPGA



- ► Runs at 2 – 4 x sample rate
- ► DDR (or not)?
- ► Mega bits per second transfer
- ► MHz Clocks

Interface : JESD204



1) Each PLL has operating range restrictions

2) DDC or other digital signal processing components that change the effective data output rate

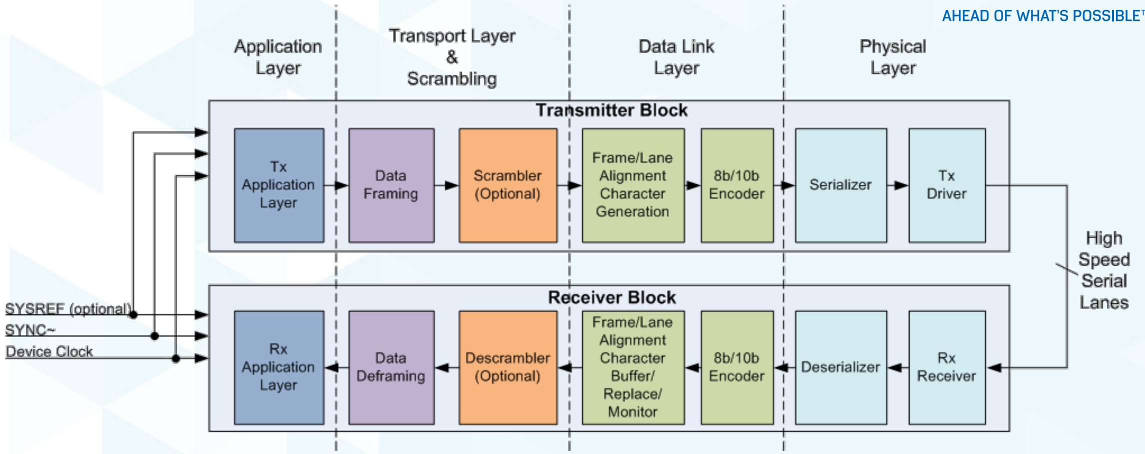


Table 8. Example Receiver Interface Rates (Other Output Rates, Bandwidth, and JESD204B Lanes Also Supported)

		Single-Channel Operation		Dual-Channel Operation	
Bandwidth (MHz)	Output Rate (MSPS)	JESD204B Lane Rate (Mbps)	JESD204B Number of Lanes	JESD204B Lane Rate (Mbps)	JESD204B Number of Lanes
80	122.88	4915.2	1	9830.4	1
100	153.6	6144	1	12288	1
100	245.76	9830.4	1	9830.4	2
200	245.76	9830.4	1	9830.4	2
200	245.76	4915.2	2	4915.2	4

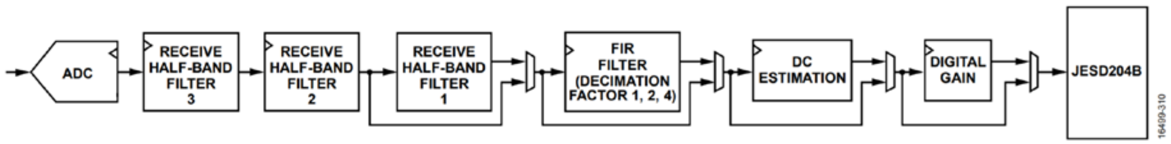
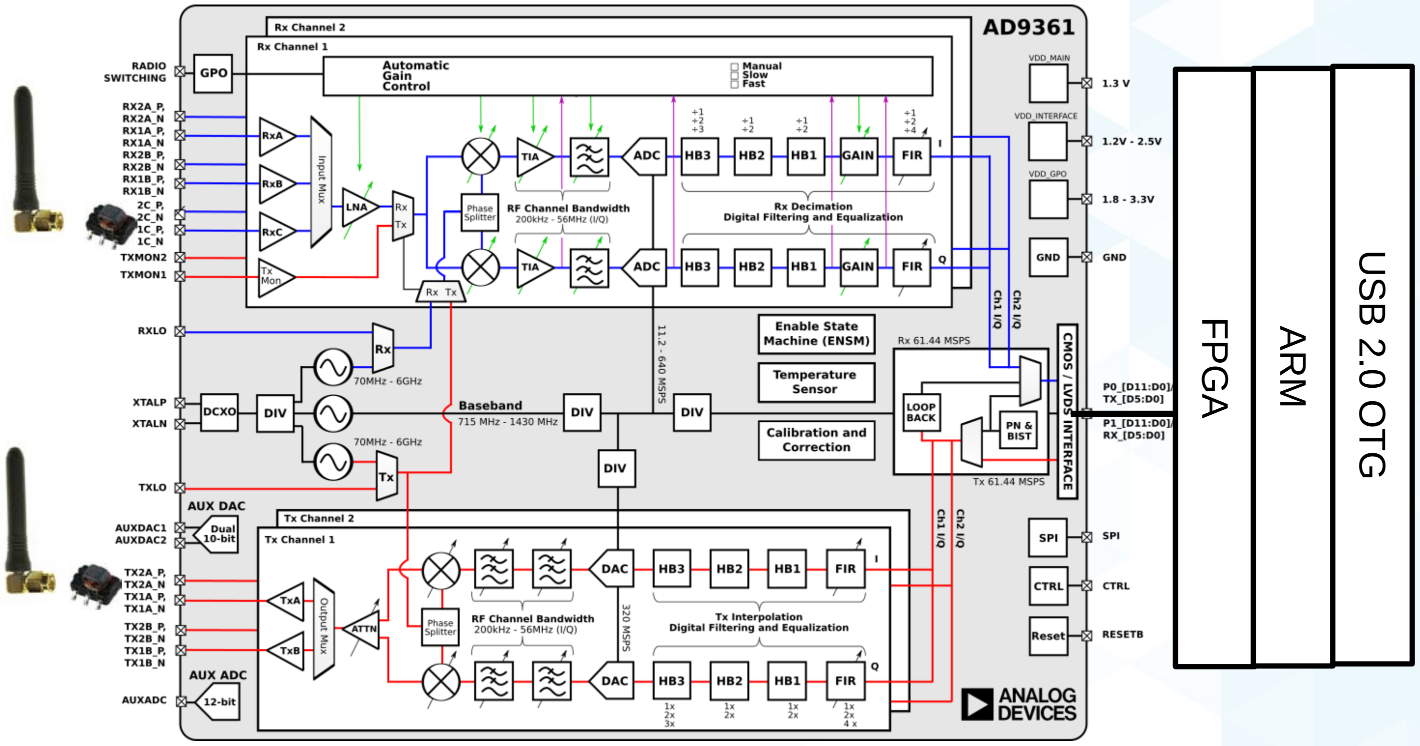


Figure 431. Receiver and Observation Receiver Datapath Filter Implementation

https://www.analog.com/media/en/technical-documentation/data-sheets/ADRV9009.pdf

Transport


AD9361
Rx Channel 2
Rx Channel 1
RADIO SWITCHING
GPO
Automatic Gain Control
Manual
Slow
Fast
RX2A_P, RX2A_N
RX1A_P, RX1A_N
RX2B_P, RX2B_N
RX1B_P, RX1B_N
2C_P, 2C_N
1C_P, 1C_N
TXMON2
TXMON1
RxA
RxB
RxC
Tx Mon
Input Mux
LNA
Rx Tx
Phase Splitter
TIA
ADC
HB3
HB2
HB1
GAIN
FIR
RF Channel Bandwidth
200kHz - 56MHz (I/Q)
Rx Decimation
Digital Filtering and Equalization
I
Q
Ch1 I/Q
Ch2 I/Q
RXLO
Rx
70MHz - 6GHz
XTALP
XTALN
DCXO
DIV
Baseband
715 MHz - 1430 MHz
11.2 - 640 MSPS
Enable State Machine (ENSM)
Temperature Sensor
Calibration and Correction
Rx 61.44 MSPS
LOOP BACK
PN & BIST
Tx 61.44 MSPS
CMOS / LVDS INTERFACE
TXLO
Tx
AUX DAC
AUXDAC1
AUXDAC2
Dual 10-bit
Tx Channel 2
Tx Channel 1
TX2A_P, TX2A_N
TX1A_P, TX1A_N
TX2B_P, TX2B_N
TX1B_P, TX1B_N
TxA
TxB
Output Mux
ATTN
DAC
320 MSPS
Tx Interpolation
Digital Filtering and Equalization
AUX ADC
AUXADC
12-bit
VDD_MAIN
1.3 V
VDD_INTERFACE
1.2V - 2.5V
VDD_GPO
1.8 - 3.3V
GND
P0_[D11:D0]/TX_[D5:D0]
P1_[D11:D0]/RX_[D5:D0]
SPI
CTRL
Reset
RESETB
ANALOG DEVICES
FPGA
ARM
USB 2.0 OTG

Transport

ADALM-PLUTO

MHz	MSPS	MB/s single channel	MByte/s (I/Q)	External Memory (Mbytes)	Seconds of RF Data in Memory
56	61.44	122.88	245.76	128	0.521
18	30.72	61.44	122.88	128	1.042
9	15.36	30.72	61.44	128	2.083
4.5	7.68	15.36	30.72	128	4.167
2.25	3.84	7.68	15.36	128	8.333
.200	0.520	1.04	2.08	128	61.44

512 MBytes on Pluto SDR

Linux kernel continuous memory allocator; 128MBytes for Tx, and 128MBytes for Rx

Takes about ~4 seconds to transfer 128 Mbytes over USB 2.0

480 Mbps * 8/10 / 8bits/byte = 48 MB/s

48 Mbytes/s * USB overhead * libiio overhead = ~ 32 MB/s

USB 2 is half duplex, so full duplex is ½ the datarate

Transport

ADRV9009-ZU11EG

MHz	MSPS	MB/s single channel	MByte/s (I/Q)	Number of Channels	External Memory (Mbytes)	Seconds of RF Data in Memory
200	245.76	491.52	983.04	1	4096	4.167
200	245.76	491.52	983.04	8	4096	0.520
100	122.88	245.76	491.52	1	4096	8.333
100	122.88	245.76	491.52	8	4096	1.042
56	61.44	122.88	245.76	1	4096	16.667
56	61.44	122.88	245.76	8	4096	2.083

4096 MB (PS) + 4096 MB (PL)
on ADRV9009-ZU11EG

Takes about ~16 seconds to transfer 4096 Mbytes over USB 3.0

PCIe 3.0 / x8 lanes = 7.88 Gbytes/s

Accuracy – significant digits

$$BBPLL\ Clock\ Rate = F_{REF} \times \left[N_{INTEGER} + \frac{N_{FRACTIONAL}}{2088960}\right]$$

$$ADC\ Clock\ Rate = \frac{BBPLL\ Clock\ Rate}{2^{BBPLL\ Divider[2:0](decimal)}}$$

- F_{REF} = Reference Clock Frequency
- $N_{Integer}$ = 8-bit Integer word
- $N_{Fractional}$ = 20-bit Fractional word

- Smallest Step based on 40 MHz Ref Clock
  - 40.0000 MHz * 1/2088960 = 19.15 Hz

- BBPLL Divider is valid from 1 through 6
  - 64 = 0.29919194240196078431372549019608 Hz step size

$$F_{RFPLL} = F_{REF} * \left(N_{Integer} + \frac{N_{Fractional}}{8{,}388{,}593}\right)$$

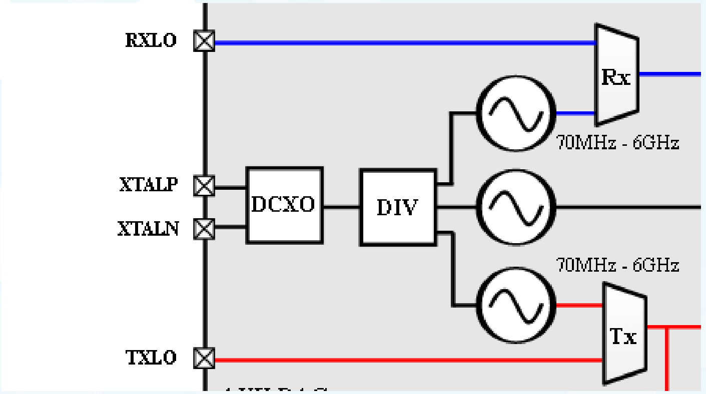
- F_{REF} = Reference Clock Frequency
- $N_{Integer}$ = 11-bit Integer word
- $N_{Fractional}$ = 23-bit Fractional word

- Smallest step based on 40MHz Ref Clock
  - 40.0000 MHz * 1/8,388,593 = 4.7746411170845850353436840390 79 Hz

- 2.400 GHz with a 40.0000 MHz Ref clock is integer $N_{Integer}$ (60) and $N_{Fractional}$ (0).
- 2.400 GHz with a 39,999,898 Hz REF CLK, is not possible.
  - $N_{Integer}$ (60) and $N_{Fractional}$ (1283.45)
  - $N_{Integer}$ (60) and $N_{Fractional}$ (1283) = 2,399,999,997.816079
  - $N_{Integer}$ (60) and $N_{Fractional}$ (1284) = 2,400,000,002.584447

Stability

- Accuracy
  - The degree of conformity of a measured or calculated value to some specified value or definition
- Initial accuracy
  - Due to manufacturing tolerance
    - Can be calibrated out (initial settings)



- Aging
  - The change in frequency with time due to internal changes in the oscillator.
- Drift
  - The change in frequency with time that one observes in an application.
- Temp
  - The change in frequency with time that one observes due to temperature changes.
    - Is very repeatable between runs

$$\Delta T = \frac{1}{2} a t^2$$

ΔT = Time Error
a = aging
t = Elapsed Time

- Doppler shift due to mobility $f_D = \frac{v_r f}{c} \cos \alpha$;
  - 6 GHz LO, 150 kph = 0.139 ppm offset
  - 1 GHz LO, 450 kph = 0.417 ppm offset

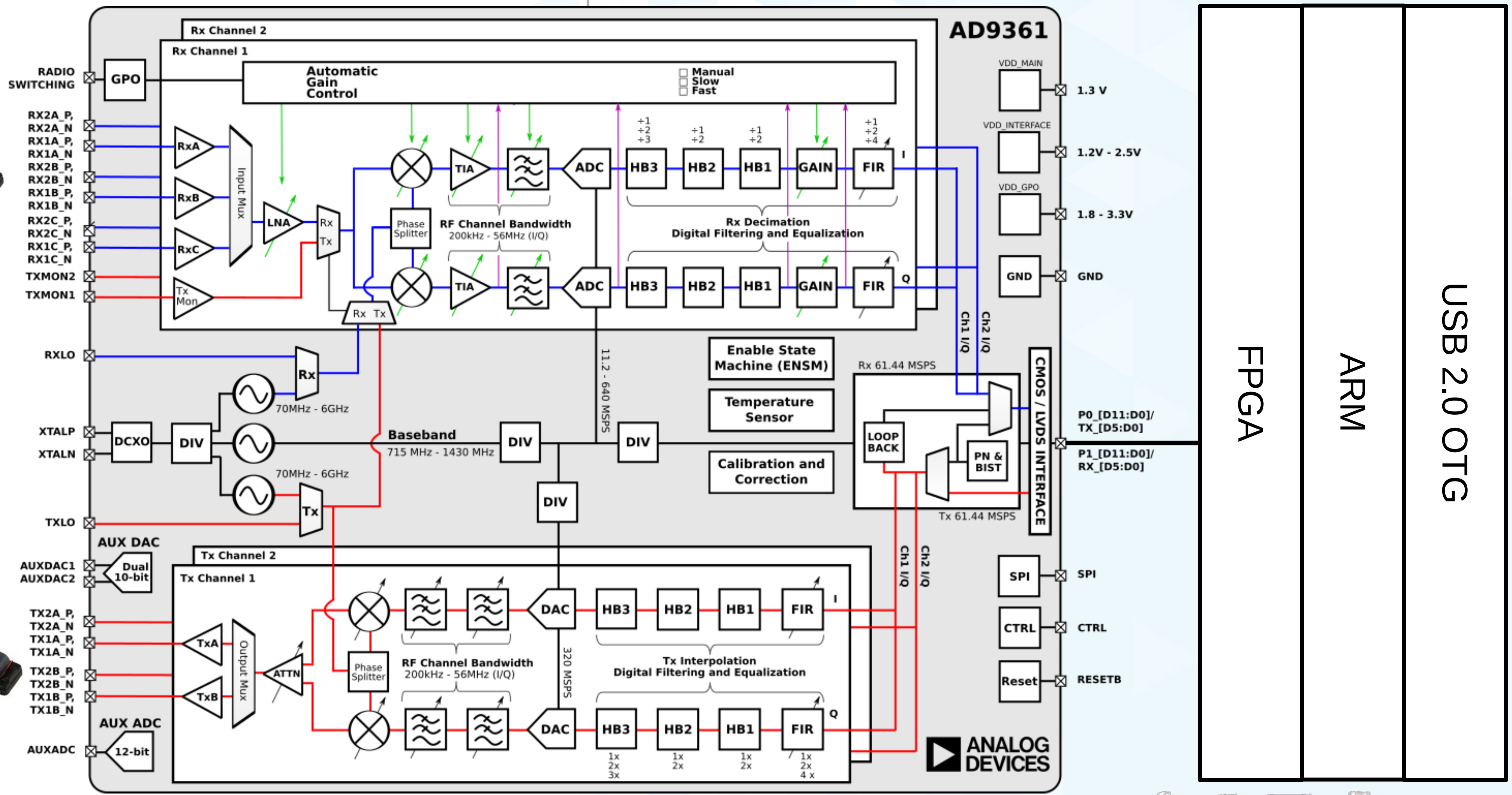
v_r is the relative speed between the transmitter and the receiver
f is the carrier frequency
α is the angle of the velocity vector
c is the speed of light

Accuracy - Magnitude

Rx

PCB Component frequency wide turning range (70 – 6000 MHz)
(Close to datasheet specs)

Tx



Accuracy - Magnitude

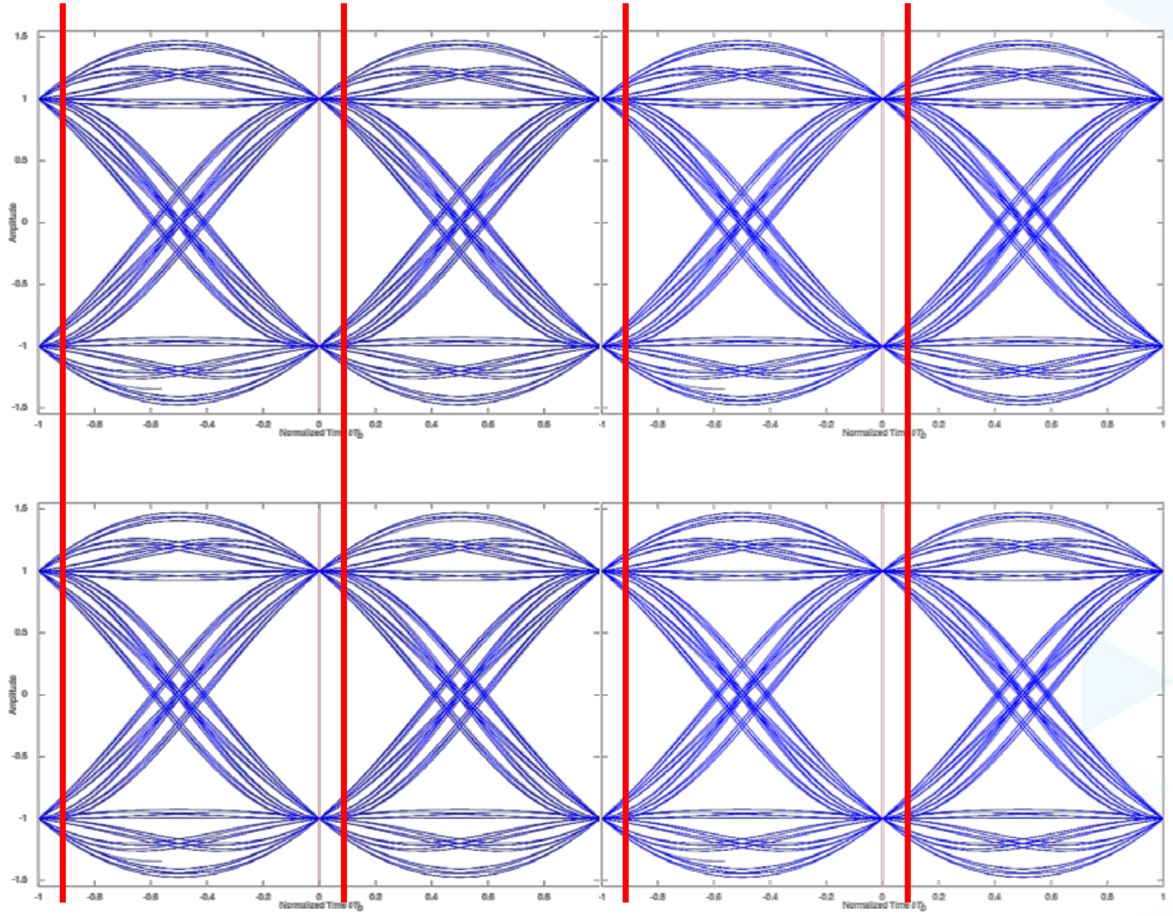
- dBm
  - sometimes dB_{mW} (or decibel-milliwatts) is unit of level used to indicate that a power ratio is expressed in decibels (dB) with reference to one milliwatt (mW)
- dBFS
  - Power ratio with respect to full-scale (whatever that is)
- dB
  - ratio with respect to something

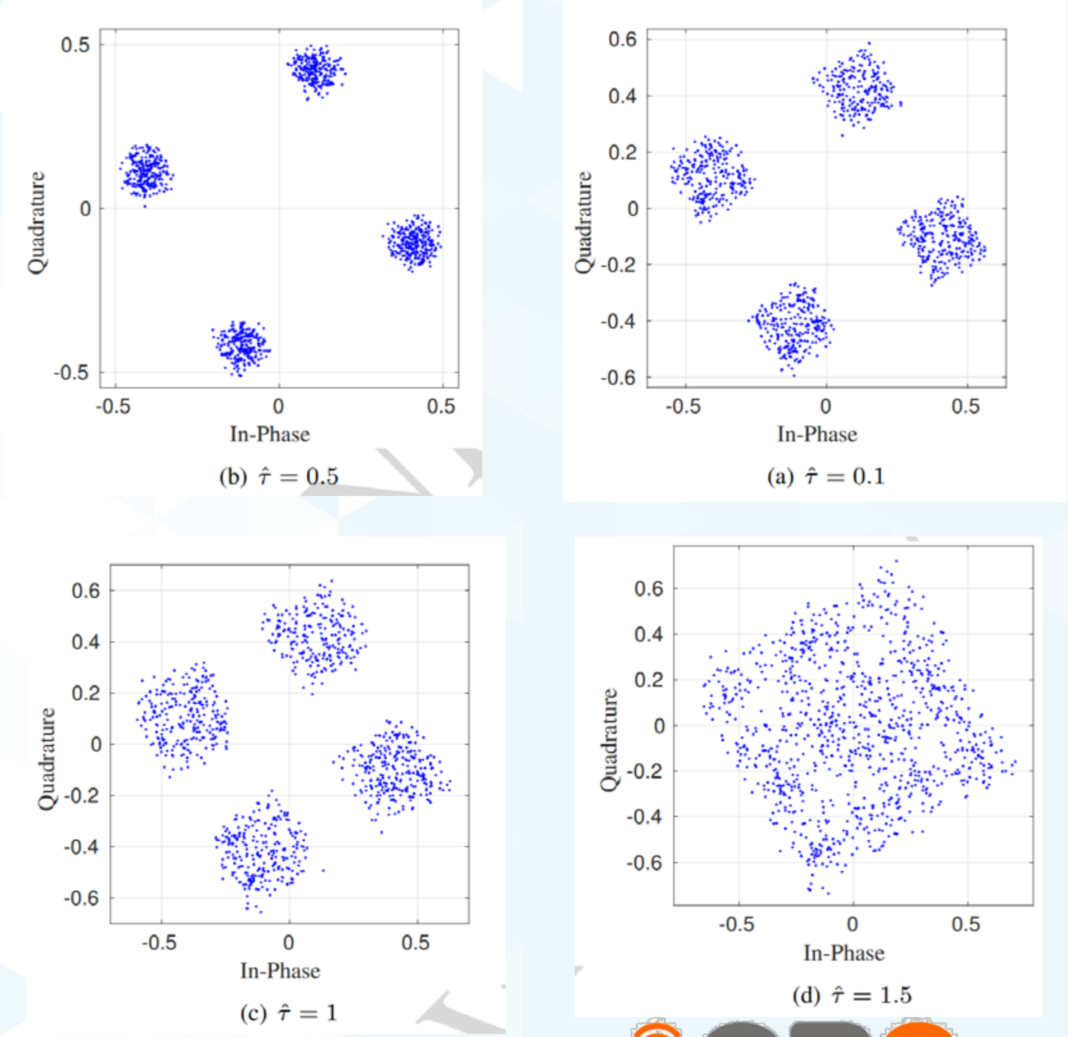
- Factory calibrations are necessary to limit the amount of variation seen across a large quantity of circuit boards.
- Some calibrations are used to increase the accuracy of the device, while others are needed to calibrate non-linearities of external components in the RF front-end.

	(Your) Factory Calibration
1	Internal DCXO (AFC tune range)
2	TX RSSI (TX Monitor)
3	RX RSSI (Absolute Power Correlation)
4	RX GM / LNA Gain Step Error
5	TX Power out Vs TX attenuation
6	TX Power out Vs Frequency

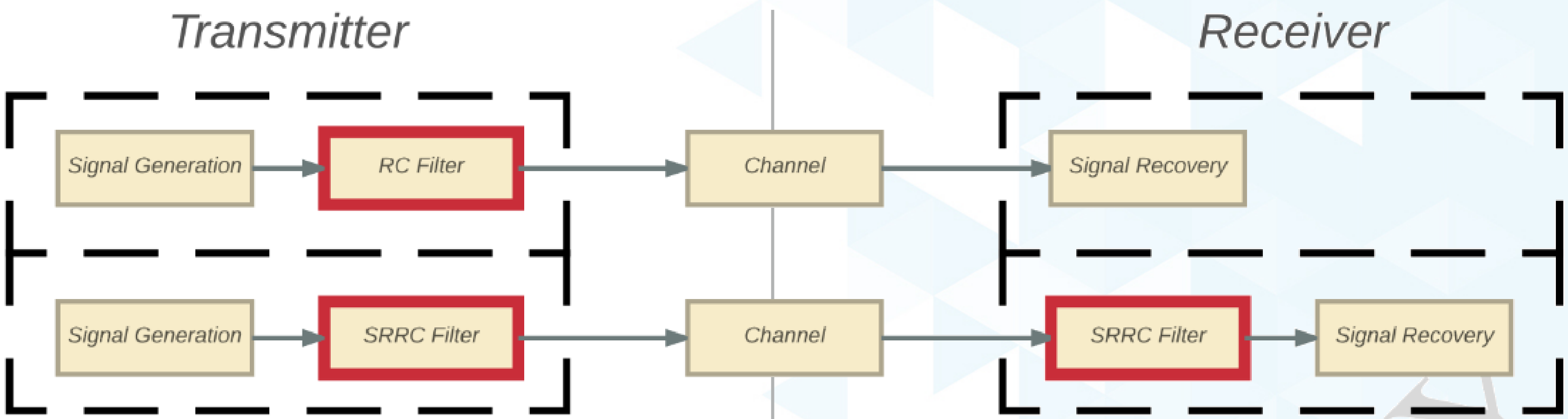
Samples -> Symbols

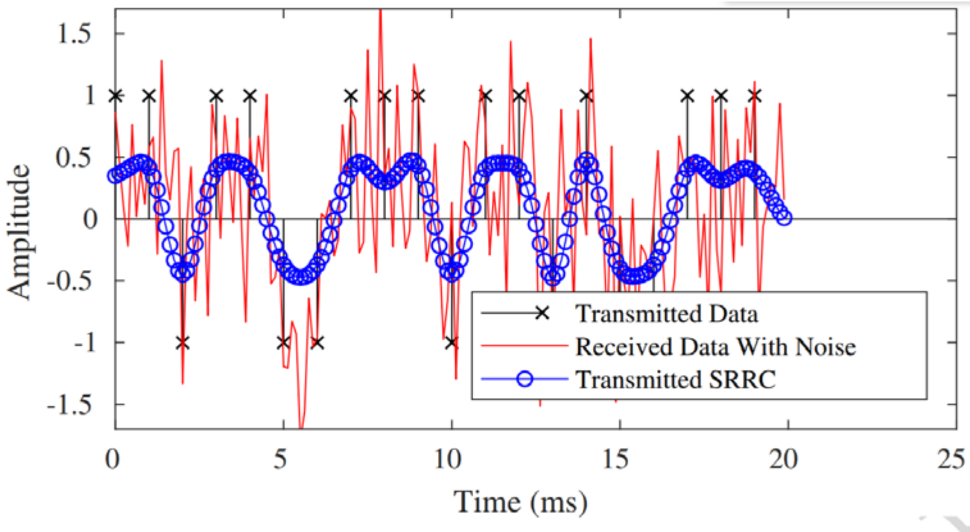
Sampling at the right time



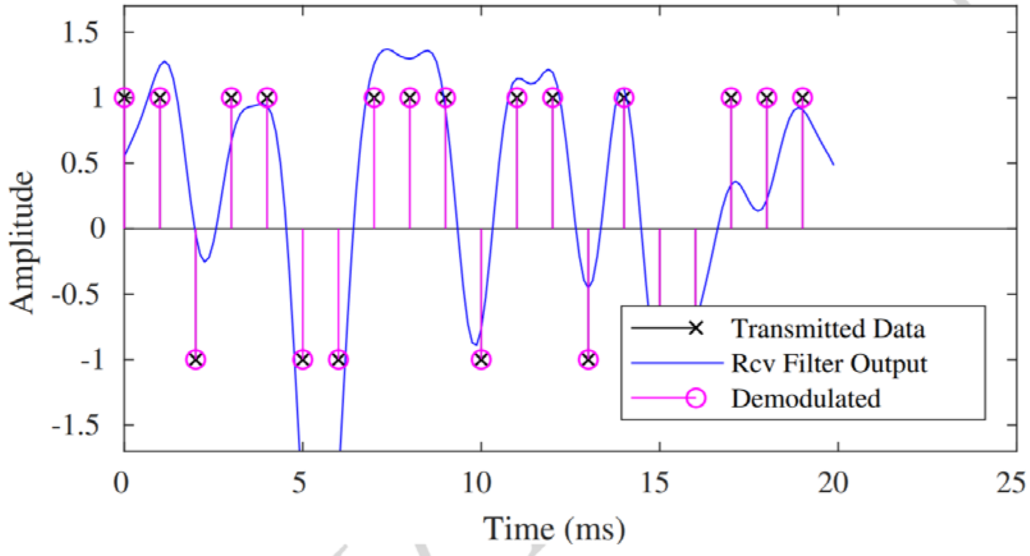


Sampling at the right time





(a) Transmitted SRRC filtered signal



(b) Received SRRC filtered signal

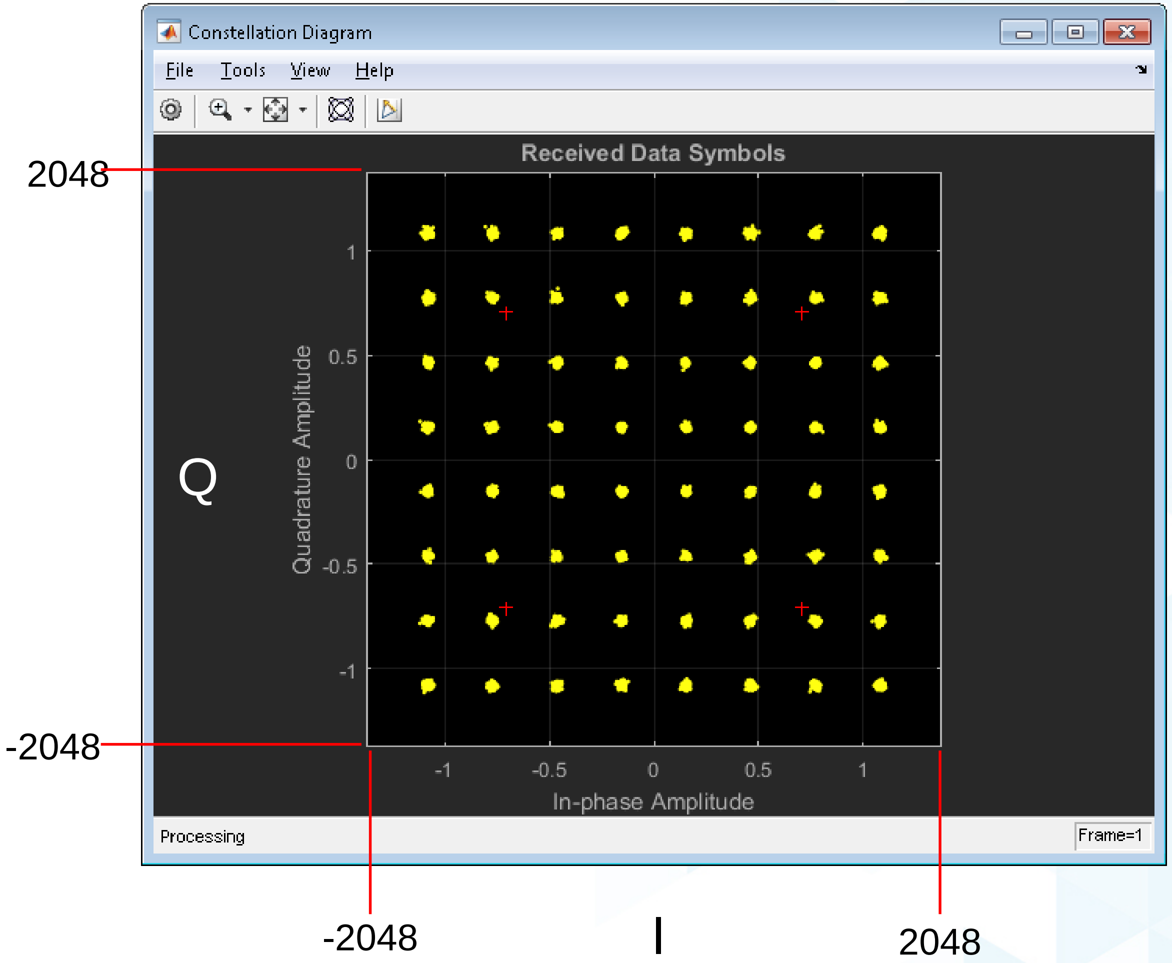
Samples -> Symbol

Modem controls:

8 Samples = 1 Symbol

4 Samples = 1 Symbol

2 Samples = 1 Symbol



QAM64 : 1 Symbol = 16 bits out

QAM16 : 1 Symbol = 8 bit out

QAM4 : 1 Symbol = 4 bits out

Error Correction Coding

- Shannon's channel capacity theorem sets an absolute limit on the best performance in a band-limited channel
- Additional bits can be added to a symbol to give it redundancy.
- This redundancy can decrease the probability of error of the system in exchange for reducing the information rate through the system.
- Additional gain can be found if the demodulator includes a certainty metric along with the data decision (soft decision).
- Optimally, the modulated waveform will contain redundancy as well which can also be extracted – e.g., MSK, CPM.

- Raw bits/second (including overhead) vs payload bits/second (excluding overhead)

Thanks

Conclusion

- Mathematics (numbers, units and equations) serves as a universal language through which scientists and engineers from around the world can communicate.

- It only works when we are all clear (use units, use significant figures, use adjectives) in our work