SDR – Software Defined Radio

from Theory to Practice

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SDR-course.com

BMR2017 – Broadcast, Mobile, RF
10:30 April 27, 2017, Hertzlia, Israel

Preface

A relatively new SDR tool for evaluation and design of diverse radio communications techniques is presented.

The SDR tool supports the whole range from setting-up and analyzing a Tx-Channel-Rx chain, up-to operating the above with real-time firmware.

In addition, this tool may be used for education, with emphasis on illustrating the material on a platform that allows viewing and measuring signal parameters, and sensing the effects of varying the modulation parameters.

Outline

- I - Introduction and a historical perspective
- II - SDR Architectures
- III - The SDR-RTL based platform
- IV - Analog Communications – an FM Demo
- V - Digital Communications – an APSK Demo
- VI - Conclusion

SDR Definition

Software-defined radio is a radio communication system where components that have been implemented in hardware (mixers, filters, amplifiers, modulators/demodulators, detectors, etc.) are instead implemented by means of **software on a computer or embedded system.**

Software Defined Radio

- ► TRW (Gold Room “digital radio” lab) 1970
- ► E-Systems (now Raytheon) coins “SW Radio” 1984
- ► SPEAKeasy (DARPA): Software Defined Radio (SDR) 1991
- ► Joseph Mitola in IEEE, 1992
- ► SDR Forum 1996, JTRS (US DoD) 1997, Automated code generation (1998), GNU Radio 2001 (Linux)
- ► TI & Xilinx lead developing a platform (DSP, FPGA, ARM) 2006, Lime Micro Systems develops an RFIC front-end 2009
- ► Realtek, Matlab – RTL-SDR I/F (DAB+FM 2010, DTV-T 2012)

SDR Vision

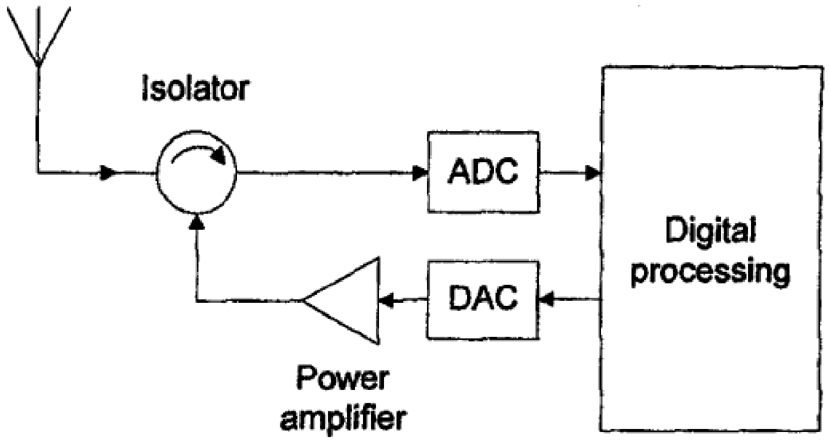
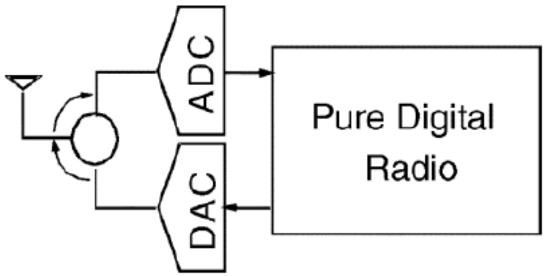


Fig. 1. Software-defined radio, as envisioned by Mitola [1]. This would be the ultimately flexible device for wireless communication.



Classic SDR as defined by Mitola

A. A. Abidi, "The Path to the Software-Defined Radio Receiver," *IEEE Journal of Solid-State Circuits*, Vol.42, No. 5, May 2007.

[1] J. Mitola, "The software radio architecture," *IEEE Commun. Mag.*, vol. 33, no. 5, pp. 26–38, May 1995.

What Is a Software Defined Radio?

- Software defined radio (SDR): This is the term adopted by the SDR Forum.
- Multi-standard terminal (MST): a terminal which is capable of operation on a number of differing air interface standards.
- Reconfigurable radio: both software and firmware reconfiguration.
- Flexible architecture radio (FAR): a wider definition than those above. This is clearly an utopian goal for the software radio.

Operational Requirements - Key Requirements

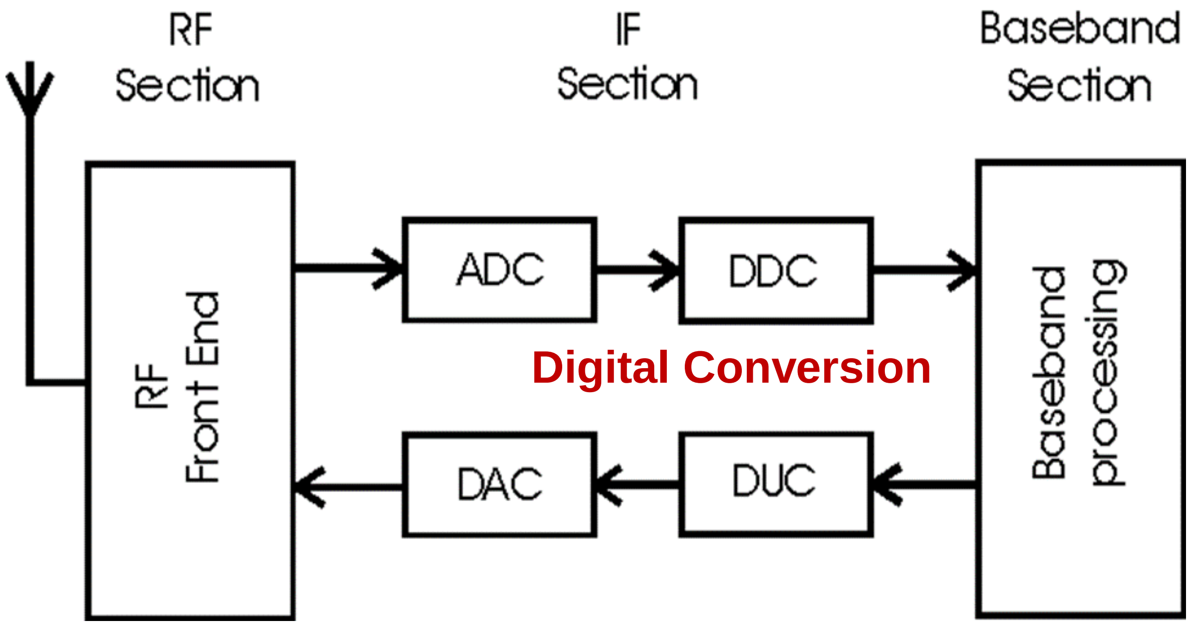
- Software-Definable Operation
  - Ability to be reconfigured: during manufacture, prior to purchase, following purchase, and in operation. This impacts primarily the digital and baseband sections of the terminal and will require the use of reprogrammable hardware as well as programmable digital signal processors in a power and cost-effective implementation.
- Multi-Band Operation
  - The ability to process signals corresponding to a wide range of frequency bands and channel bandwidths.
- Multi-Mode Operation
  - The ability to change mode and, consequently, modulation, coding, burst structure, compression algorithms, and signaling protocols.

II - SDR Architectures

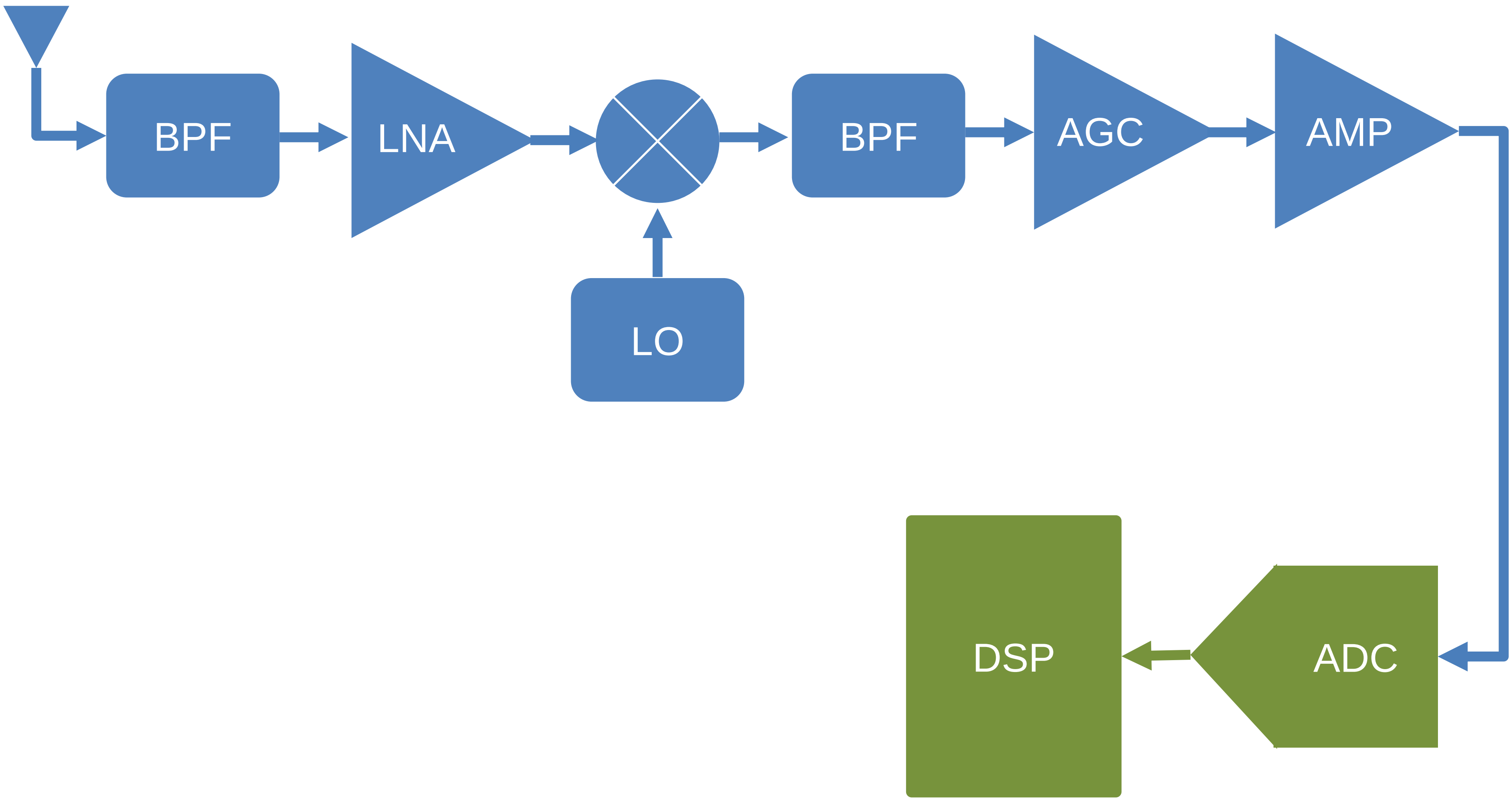
- Employ as few as possible broadband RF parts
- Digitize as close to the antenna as possible
- Employ discrete-time signal processing by HW and SW
- HW and SW - reconfigurable

Software Defined Radio

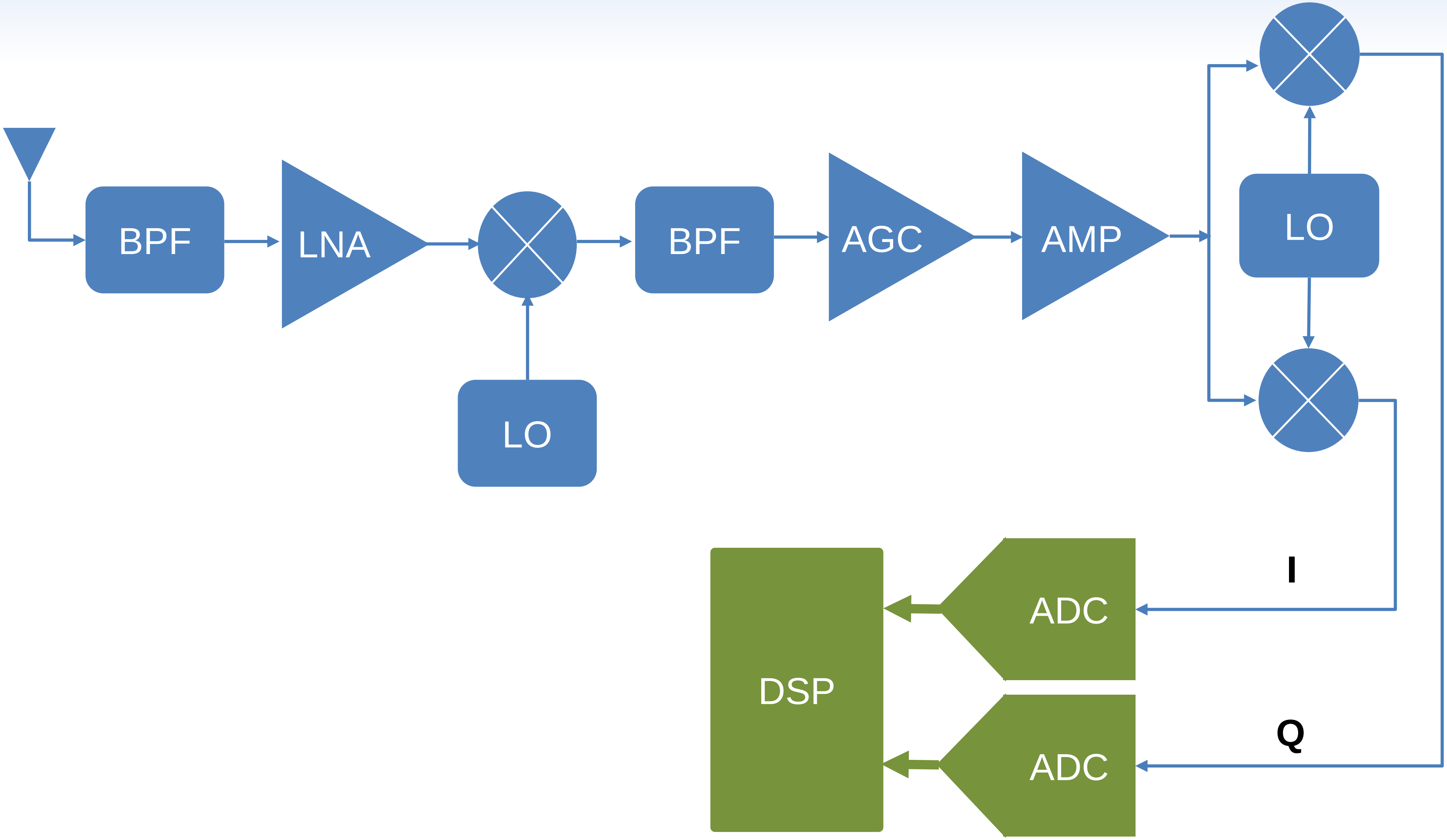
- Rx Signals are digitized immediately after the LNA and then processed entirely in software, flexible
- Tx vice versa



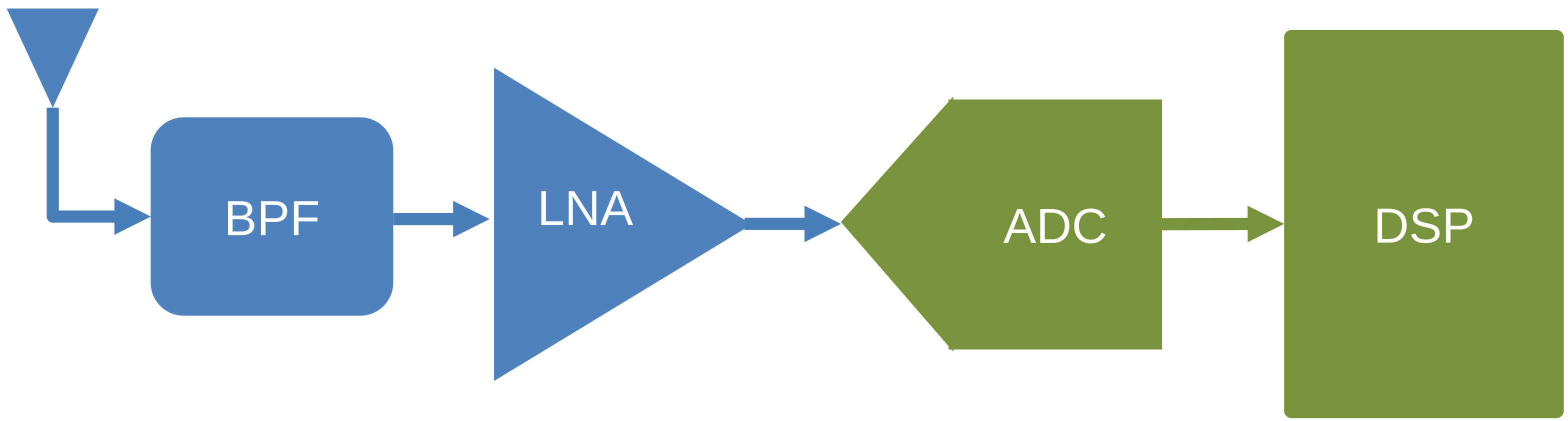
SDR Architectures-Digital IF



SDR Architectures-Digital Baseband

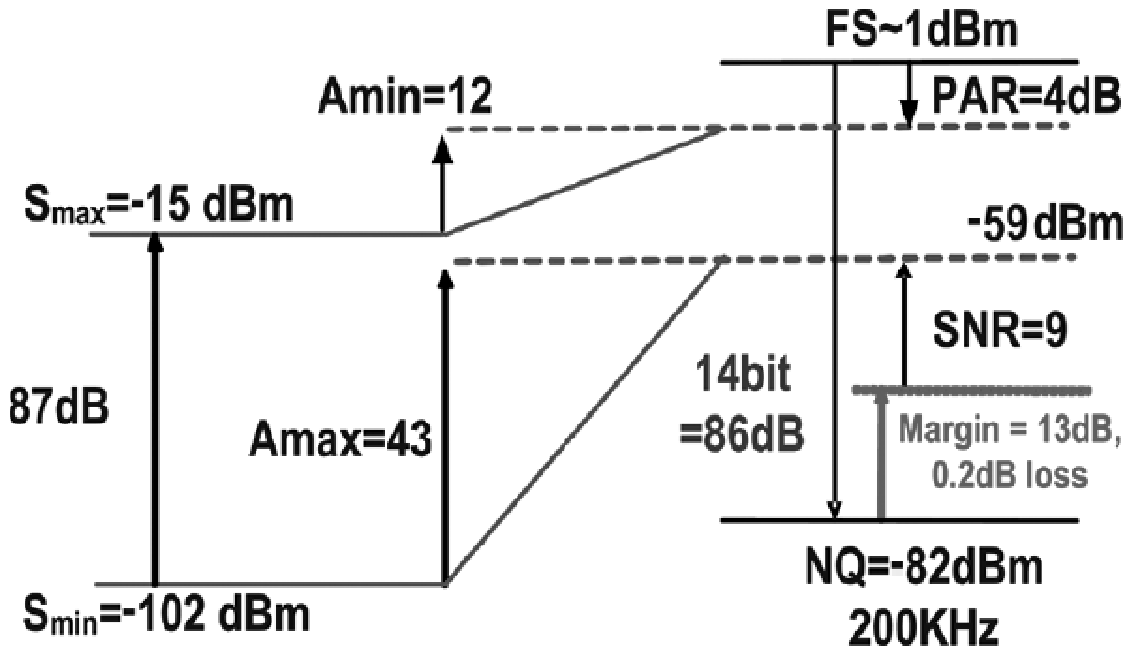


SDR Architectures-Future SDR



An Example - SW Radio Design

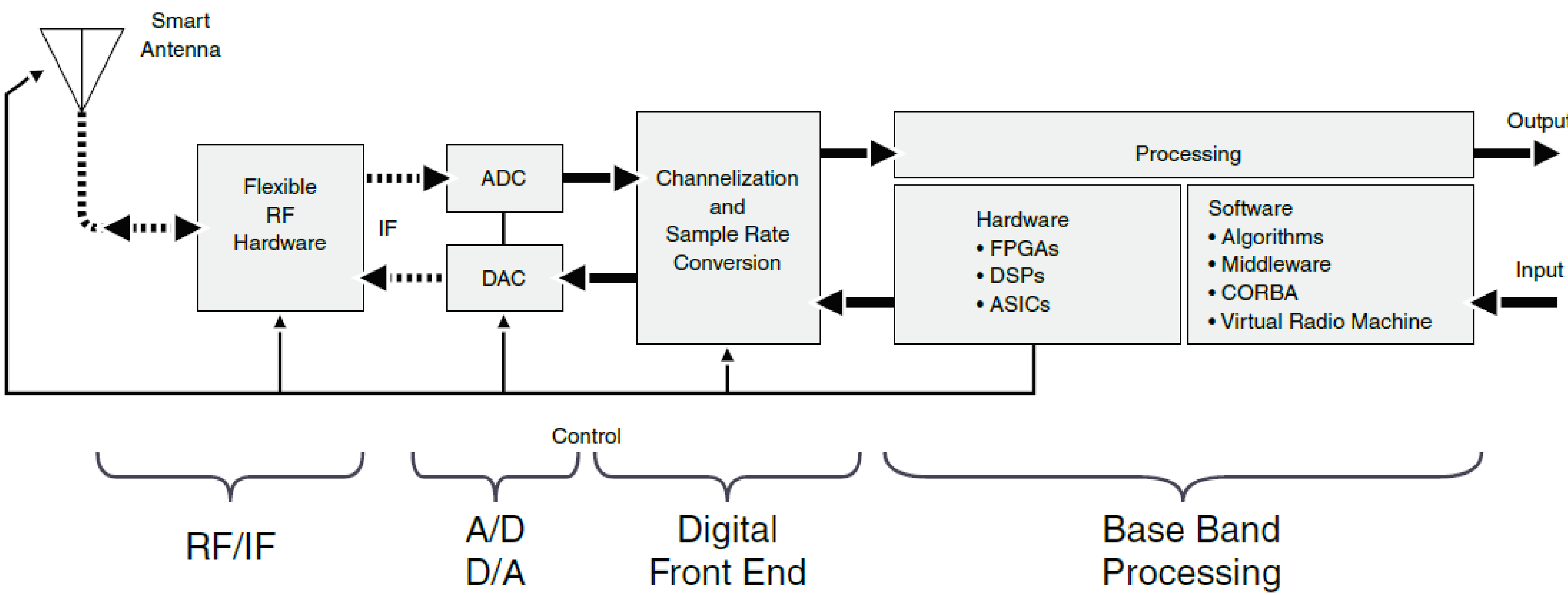
- Signal, Gain and Noise Levels for a GSM SDR:



[ABIDI, 2007]

- FE Noise >> ADC Noise

The SDR Tx-Rx Concept Block Diagram

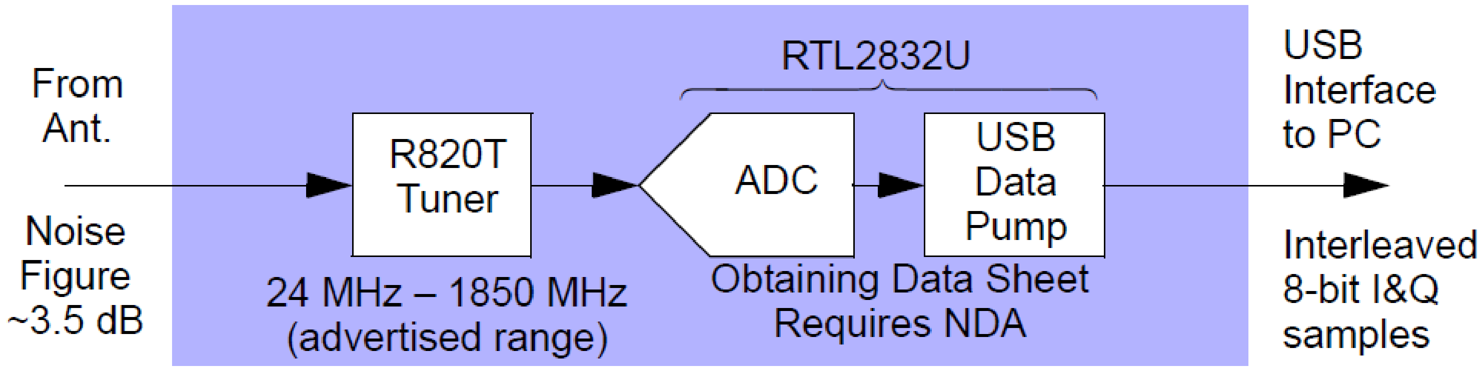


The SDR transceiver concept in block diagram form.

III - The SDR-RTL based platform

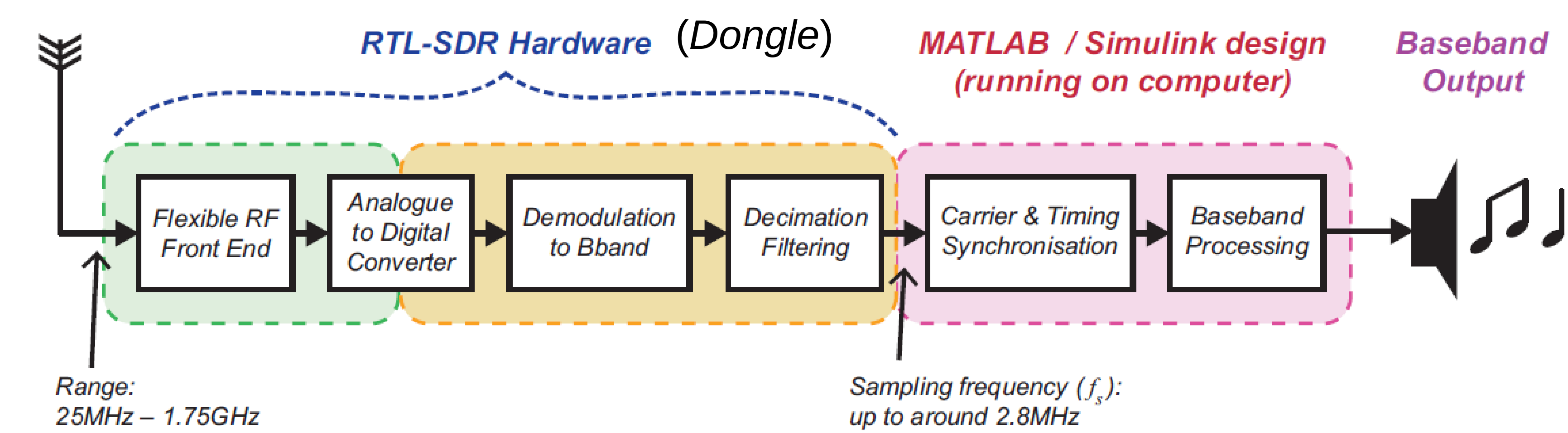
- WINTEL Platform (Windows +Intel processor)
- An RF FE (Gain, AGC, Frequency) incl. ADC
- A USB I/F to PC
- Matlab-Simulink with RTL toolbox block
- Frequency settable in 27 – 1700 MHz range
- Maximum 2.8MS/s per I or Q

The SDR Dongle Block Diagram (1)



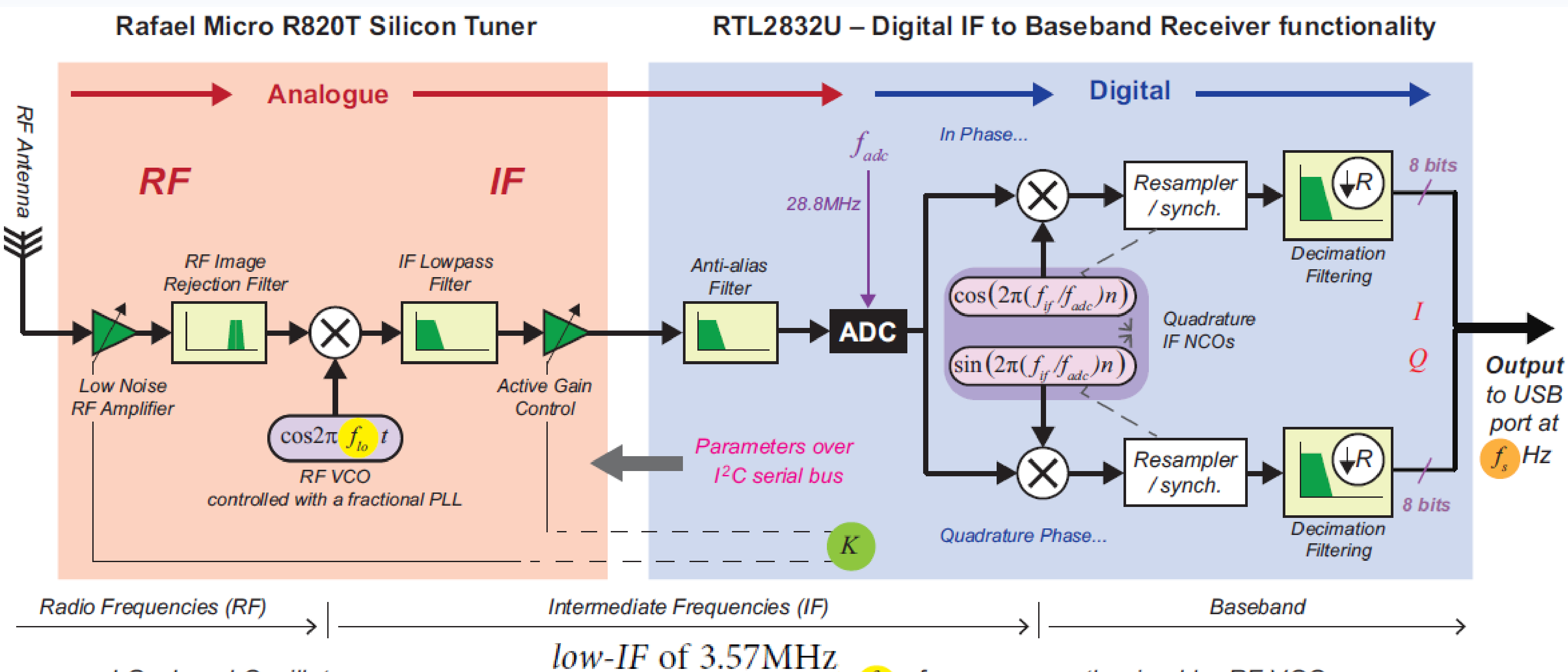
The RTL-SDR high level block diagram.

B. Stewart, K. Barlee, D. Atkinson, L. Crockett "Software Defined Radio," Strathclyde Academic Media, 2015.



Block diagram of the RTL-SDR receiver chain.

The RTL-SDR Dongle Block Diagram (2)



LO - Local Oscillator

NCO - Numerically Controlled Oscillator

PLL - Phase Locked Loop

RF - Radio Frequency

VCO - Voltage Controlled Oscillator

f_{lo} - frequency synthesised by RF VCO

f_{adc} - sampling rate of ADC (28.8MHz)

f_{if} - intermediate frequency

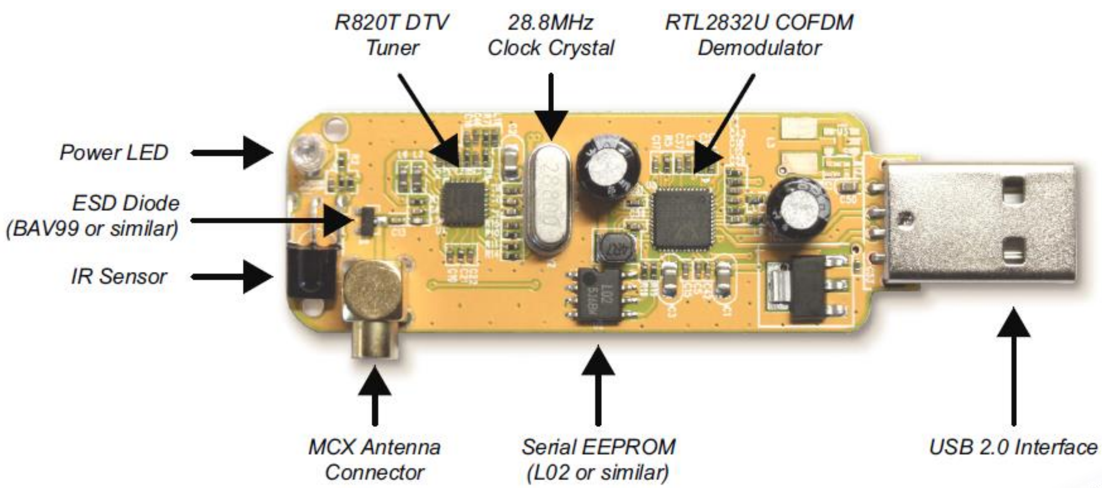
f_s - frequency of output IQ samples (up to 2.8MHz)

K - gain of RF amplifiers

n - discrete sample index

B. Stewart, K. Barlee, D. Atkinson, L. Crockett "Software Defined Radio,"
Strathclyde Academic Media, 2015.

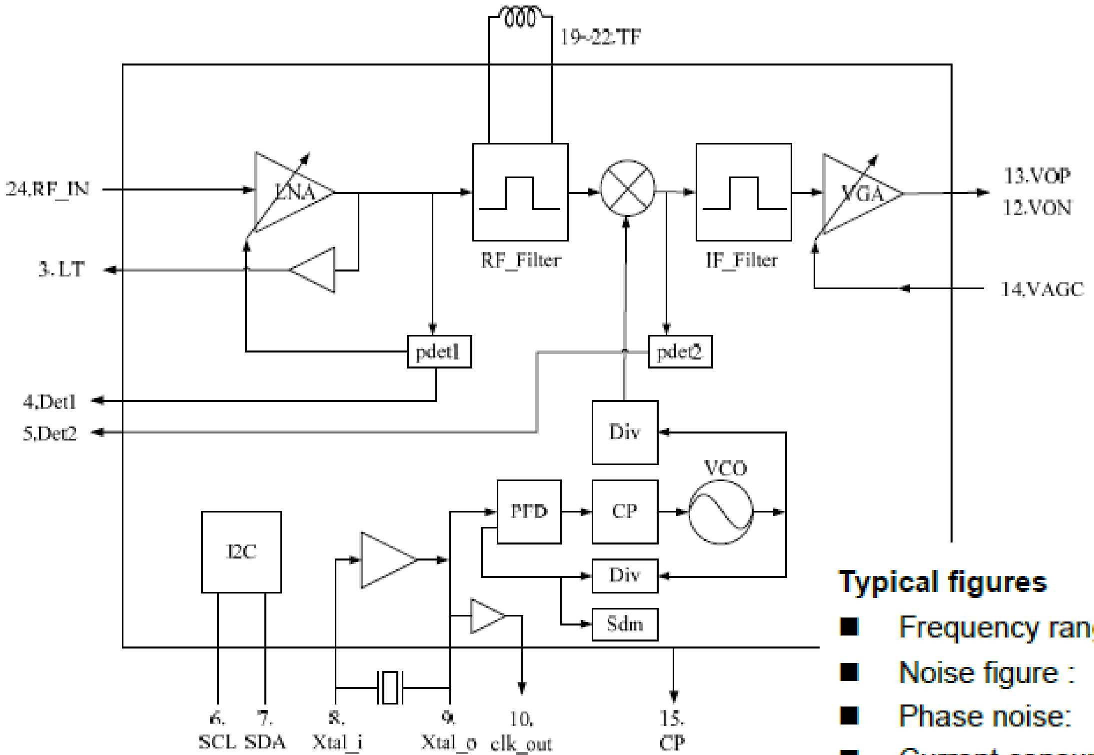
The RTL-SDR


R820T DTV Tuner
28.8MHz Clock Crystal
RTL2832U COFDM Demodulator
Power LED
ESD Diode (BAV99 or similar)
IR Sensor
MCX Antenna Connector
Serial EEPROM (L02 or similar)
USB 2.0 Interface


NooElec.com
NooElec

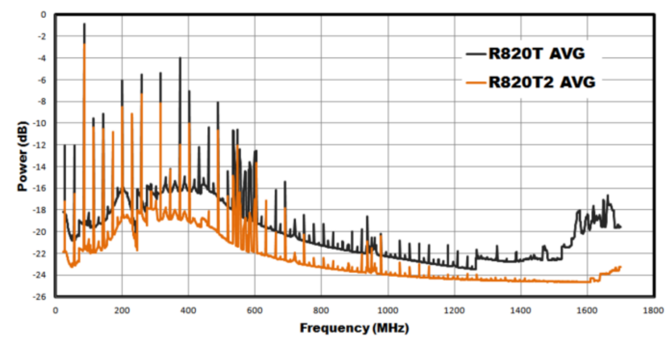

NooElec

The RTL-SDR RF Front-End



Simplified R820T Block Diagram

Rafael Micro **R820T**



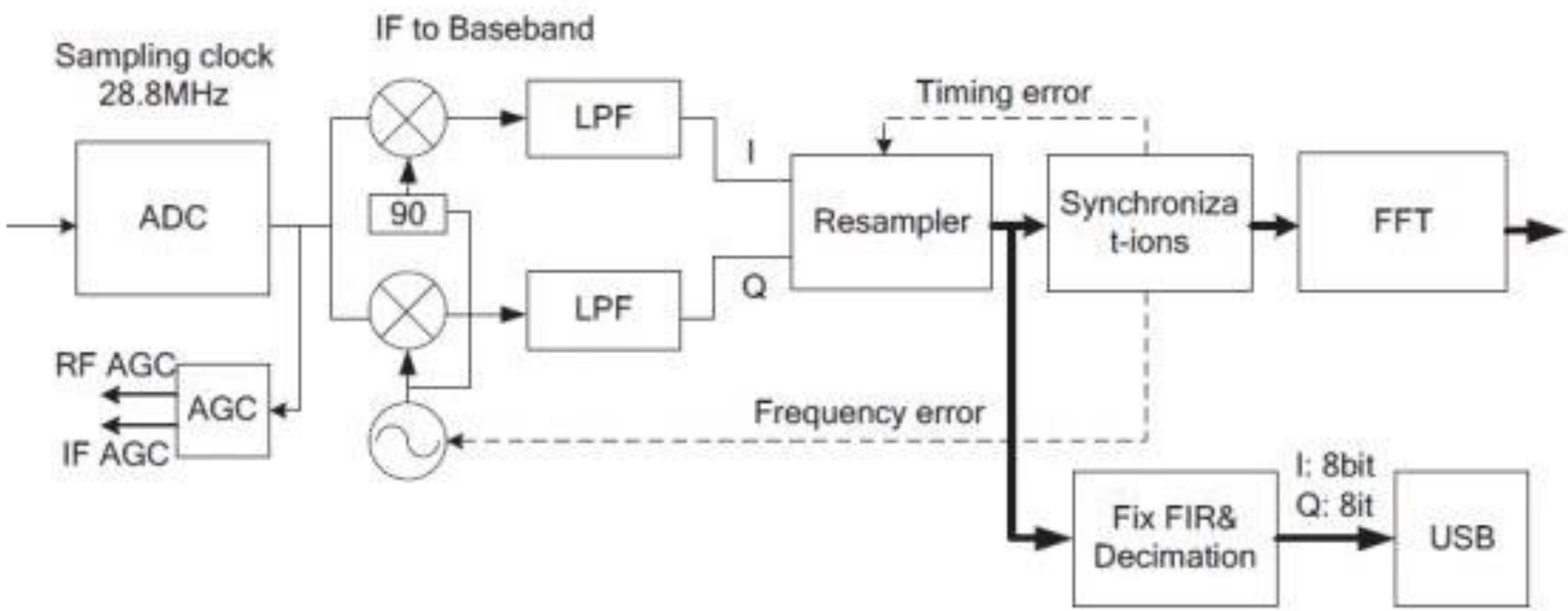
Typical figures

- Frequency range: 42 to 1002 MHz
- Noise figure : 3.5 dB @ RF_IN
- Phase noise: -98 dBc/Hz @ 10 kHz
- Current consumption: <178 mA @ 3.3V power supply
- Max input power: +10 dBm
- Image rejection: 65 dBc

note: [dBm]=[dBuV on 75Ω] -108.75dB

SDR IF to Baseband

- ►IF to baseband processing (in RTL2832U)



- ►Down conversion into I and Q is performed digitally.

Acknowledgement

Albert Profis

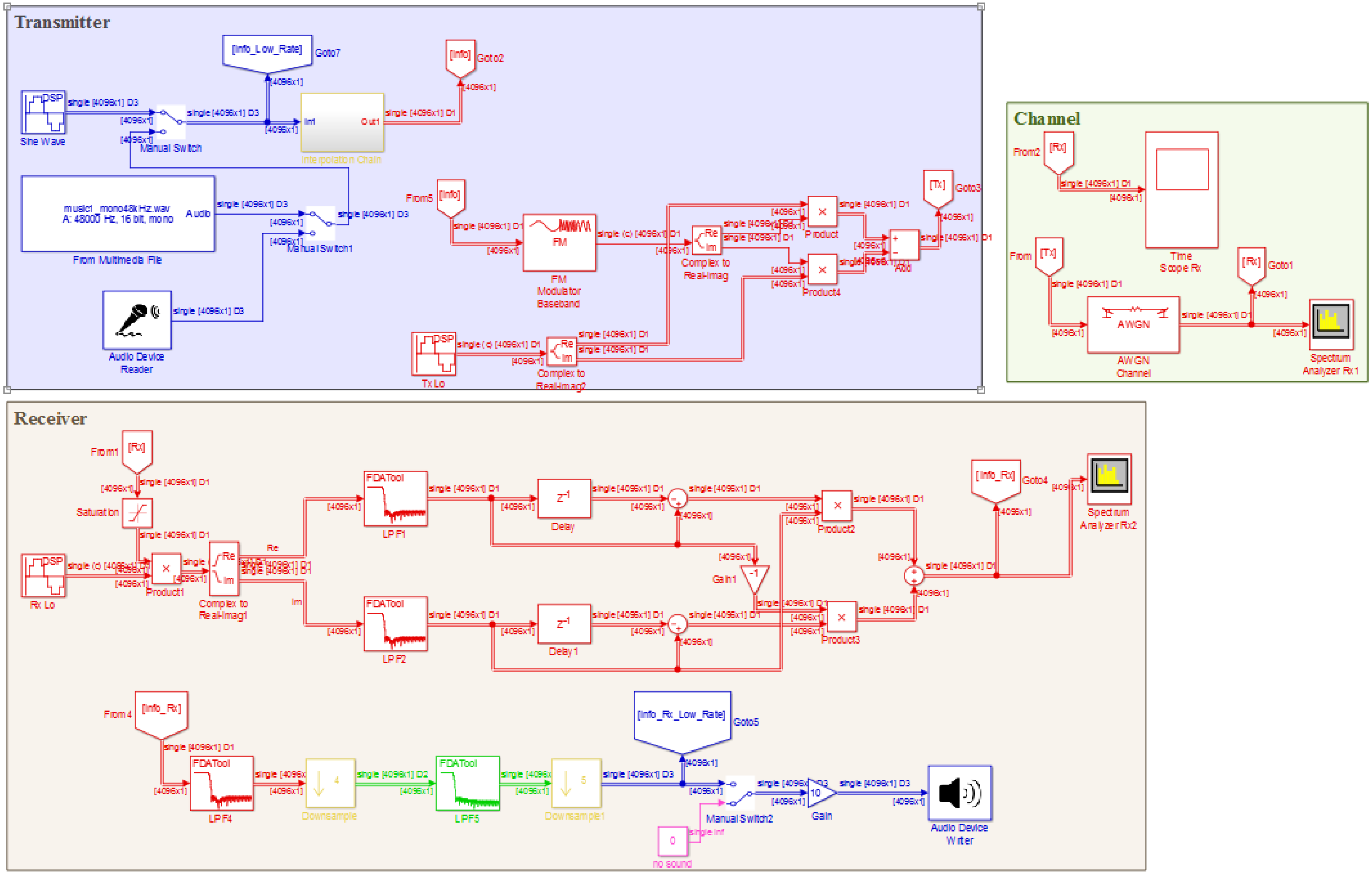
who will be demonstrating the Simulink cases hereafter, had a major role in developing the SDR Course Simulink modulation cases, and much contributed to the Examples that will be demonstrated here - now.

IV - Analog Communications – an FM Demo

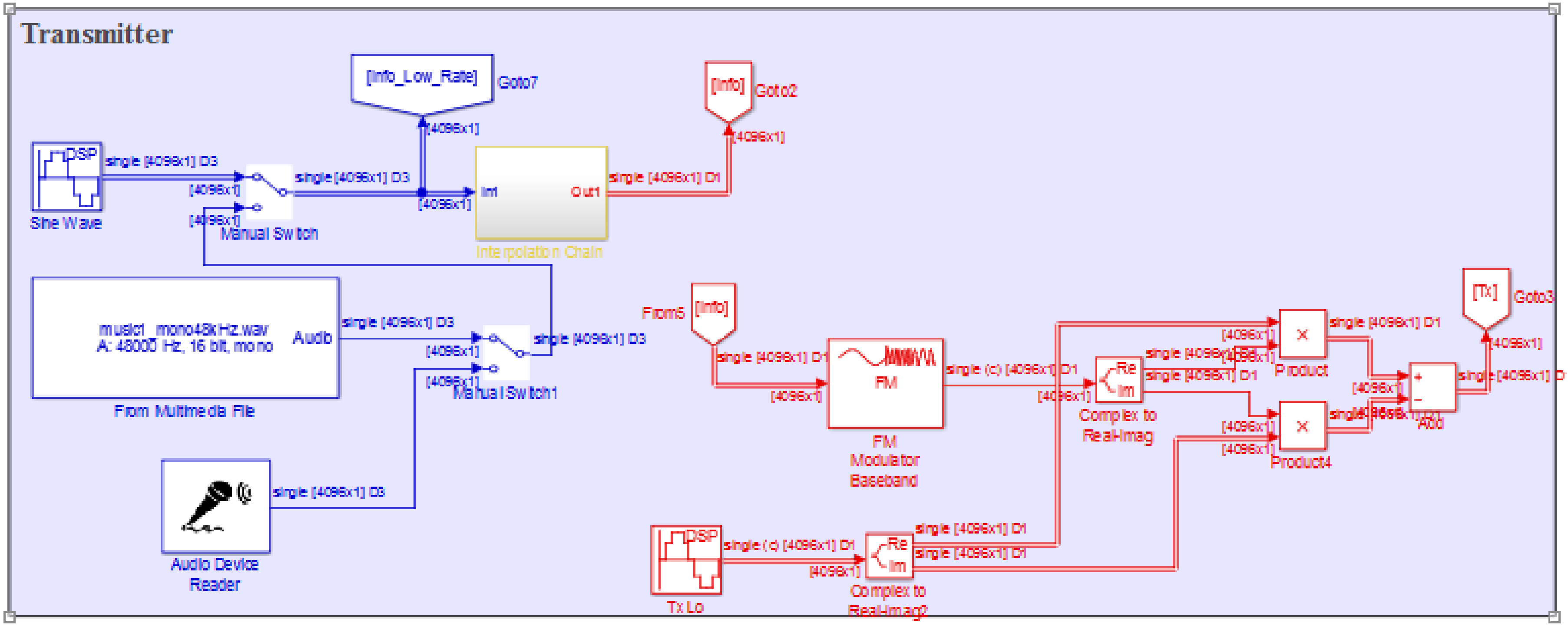
- Transmit an FM (*Frequency Modulated*) signal.
- The signals' parameters are $W\ (f_m)$, Δf and β.
- In the channel add white Gaussian noise (AWGN).
- Receive the corrupted modulated signal by:
  - Tuner front-end (if receiving wirelessly)
  - Discriminator – an approximate realization of a time – differentiator
  - After LPF – direct to speaker, etc.
- In addition, show and use spectrum analyzer, oscilloscope.
- FM signal equation:

$$x(t) = A_0 \cos\left[2\pi f_0 t + 2\pi\Delta f \int_{-\infty}^{t} s(\tau)d\tau \right]$$

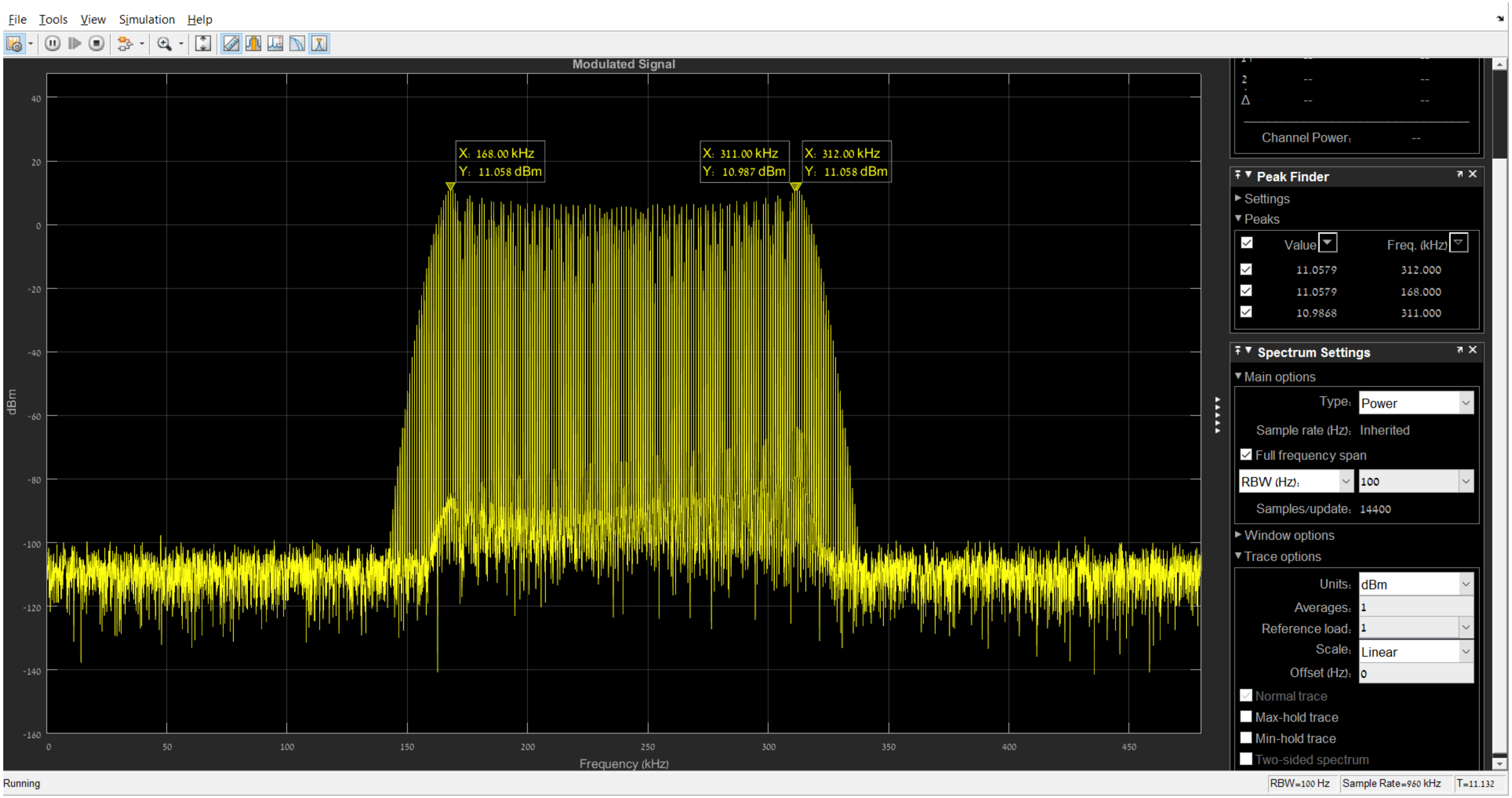
FM Communications - Overall Block Diagram



FM Communications - Transmitter

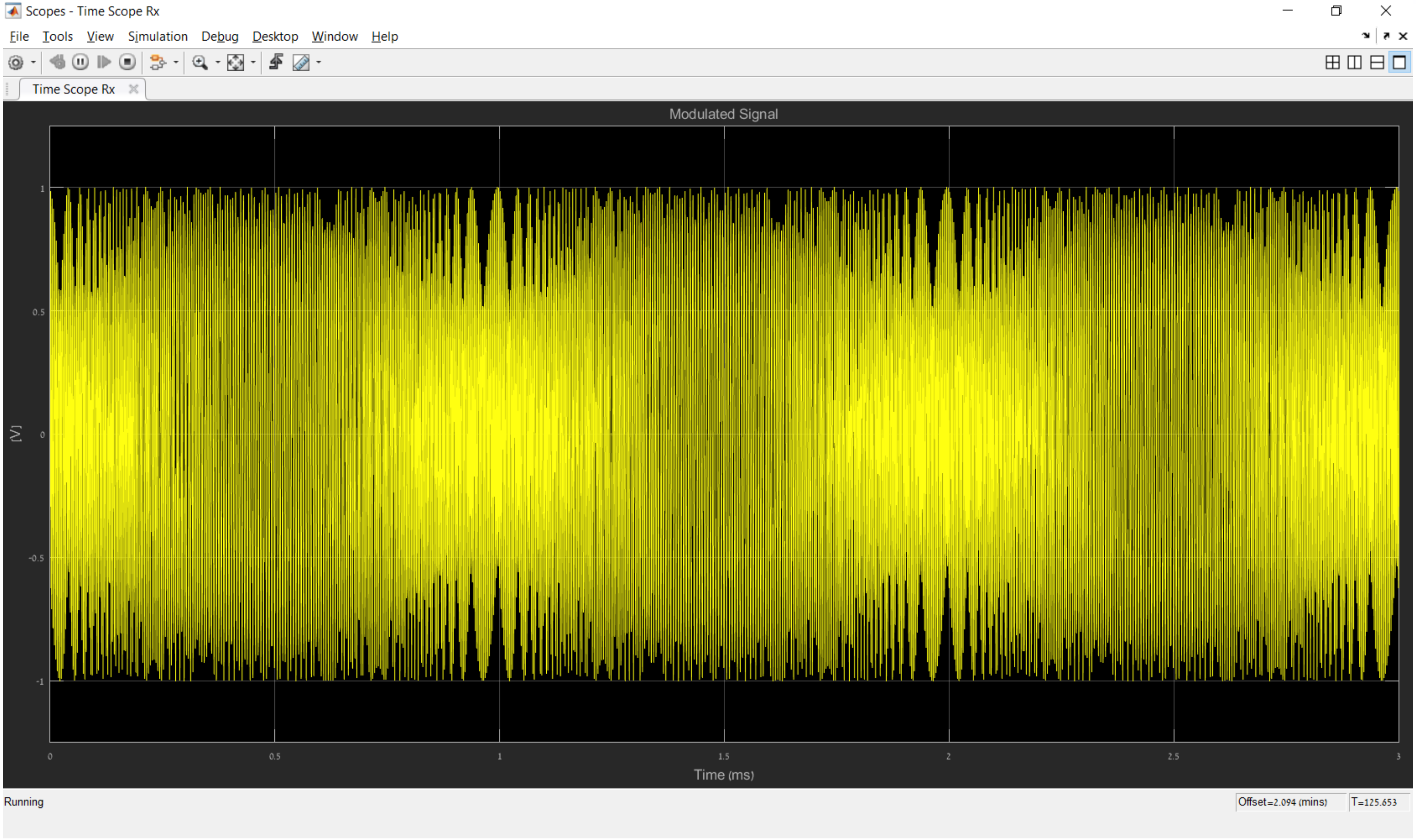


FM Communications – Tx Spectrum

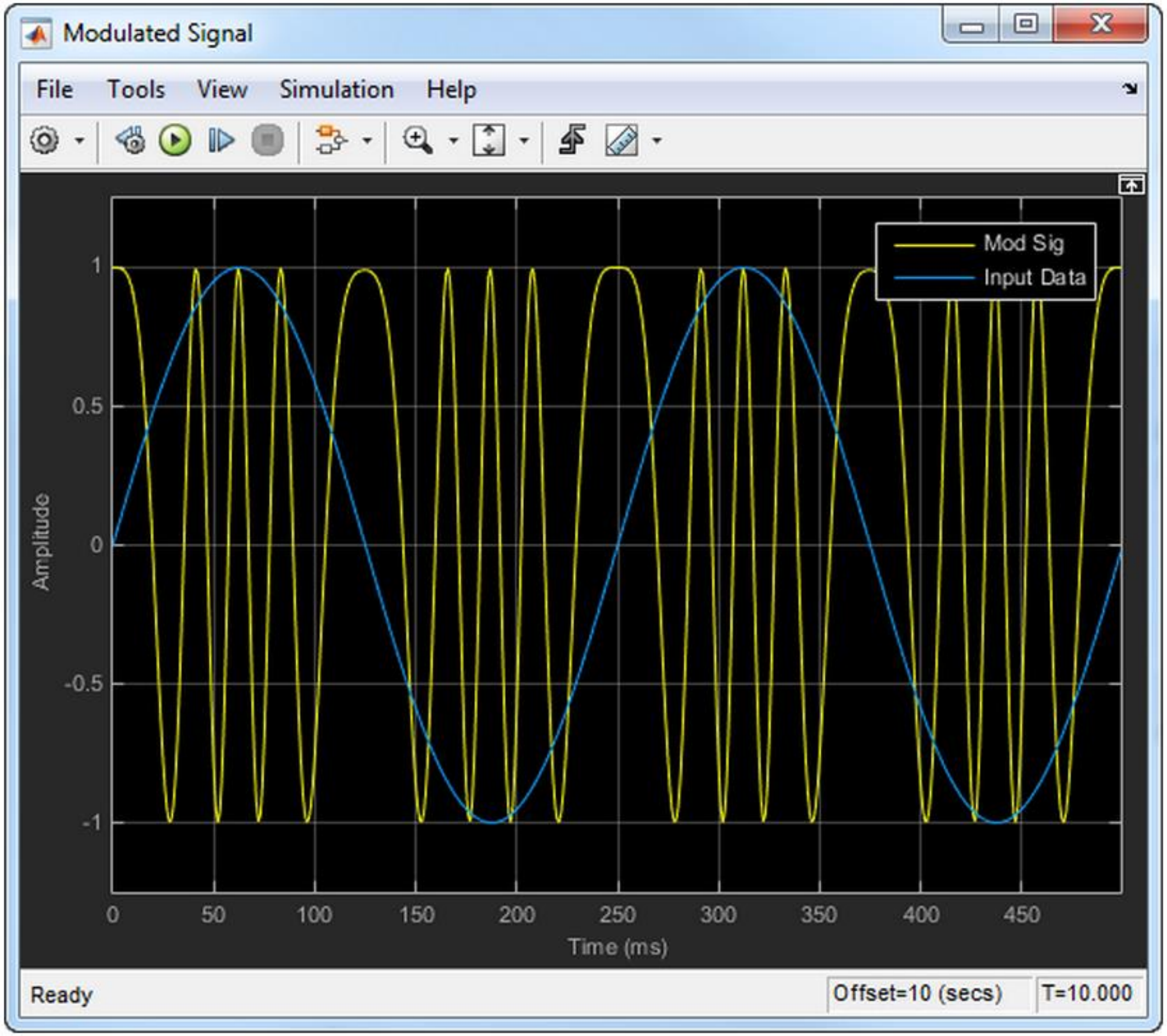


COMMTECH knowledge

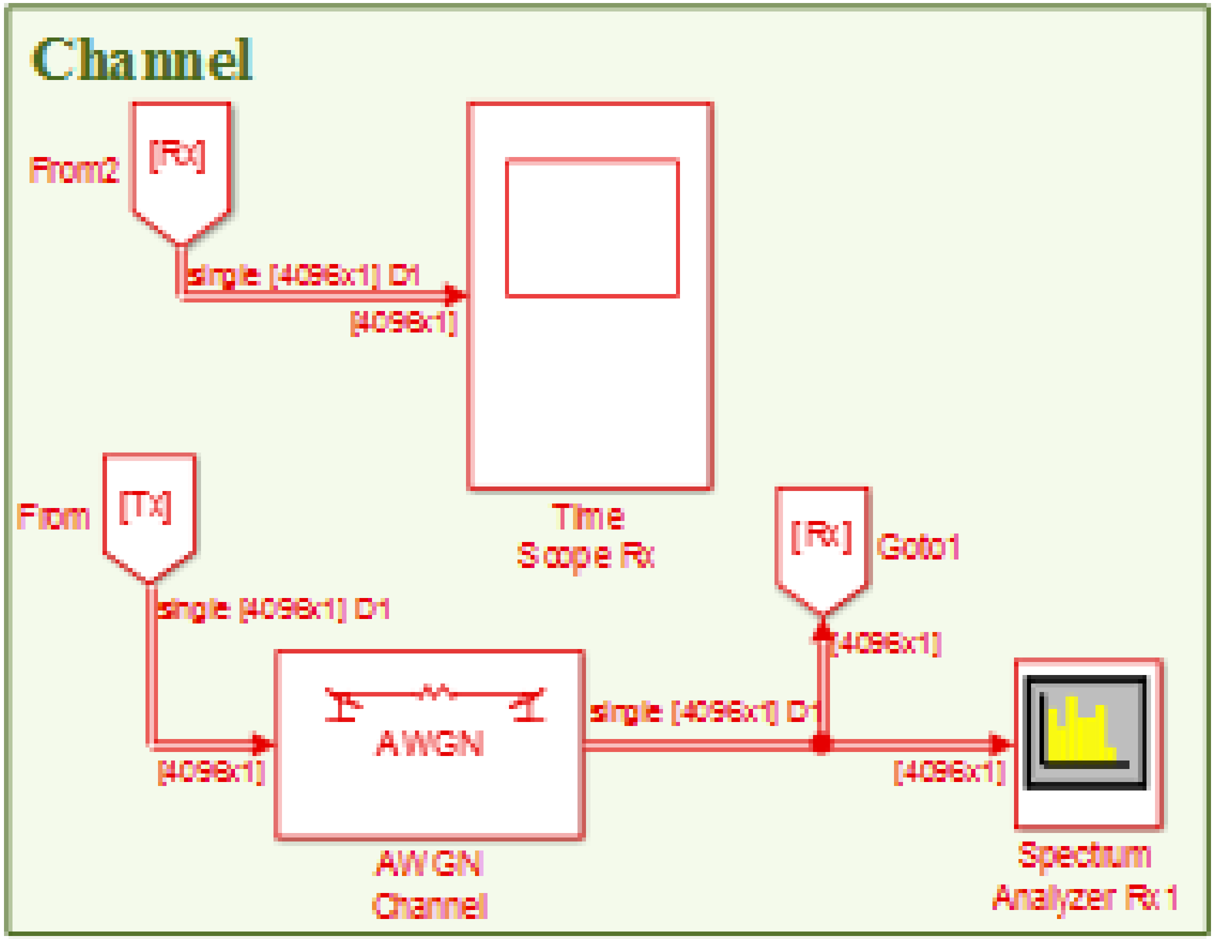
FM Communications – Tx in Time Domain



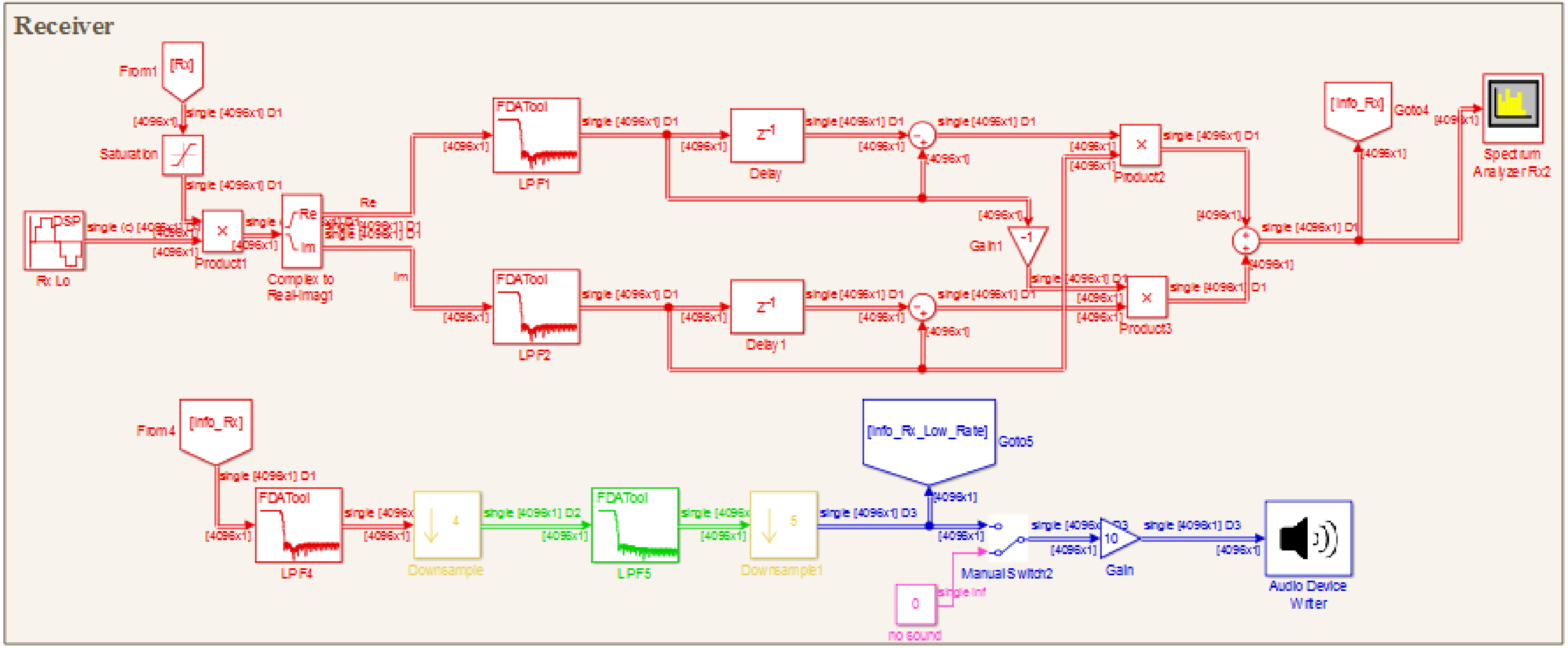
FM Communications – Tx in Time Domain



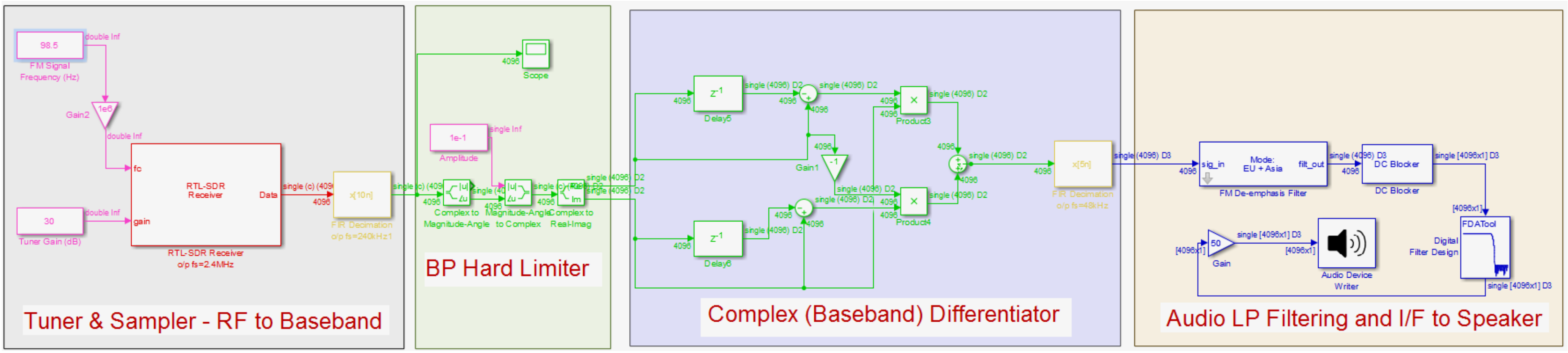
FM Communications - Channel (AWGN)



FM Communications - Receiver



FM Communications – Over the Air



V - Digital Communications – an APSK Demo

- A short history account
- Uncoded and Coded performance
- Present a Tx-Rx Simulation
- Run a wireless Demo with R&S SGT100A as transmitter

Historical Background

ON THE CAPACITY OF PEAK POWER CONSTRAINED GAUSSIAN CHANNELS

I. BAR-DAVID

DEPARTMENT OF ELECTRICAL ENGINEERING
TECHNION - ISRAEL INSTITUTE OF TECHNOLOGY
HAIFA 32000, ISRAEL.

Proceedings of the NATO Advanced Study Institute on
Performance Limits in Communication Theory and Practice
Il Ciocco, Castelvecchio Pascoli, Tuscany, Italy
July 7–19, 1986

J. K. Skwirzynski (ed.), Performance Limits in Communication Theory and Practice, 61–73.

ISBN-13: 978-94-010-7757-6 e-ISBN-13: 978-94-009-2794-0
DOI: 10.1007/978-94-009-2794-0

4. AKPM: Amplitude Keying and Phase Modulation

62

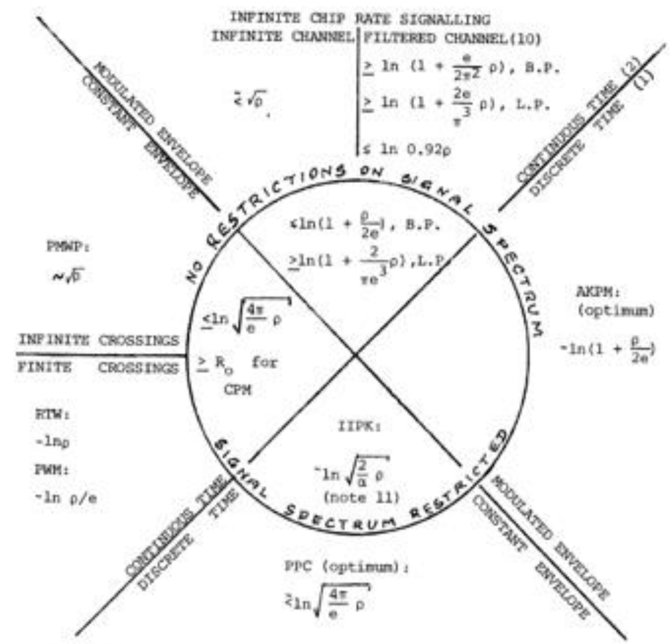


FIGURE 1. CAPACITY IN PEAK POWER LIMITED COMMUNICATIONS

NOTES: Capacity values are in nats per dimension. ρ is signal to noise ratio.
1. "DISCRETE TIME" includes sinusoids with piecewise constant parameters.
2. "CONTINUOUS TIME" includes signals with infinite rate of parameter changes.
3. PMWP: Phase Modulation by Wiener Process
4. AKPM: Amplitude Keying and Phase Modulation
5. CPM : Continuous Phase Modulation
6. IIPK: Independent Increment Keying
7. RTW : Random Telegraph Wave
8. PWM : Pulse Width Modulation
9. PPC : Polyphase Coding
10. Lower bounds are for signals not necessarily bounded at the filter output. Filters are strictly bandlimiting.
11. Here a is approximately also the factor of spectral sidelobe suppression.

Historical Background (2)

Thomas C.M., Weidner M.Y., and Durrani S.H., "Digital amplitude phase keying with M-ary alphabets," *IEEE Transactions on Communications*, vol. 22, no. 2, pp. 168–180, February 1974.

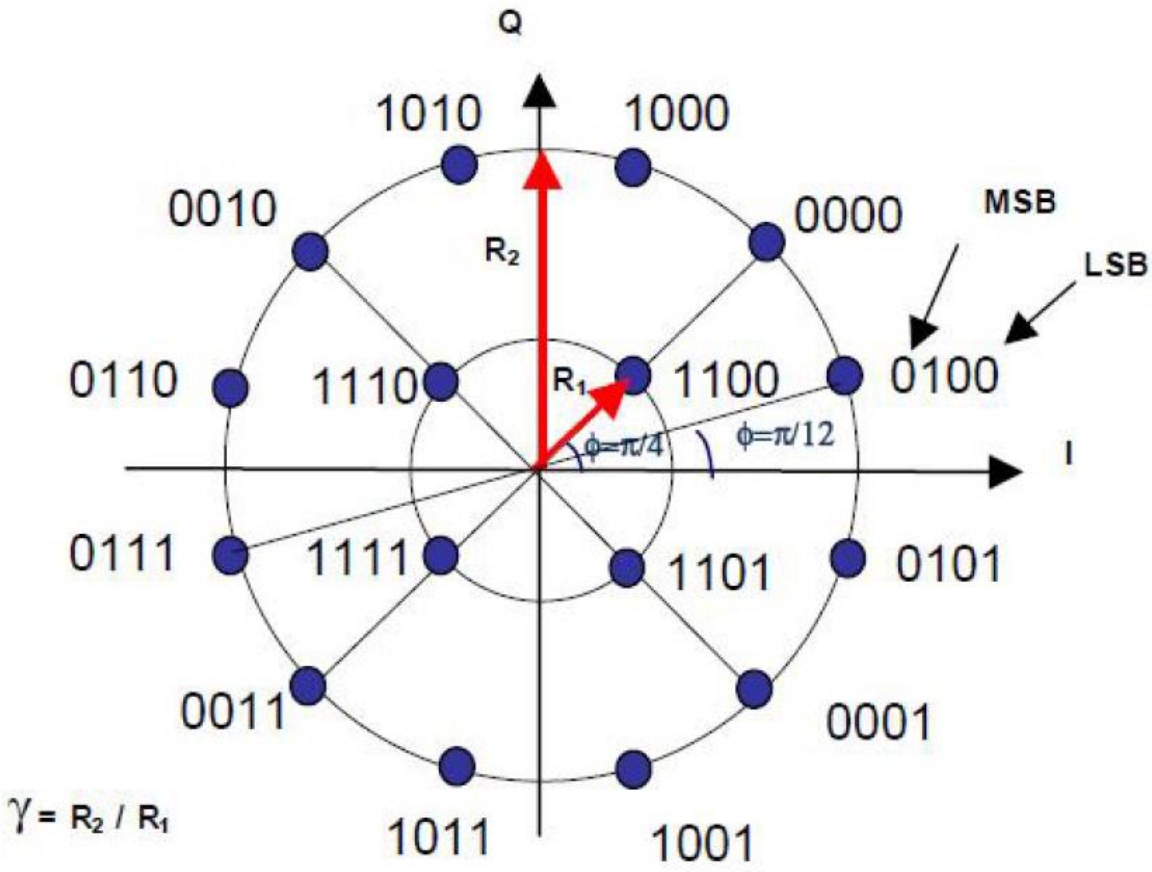
1060 IEEE TRANSACTIONS ON INFORMATION THEORY, VOL. 41, NO. 4, JULY 1995

The Capacity of Average and Peak-Power-Limited Quadrature Gaussian Channels

Shlomo Shamai (Shitz), *Fellow, IEEE*, and Israel Bar-David, *Fellow, IEEE*

- DVB-S 2 employs M-APSK since 2005÷2006
- Considered also in Cellular LTE and 5G

16APSK Constellation



16APSK Signal Constellation

16APSK Reduced PAPR

PARP in 4+12-APSK and 16-QAM, for different values of the roll-off factor

Modulation	$\alpha = 0.1$	$\alpha = 0.3$	$\alpha = 0.5$
16-QAM	7.2dB	6.3dB	5.7dB
4+12-APSK	5.7dB	4.8dB	4.2dB

M. Baldi, F. Chiaraluce, A. de Angelis, R. Marchesani and S. Schillaci, *A comparison between APSK and QAM in wireless tactical scenarios for land mobile systems*,
EURASIP Journal on Wireless Communications and Networking 2012

APSK Simulation Setting

Simulation Parameters	Settings
Frame size	64800(Normal)
LDPC Encoder Input Type	Bit
LDPC Decoder output Type	Information Part
LDPC Decoder Decision Input Type	Hard Decision
LDPC Decoder Number Of Iterations	50
Modulator Input Type	Bit
Modulator Symbol Order	Gray
Demodulator Output Type	Bit
Demodulator Decision Type	Soft Decision
LLR Algorithm	Approximate LLR
Channel Noise Factor	SNR

Simulation Parameters and Settings

M-APSK Uncoded Error Rates

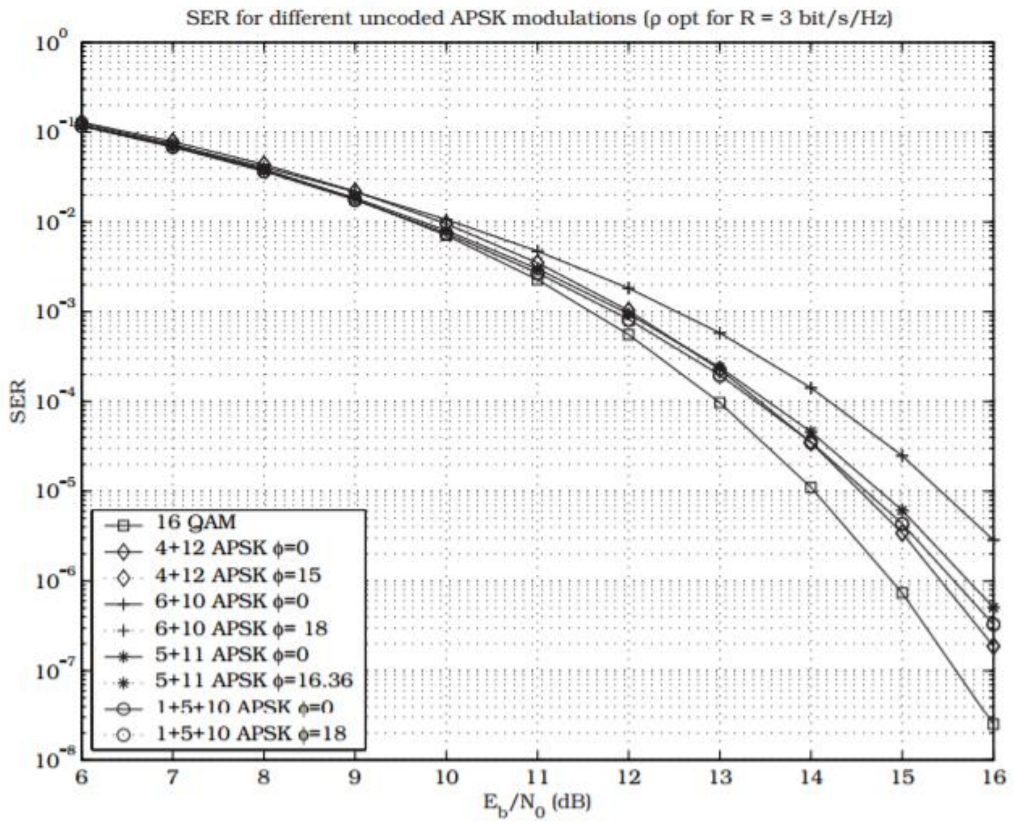
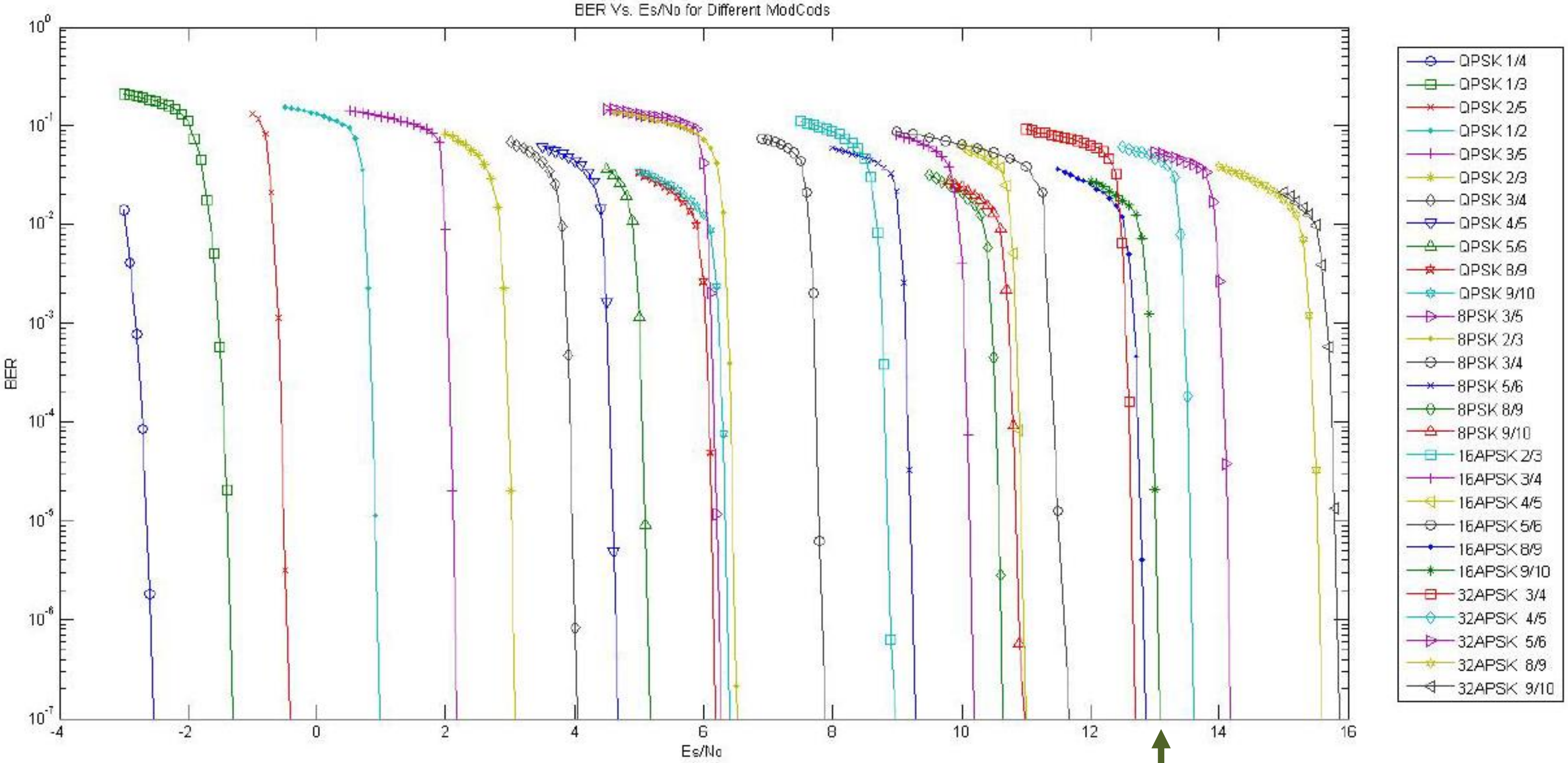


Figure 4: Union bound on the uncoded symbol error probability for several APSK modulations. Note that the continuous line and the dashed line are indistinguishable because they are superimposed. Turbo-Coded APSK Modulations Design for Satellite Broadband Communications Riccardo De Gaudenzi, Albert Guillén i Fàbregas, Alfonso Martinez International Journal of Satellite Communications and Networking 24(4): 261 - 281 · July 2006

16APSK Performance



BER Vs. Es/No For Different ModCods

QEF – Quasi Error Free

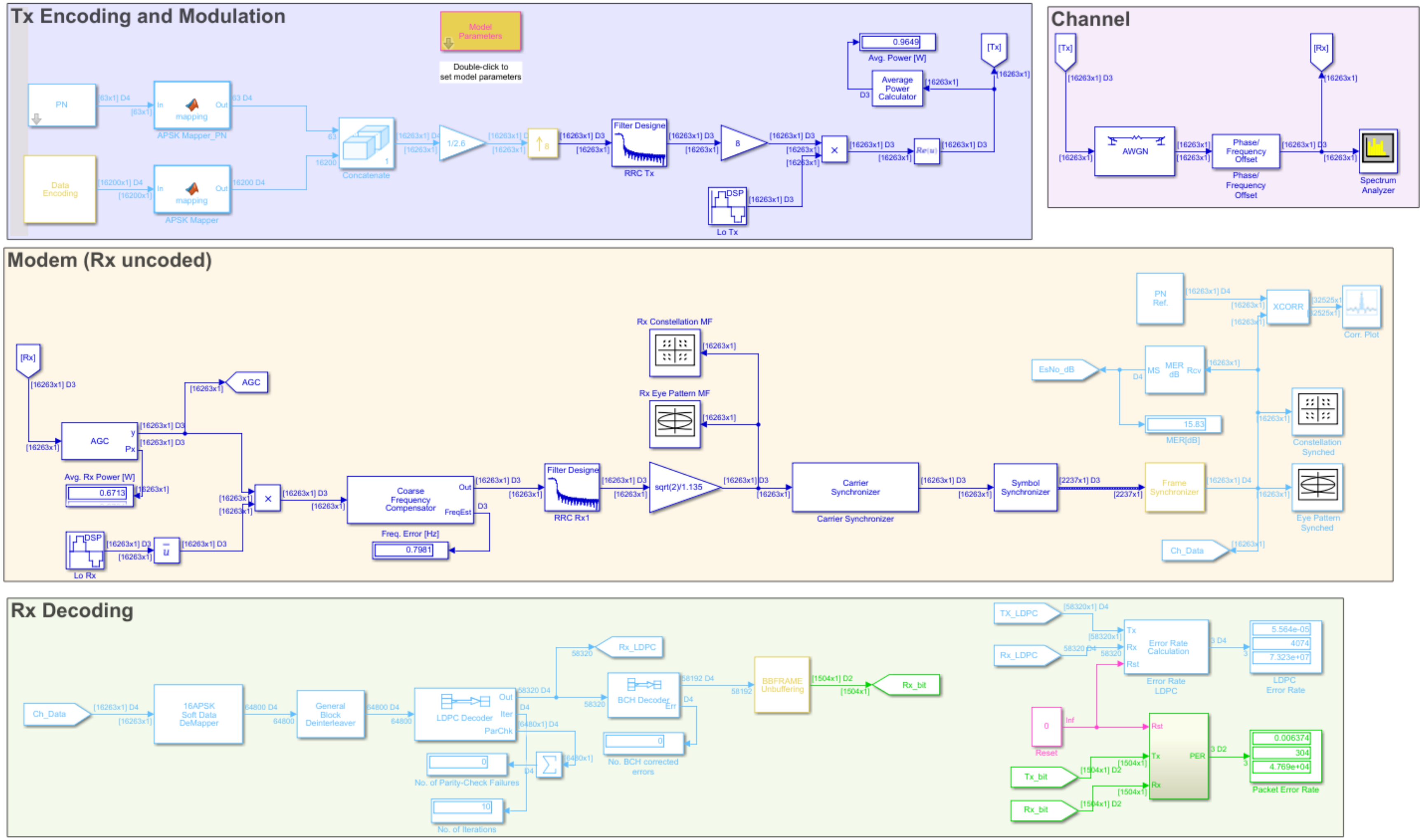
B. Azarbad and A. B. Sali, *DVB-S2 Model in Matlab: Issues and Impairments*, INTECH, Ch. 10, 2012

COMMTECH knowledge

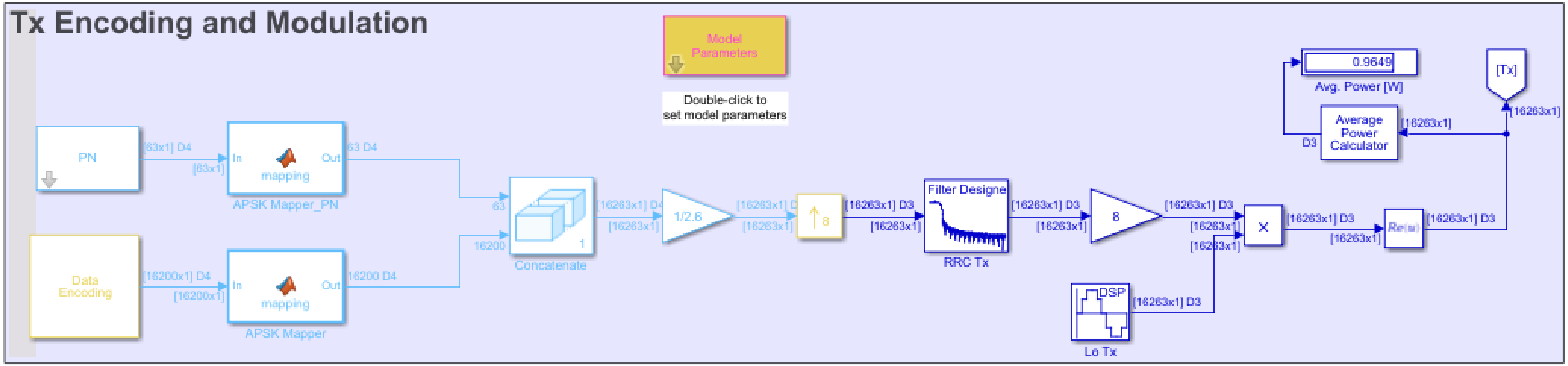
Implementation of APSK Communications

- Transmit an APSK (*Amplitude-Phase Shift Keying*) signal.
- The signals' parameters are m[bits/sym], *R*, α and f_0.
- In the channel adds white Gaussian noise (AWGN).
- Receive the corrupted modulated signal by:
  - Tuner front-end (when receiving wirelessly)
  - Tracking loops (AGC, Coarse/Fine Freq. Lock, Synchronization)
  - Set an optimal soft - demapping for min. error-rate detection
- In addition, use spectrum analyzer, oscilloscope.

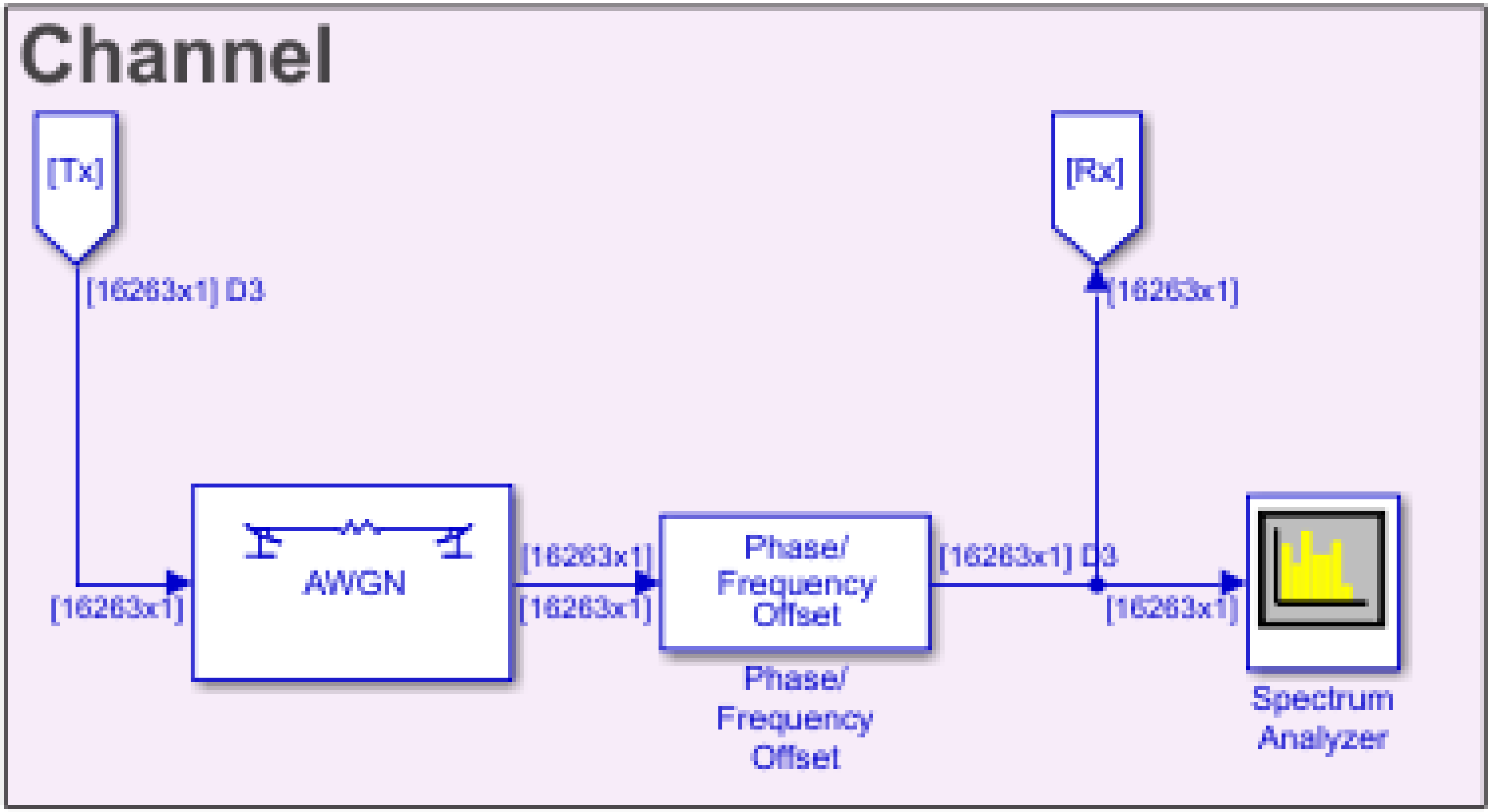
16APSK - Overall Block Diagram



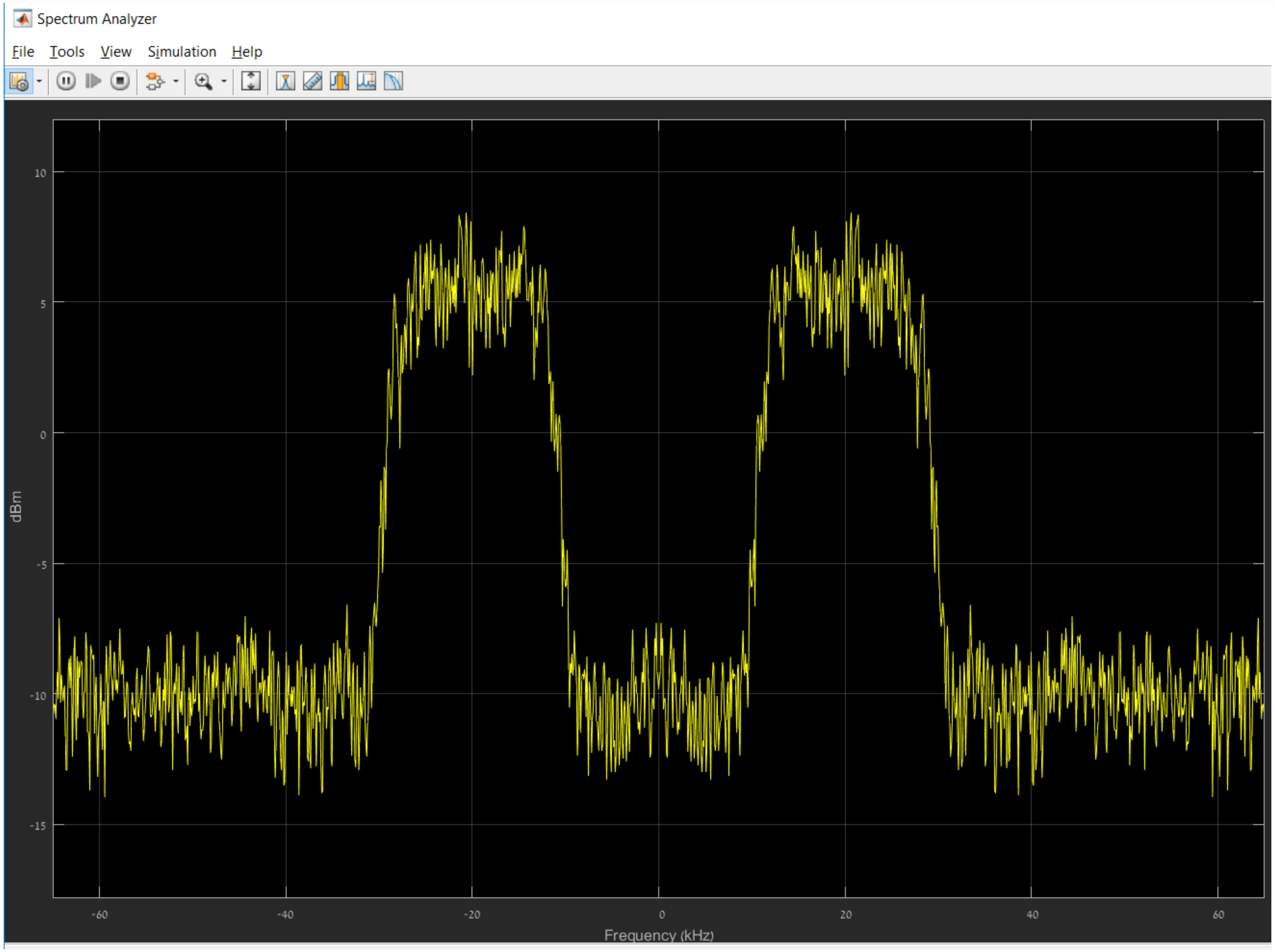
Mapped Data and Modulation Expanded



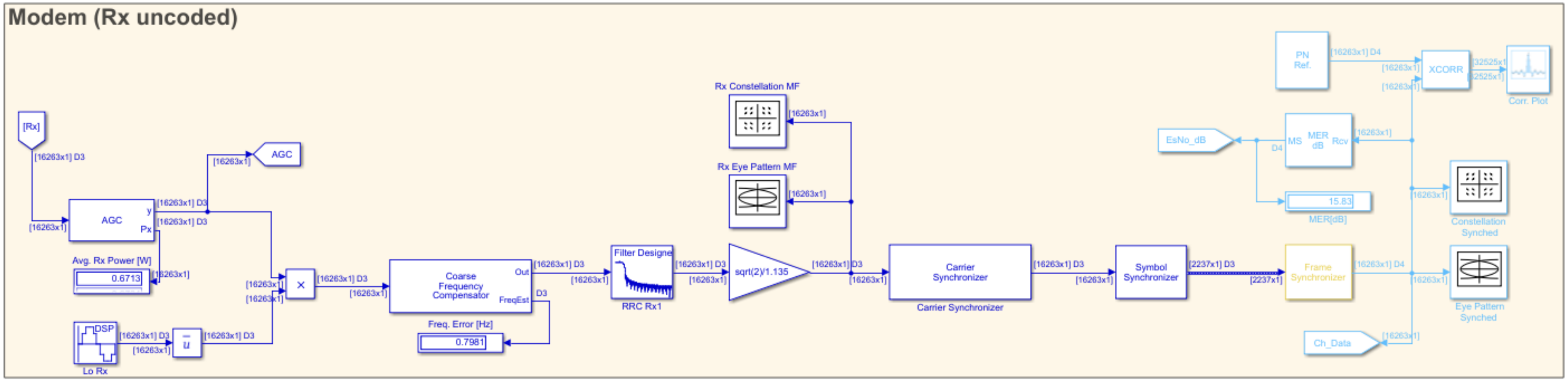
Channel


Channel
[Tx]
[16263x1] D3
[16263x1]
AWGN
[16263x1]
[16263x1]
Phase/
Frequency
Offset
Phase/
Frequency
Offset
[16263x1] D3
[Rx]
[16263x1]
[16263x1]
Spectrum
Analyzer

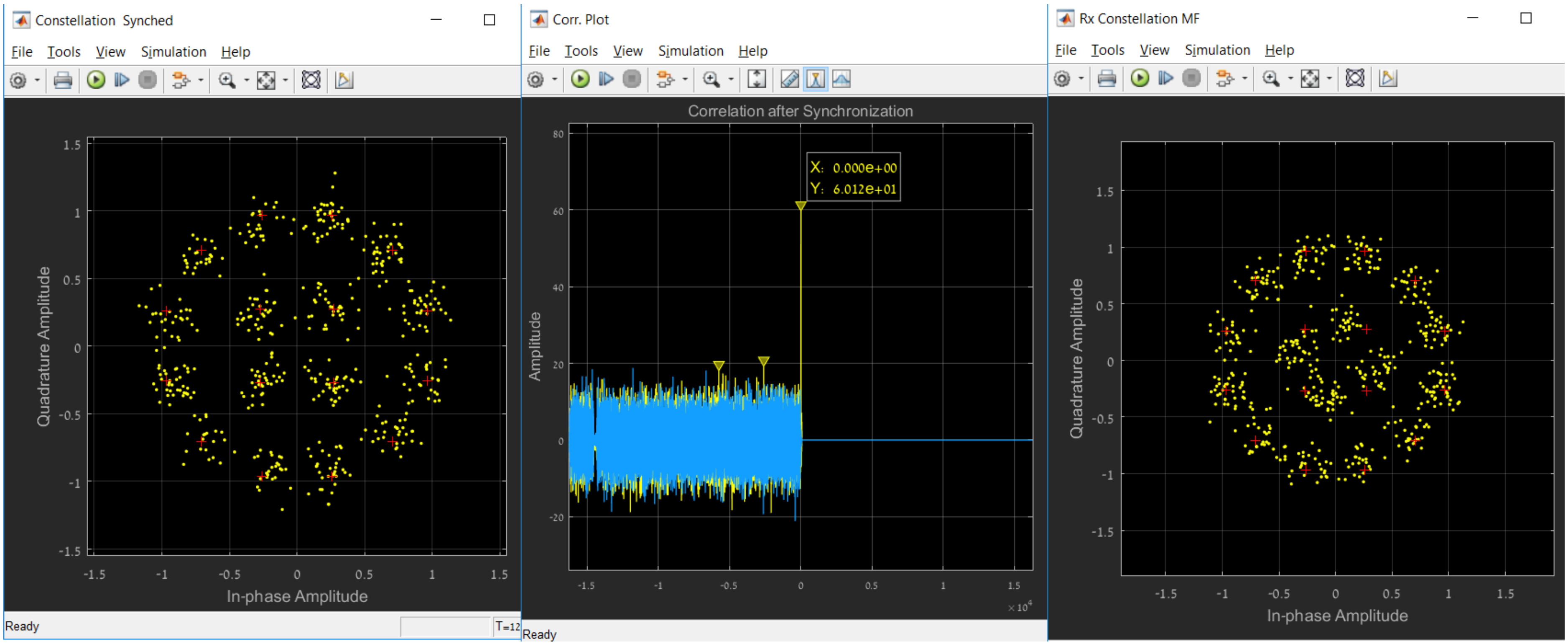
16APSK Transmission Spectrum (9/10, Es/No=16dB)



Uncoded Rx (MF and Synchronizations)

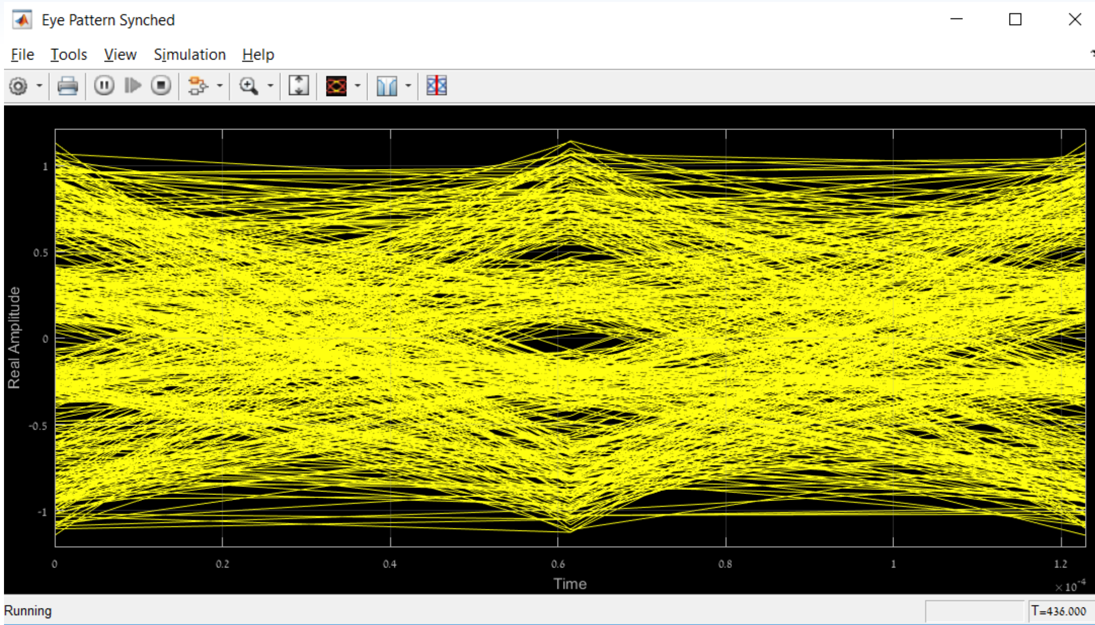


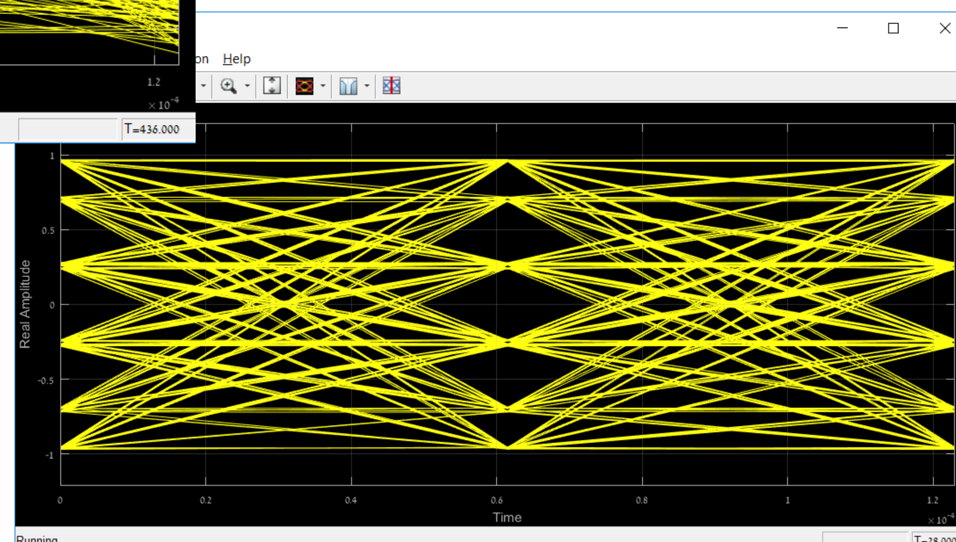
16APSK - Synchronization



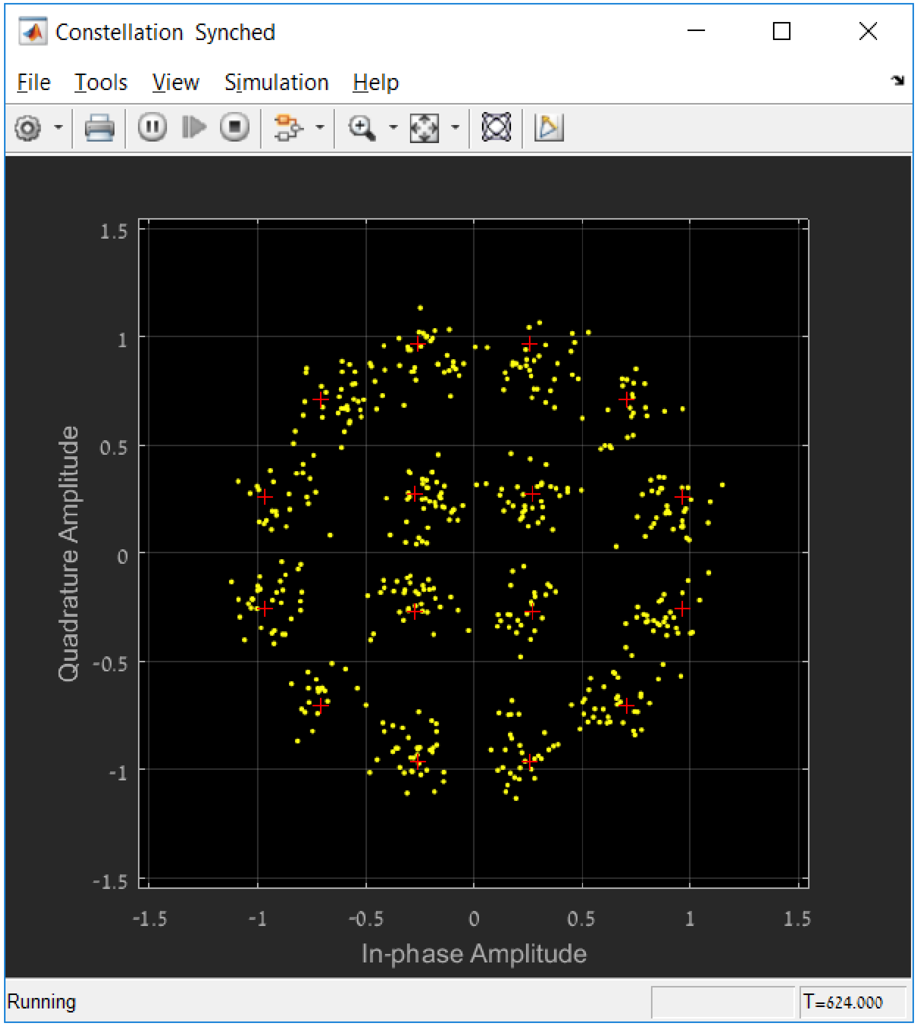
COMMTECH knowledge

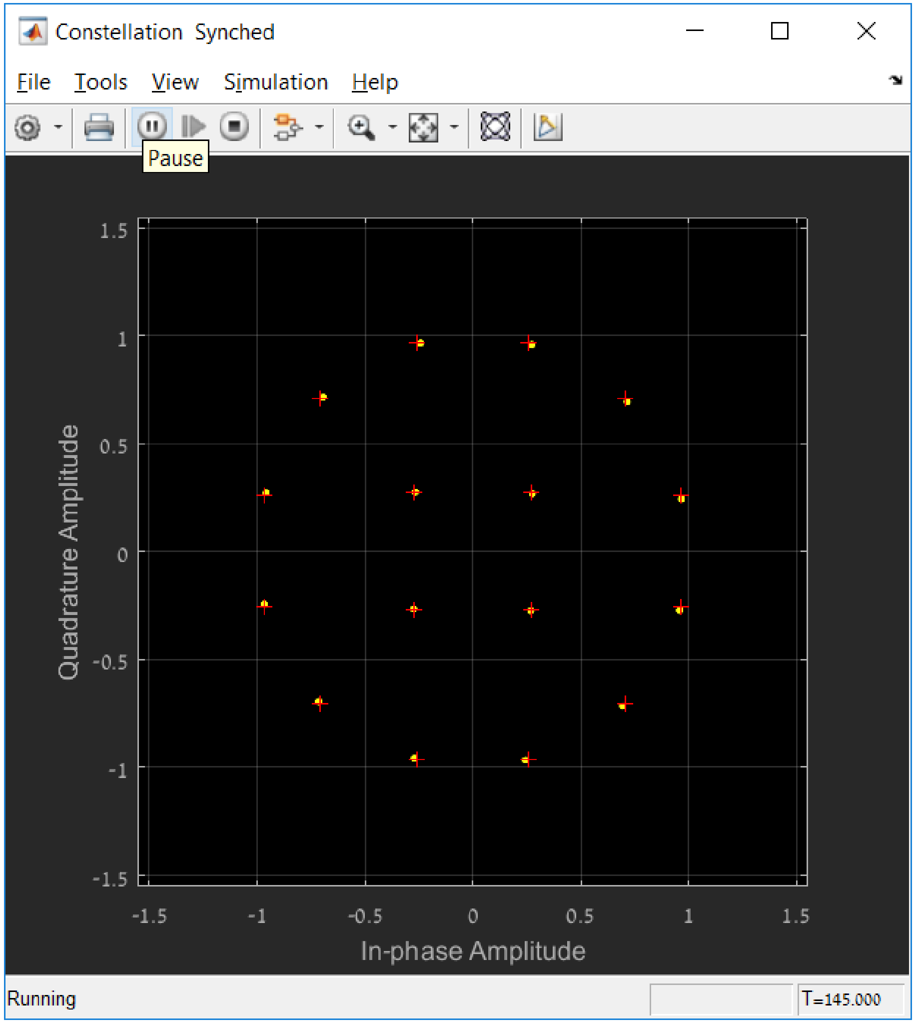
16QAM Received Eye Diagram (*I* or *Q*)



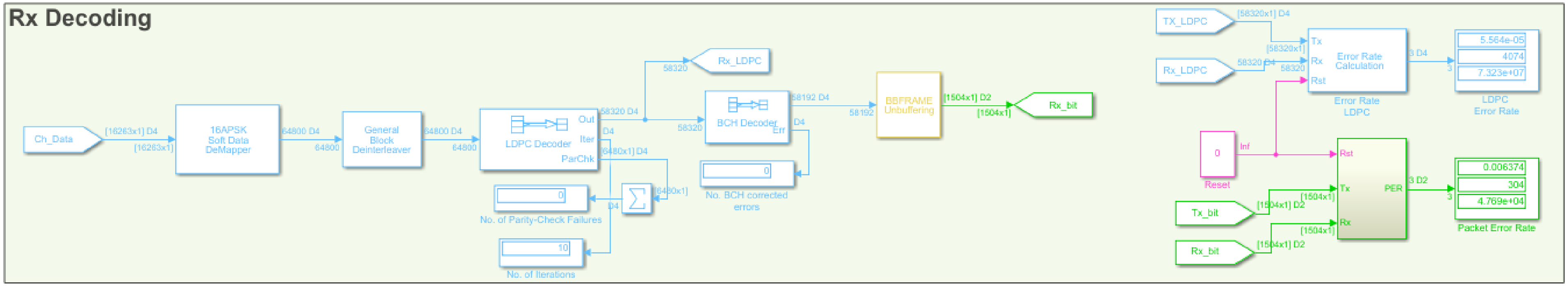


16APSK Received Constellation (9/10, Es/No=16dB)

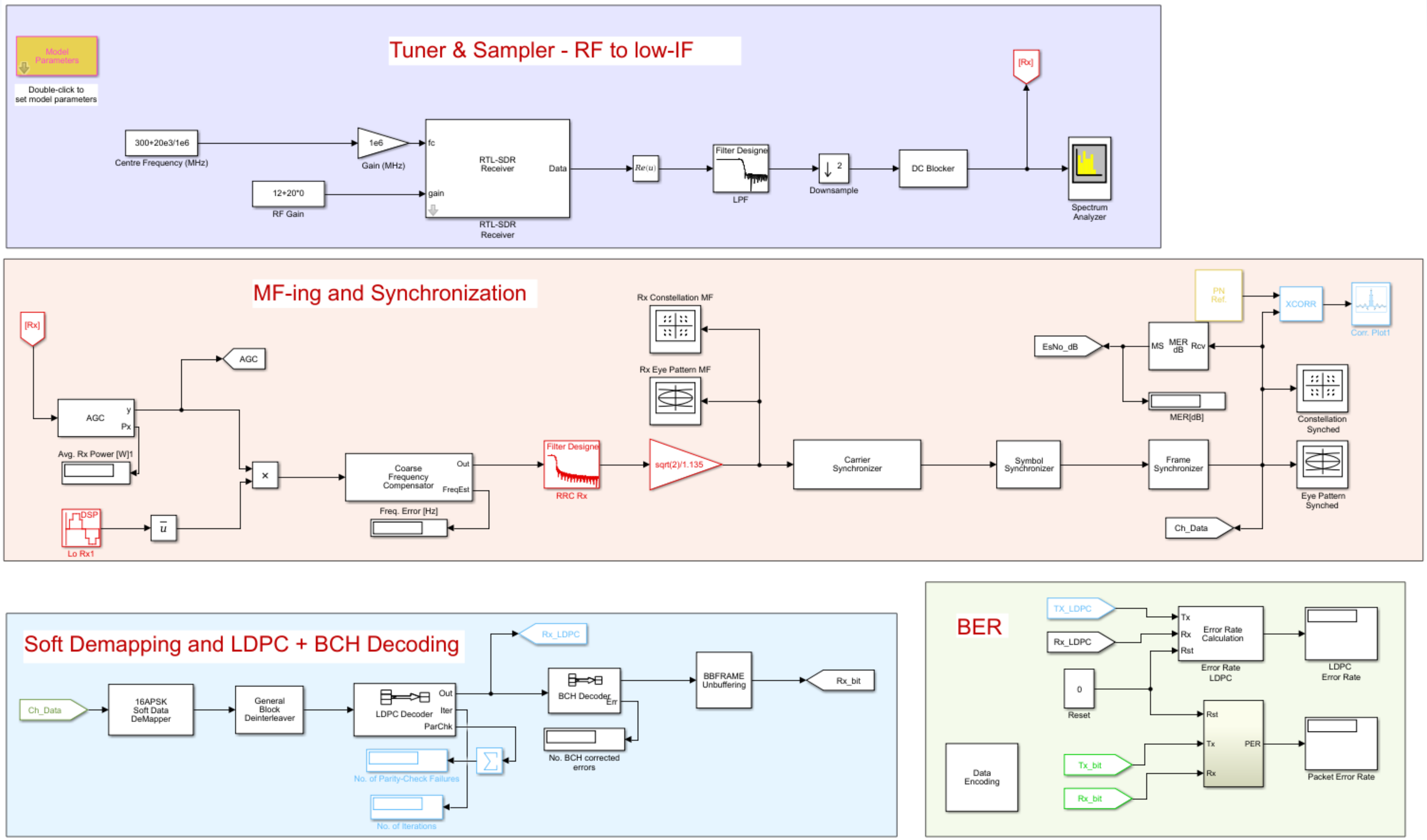




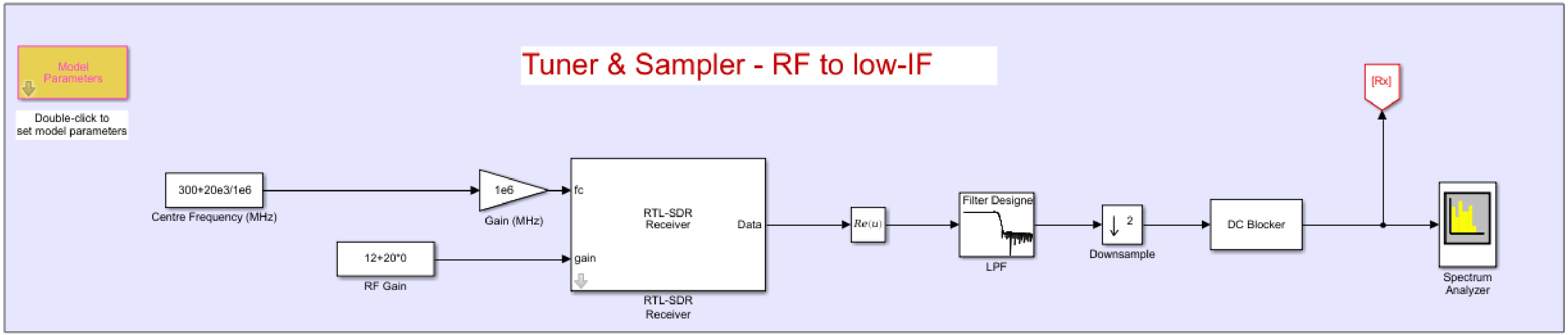
Decoded Rx (incl. LDPC and BCH)



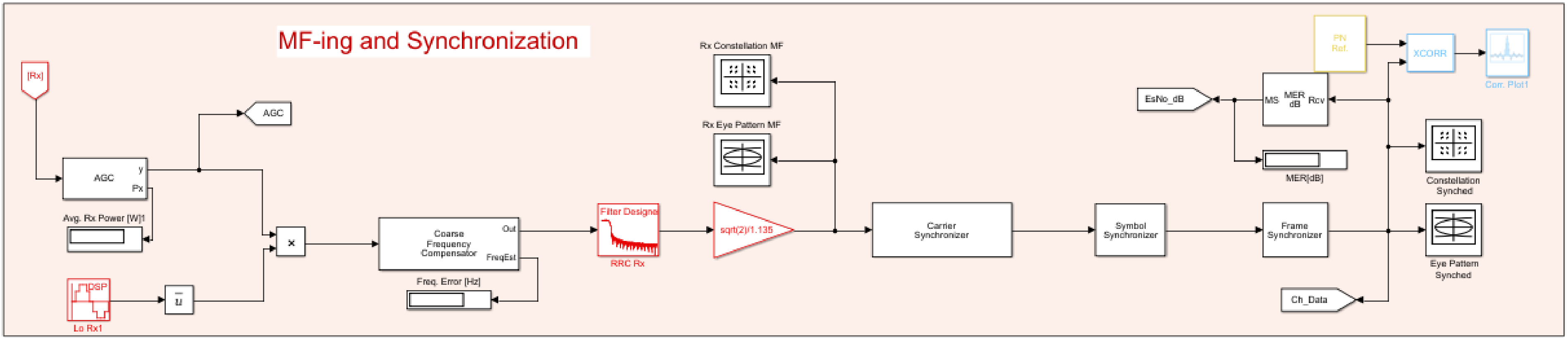
Wireless 16APSK



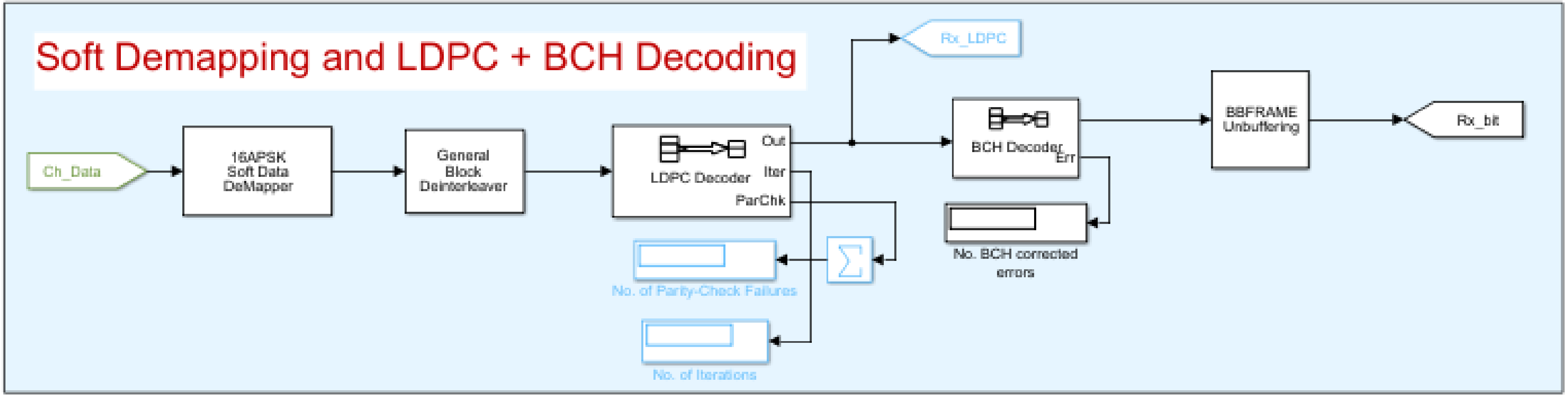
Wireless 16APSK (2)



Wireless 16APSK (3)



Wireless 16APSK (4)



Acknowledgement

Albert Kanner

My first acquaintance with the APSK usage in DVB-S2x was due to Albert. His vast practical knowledge in Satellite and Unlicensed Communication régimes including Protocols, PC's, and Connectivity keeps enriching me again and again.

VI - Conclusion

- We demonstrated a powerful Wintel tool based on rtl-sdr I/F combined with Simulink and an RF FE flexible receiver.
- This tool enables system design, fast prototyping and implementation. It may serve also for effective educational results.
- We presented 2 examples (FM and 16APSK).
- Employing a USRP I/F enables FPGA faster realizations, as well as Tx/Rx.