Modems: Modulation Waveforms: Past, Present, & Future

29 November – 2 December 2011

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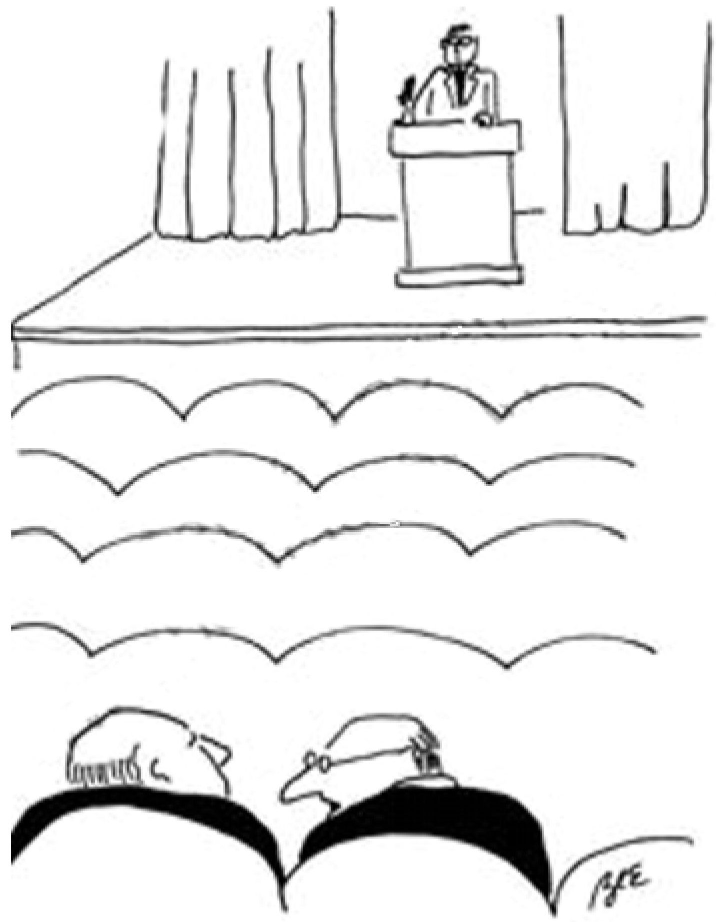
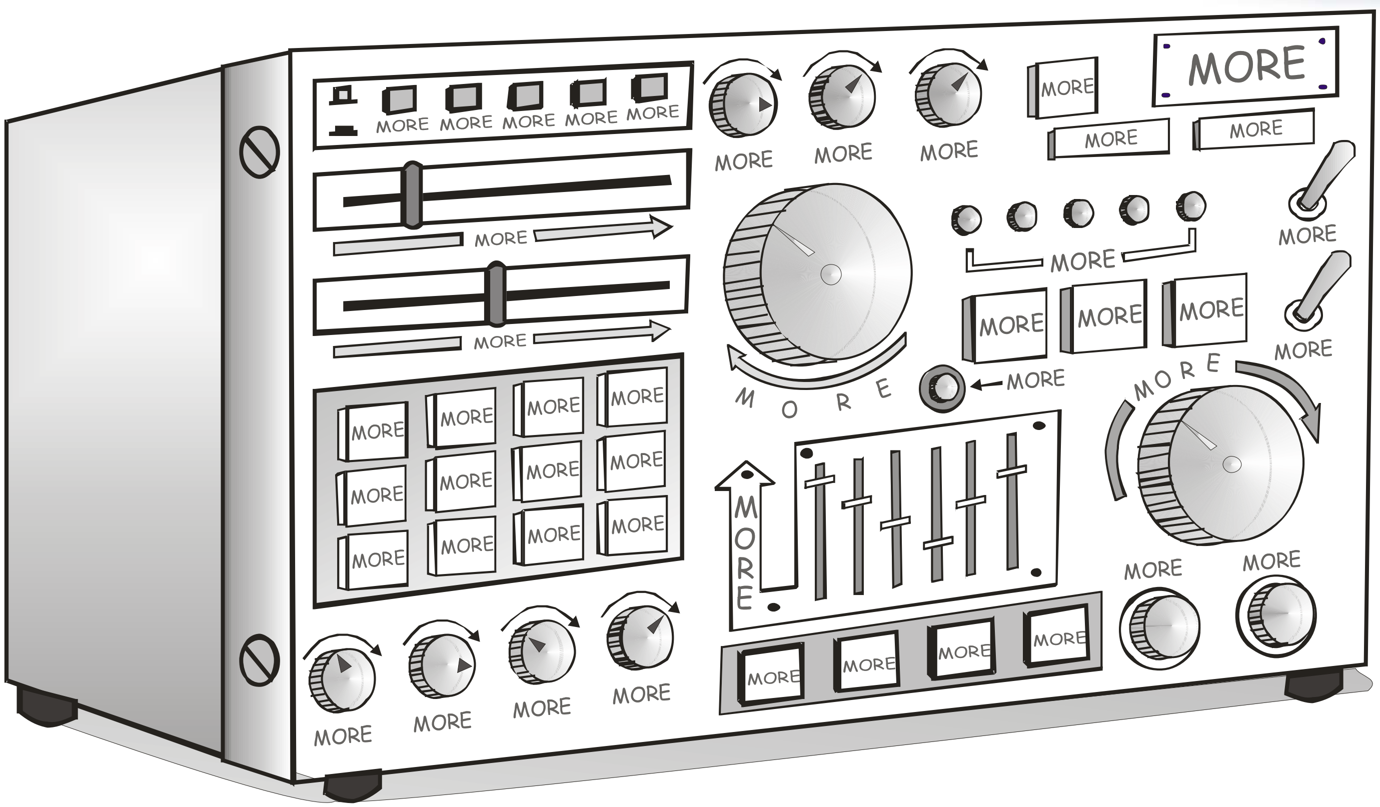
SDR'11 - WInnComm



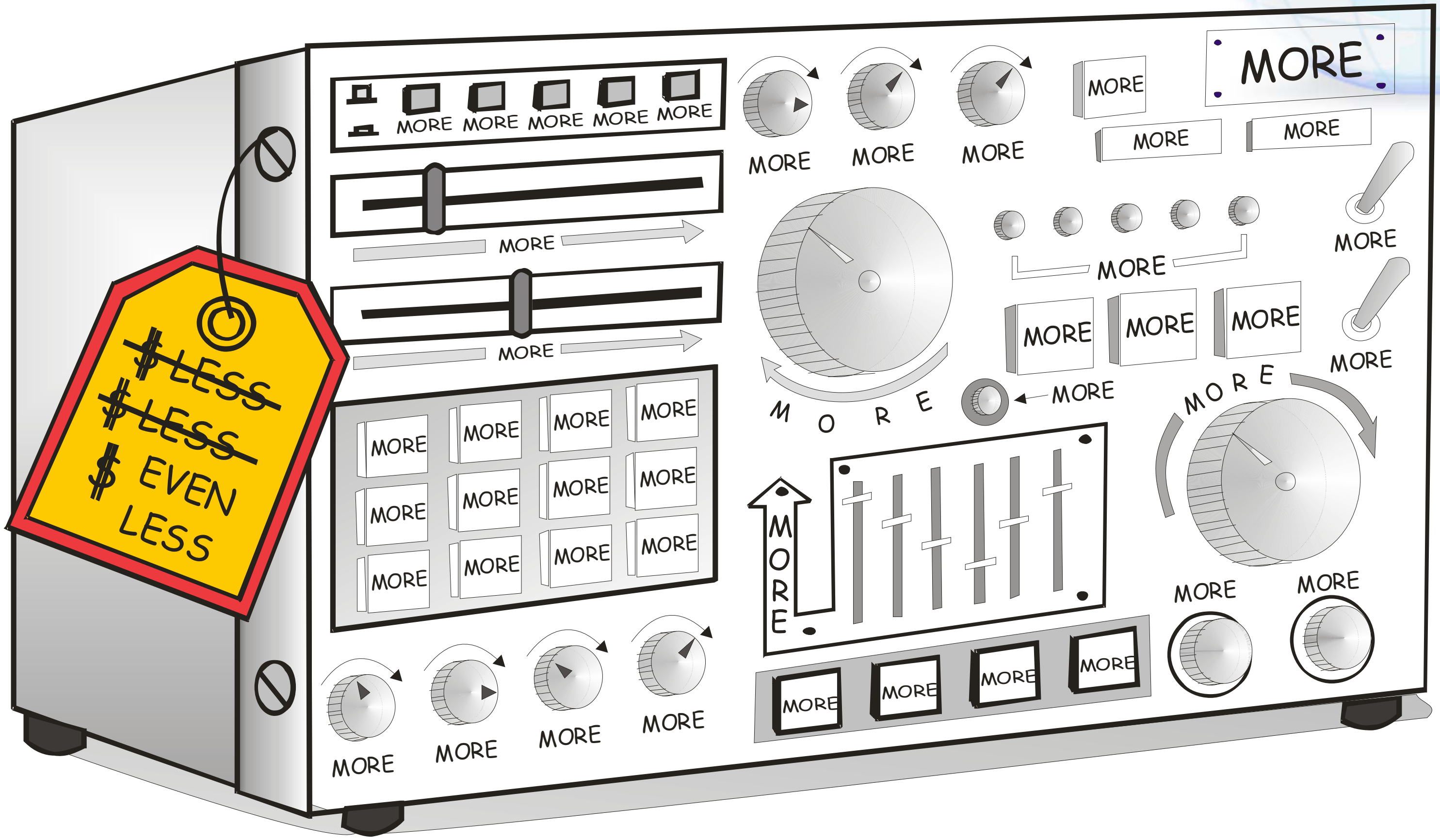
"Wake up! You're the next interesting speaker!"

"THE NEW PRODUCTIVITY GOALS ARE HERE."

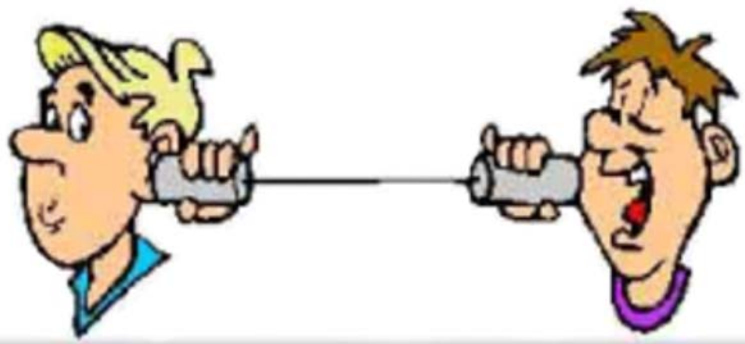
What the Customer Wants

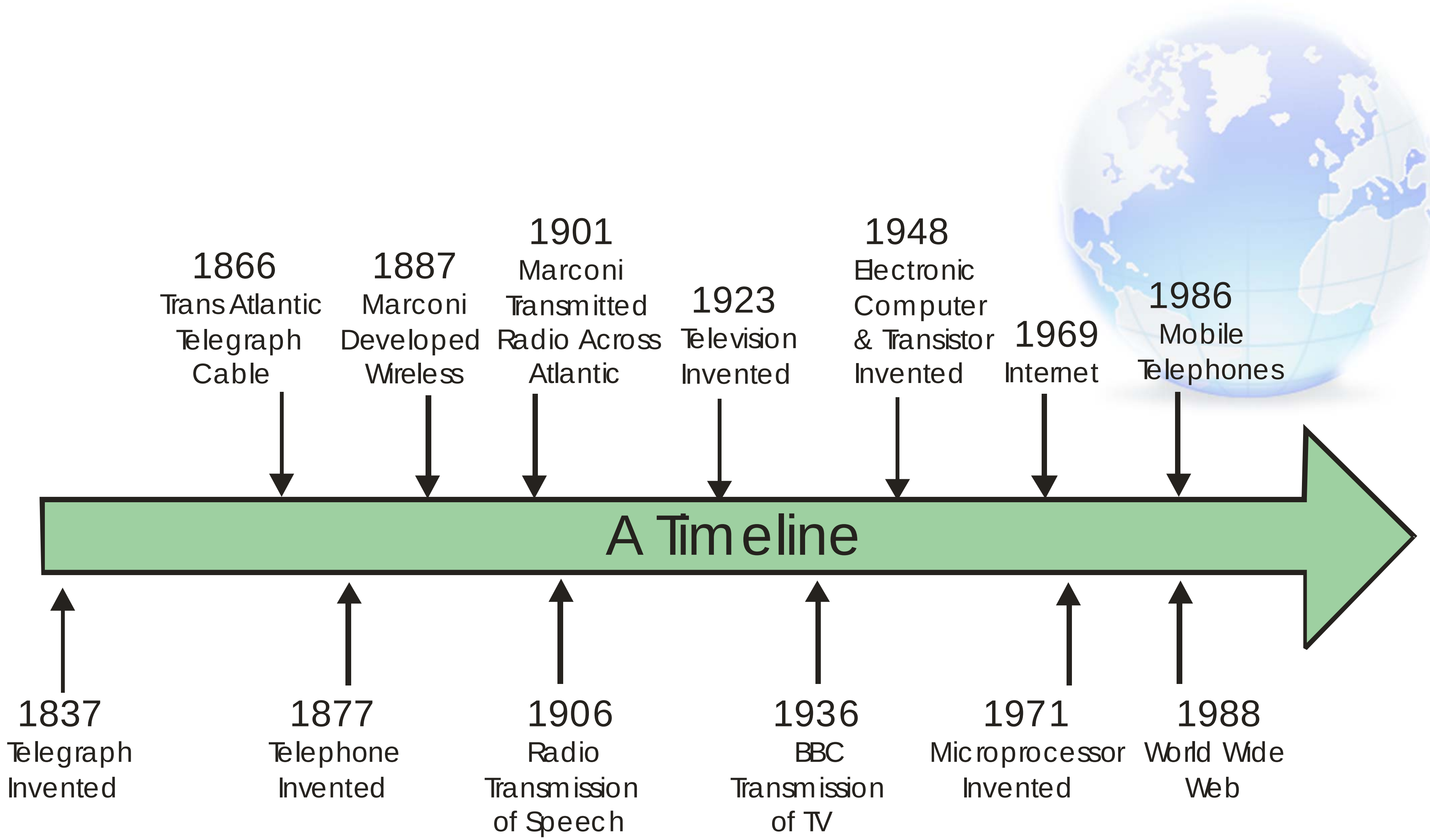


What The Customer Expects to Pay



A Short History of Communication Signals And Modem Design





Telegraph –> Telephone -> Wireless

Very Early Communications at a Distance: Free Space Acoustic and Optical Channels

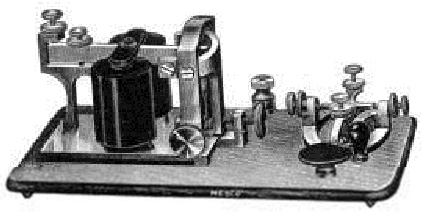
Drums, Whistles,
Cannon Fire

Claude Chappe 1793
Optical Telegraph

Smoke Signals,
Semaphore,
Beacon Fires, Ship Flags,
Heliograph,
Signal (Aldis) Lamp

Disruptive Technology in Communications

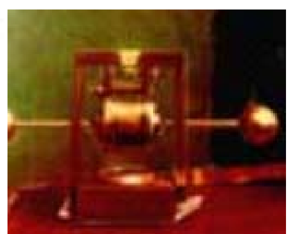
The Printing Press: 1450,
German Inventor Johannes Gutenberg



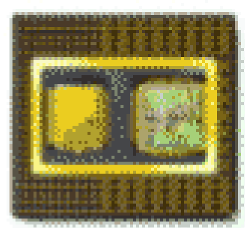
The Long Distance Electric Telegraph: 1843,
American Inventor Samuel Morse

Preparing Conditions for next Disruption

The Telephone: 1876,
British Inventor Alexander Graham Bell



Wireless (Radio): 1901,
Italian Inventor Guglielmo Marconi

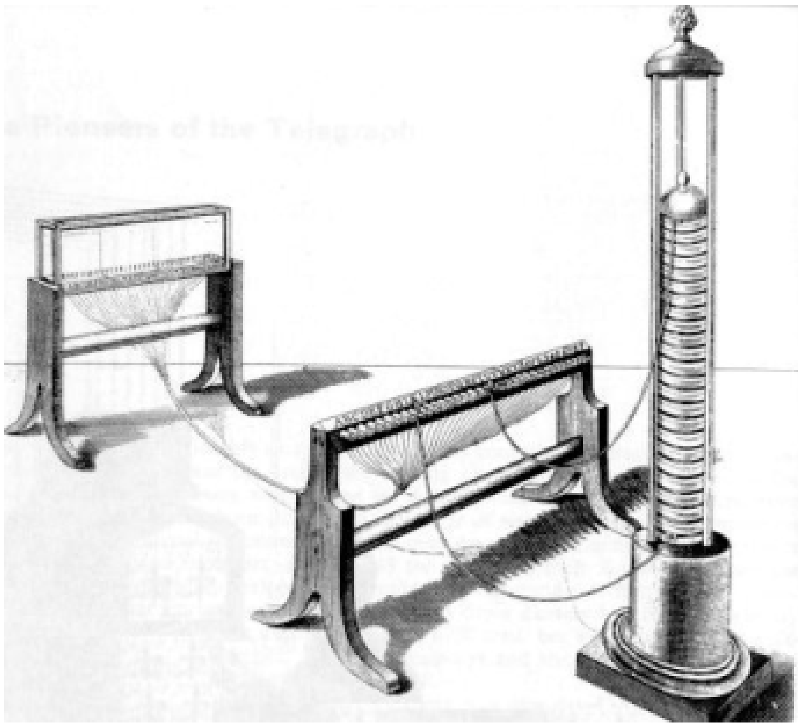


The Microprocessor: 1971
American Inventor Ted Hoff

Disruptive Technology

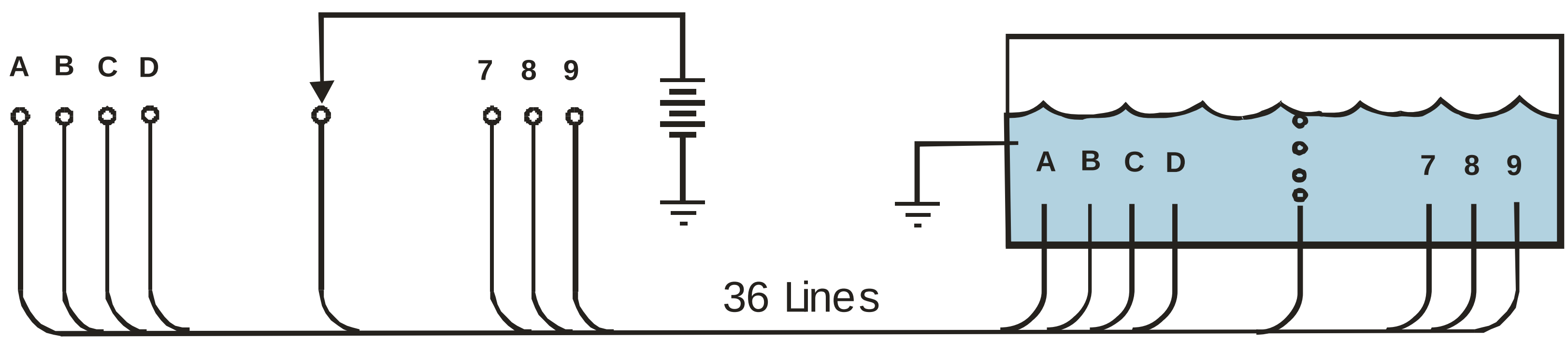
- The electric telegraph arrived in the early 19-th century and redefined communications at a distance.
- It required the confluence of three factors:
  The science of electromagnetism,
  The ability to generate and store electricity
  The Industrial Revolution to build the required infrastructure.

Converting an Electrical Connection Into a Signal

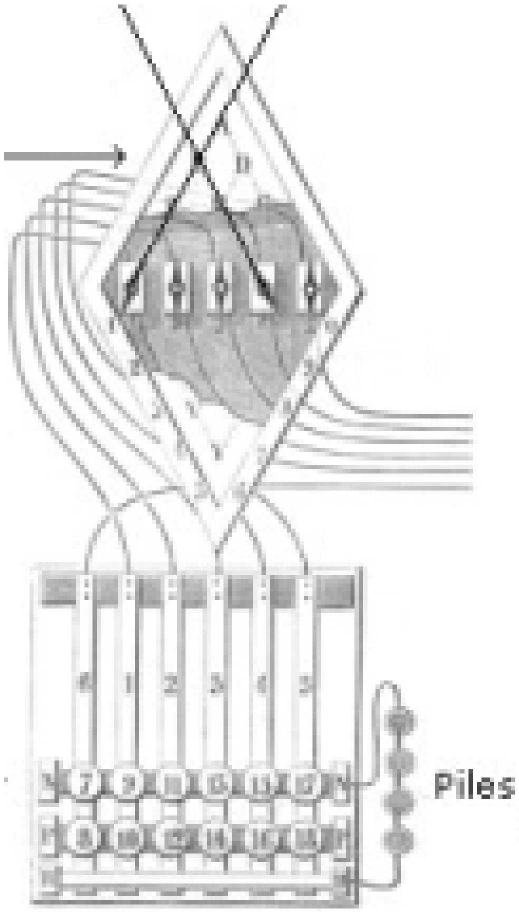


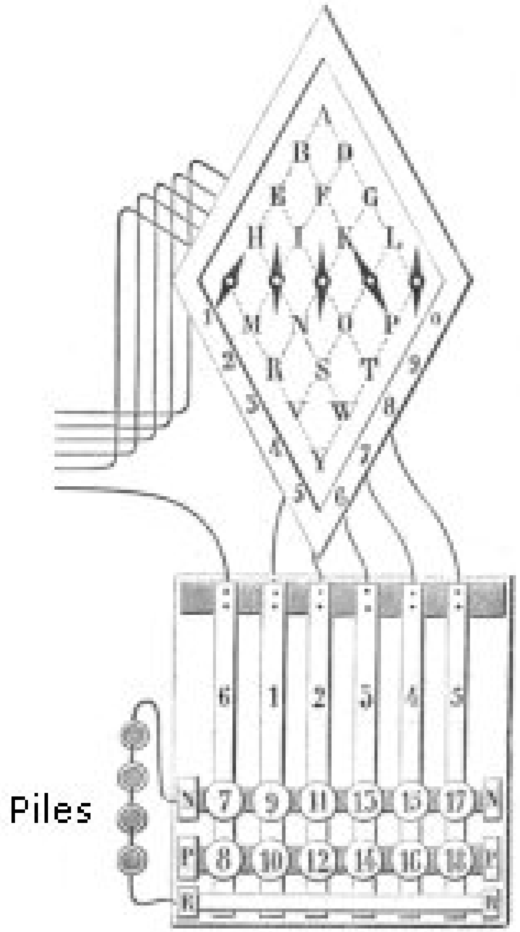
Samuel Thomas von Sömmering's (1808-10)

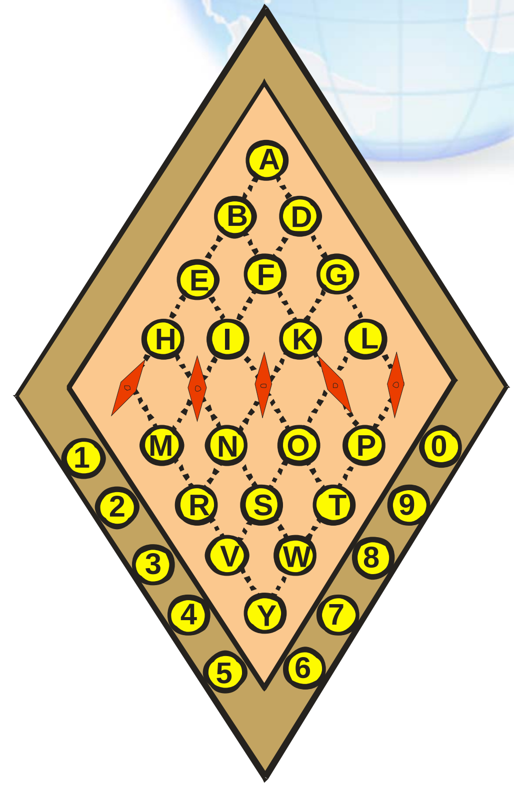
"Space Multiplexed" Electrochemical Telegraph



Cooke and Wheatstone Telegraph

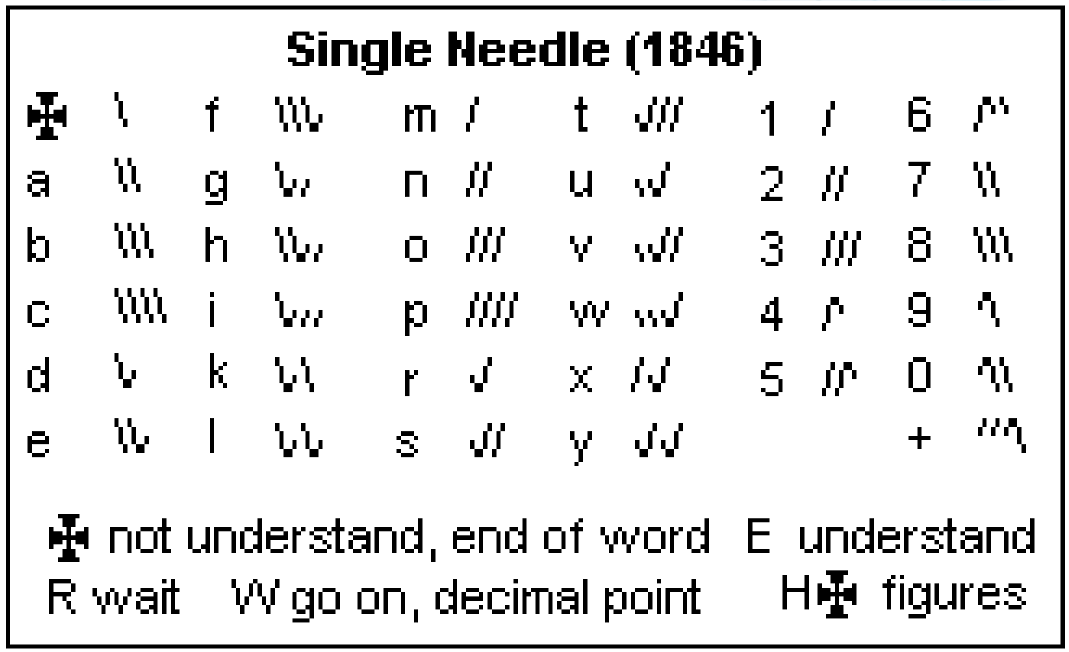






2 out of 5 Coding
(5*4 = 20)

Single Needle Telegraph Variable Length Code



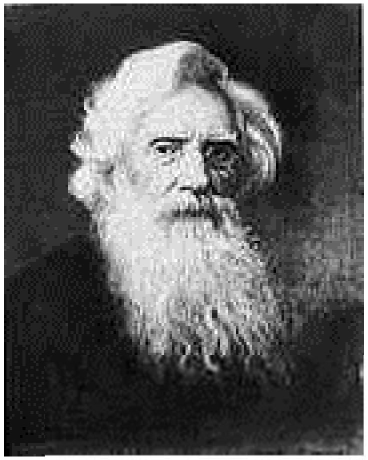
Cooke-Wheatstone Single Needle Telegraph (c 1850)

Communication at a Distance with Electricity and Magnetism

- 1831 Joseph Henry invents the first electric telegraph.
- 1843 Samuel Morse invents the first long distance electric telegraph line.
- **1858 Cyrus Field's Company Lays the Transatlantic Cable.**
- 1876 Alexander Graham Bell patents the electric telephone.
- 1894 Guglielmo Marconi improves wireless telegraphy.
- 1902 Guglielmo Marconi transmits radio signals across the Atlantic Ocean.

Brunel's Great Eastern

Telegraph -> Telephone -> Wireless



THE TELEPHONE

1876 - Alexander Graham Bell invents the Telephone.
He offers the patent to Western Union for $100,000.

The President of the Telegraph Company, appointed a committee to investigate the offer. The report reads in part:

The Telephone purports to transmit the speaking voice over telegraph wires. We found that the voice is very weak and indistinct, and grows even weaker when long wires are used between the transmitter and receiver.

Technically, we do not see that this device will be ever capable of sending recognizable speech over a distance of several miles.

Bell wants to install a "telephone device" in every city.
The idea is idiotic on the face of it.

"We do not recommend its purchase."

Early Telephone Instruments

Ericsson "Eiffel Tower" Telephone, 1885	11 digit Potbelly Dial Candlestick Strowger 1905	Dial Candlestick Automatic Electric 1921
		

Footnote: Western Electric	1877:	5 Phones
Engineers were	1894:	250,000 Phones
Wrong! Very Wrong!	1906:	7,500,000 Phones

Electrical Communication at a Distance!

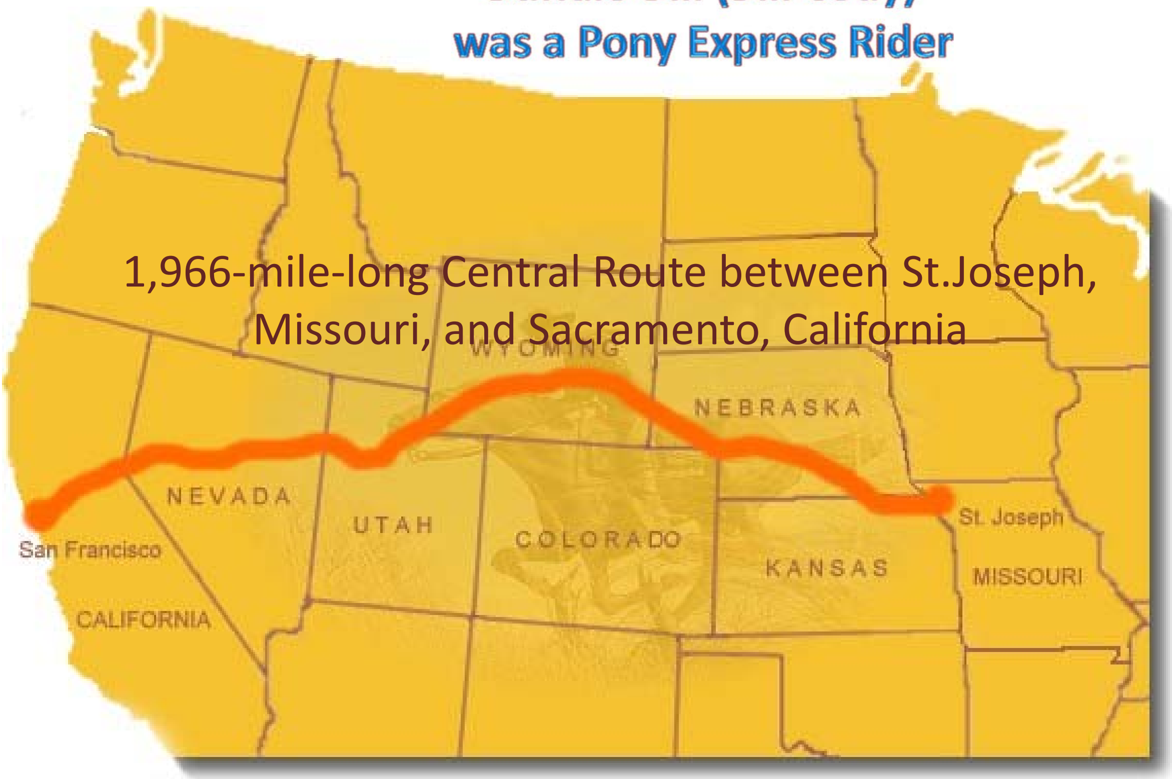
It All Started with the Telegraph!

1837	Cooke and Wheatstone patent telegraph in England.
1838	Morse's Electro-Magnetic Telegraph patent approved.
1843	First telegraph message sent between Washington and Baltimore.
1846	First commercial telegraph line completed. Lines ran from New York to Washington.
1851	New York and Mississippi Valley Printing Telegraph Company. Became Western Union.
1851	Telegraph first used to coordinate train departures.
1859	Transatlantic cable is laid from Newfoundland to Ireland. Fails after 23 days.
1861	Transcontinental telegraph completed. Pony Express Disbanded 2-days Later!
1867	Stock ticker tape service inaugurated.
1870	Western Union introduces the money order service.
1876	Alexander Graham Bell patents the telephone. Upcoming Competition for Telegraph
1924	AT&T offers Teletype system.
1926	Inauguration of direct stock ticker circuit from New York to San Francisco.
1930	High-speed ticker tape can print 500 words per minute.
1962	Western Union offers Telex for international teleprinting (Teleprinter Exchange).
1974	Western Union places Westar satellite in operation.
2006	Western Union discontinues all Telegram and Commercial Messaging services.

Pony Express Route:
10.5 Days of Hard Riding
21 Days by Overland Stage Coach

**Riders were paid $25 per week.
Unskilled labor wages at the time
was about $1 per week.**

**Buffalo Bill (Bill Cody)
was a Pony Express Rider**



1,966-mile-long Central Route between St.Joseph, Missouri, and Sacramento, California

The Pony Express

- In March 1860, William H. Russell newspapers advertisements announced: **"Wanted: Young, skinny, wiry fellows not over 18. Must be expert pony riders willing to risk death daily. Orphans preferred."** Riders had to swear not to cuss, fight, or abuse their animals.

- Starting on April 3, 1860, the Pony Express ran through parts of Missouri, Kansas, Nebraska, Colorado, Wyoming, Utah, Nevada, and California. On an average day, a rider covered 75 to 100 miles. He changed horses at relay stations 10 or 15 miles apart, transferring himself and his mail pouch to the new mount, all in one leap.

- **The first mail by Pony Express from St. Joseph to Sacramento took 10 1/2 days**, cutting the Overland Stage time by more than half. The fastest delivery was in March 1861, when President Abraham Lincoln's inaugural address was carried in 7 days and 17 hours.

- **The Pony Express operated from April 3,1860 through October 24, 1861, when the transcontinental telegraph line was completed.**

The Pony Express survives as a legend in the history of the West.

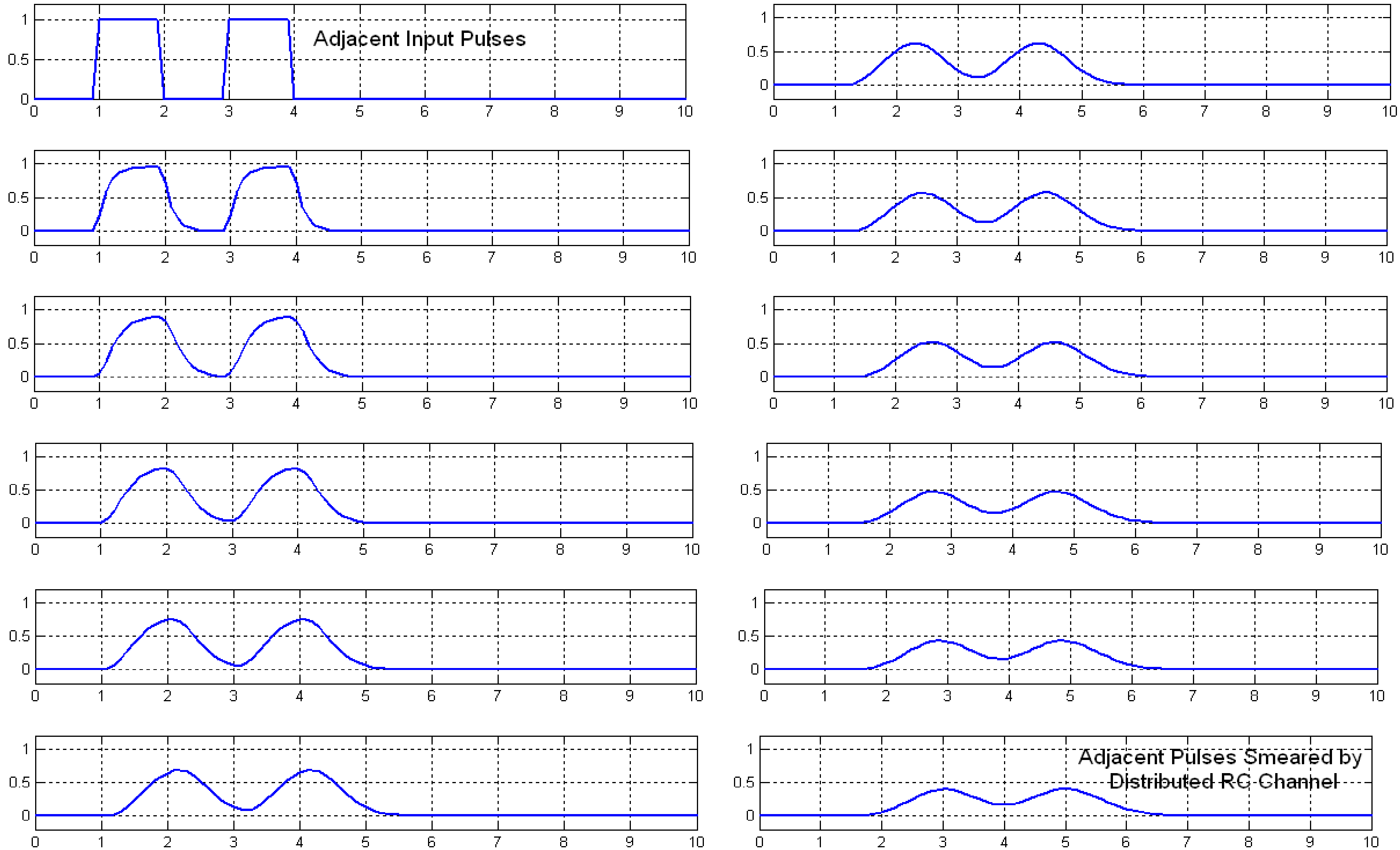
The Telegraph Network: Late 19-th and Early 20-th Century
Enabling Engine of Finance, Commerce, and Transportation

Messages Handled by the Telegraph Network: 1870-1970

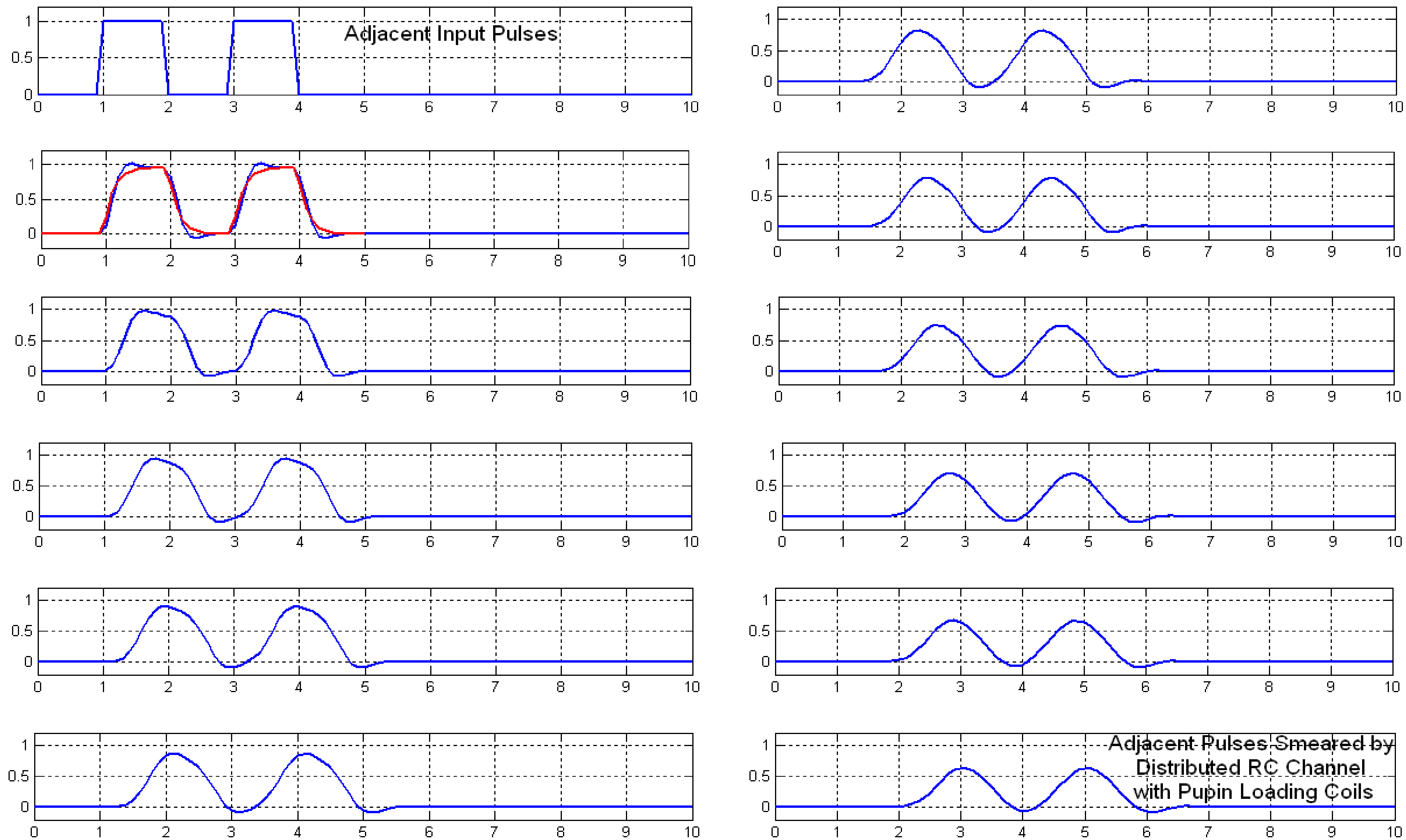
Date	Messages Handled	Date	Messages Handled
1870	9,158,000	1930	211,971,000
1880	29,216,000	1940	191,645,000
1890	55,879,000	1945	236,169,000
1900	63,168,000	1950	178,904,000
1910	75,135,000	1960	124,319,000
1920	155,884,000	1970	69,679,000

Teletype, Telegraph, Telex, Stock Ticker-Tape
Printed Records of Communication

Smearing Of Telegraph Pulses Due to Impulse Response of Distributed RC Cable Channel



Smearing Of Telegraph Pulses Due to Impulse Response of Distributed RC Cable Channel Compensated by Pupin Loading Coils



History & Birth of Modems

- Modems grew out of the need to connect teletype machines over ordinary phone lines instead of more expensive leased lines which had previously been used for current loop-based teleprinters and automated telegraphs.

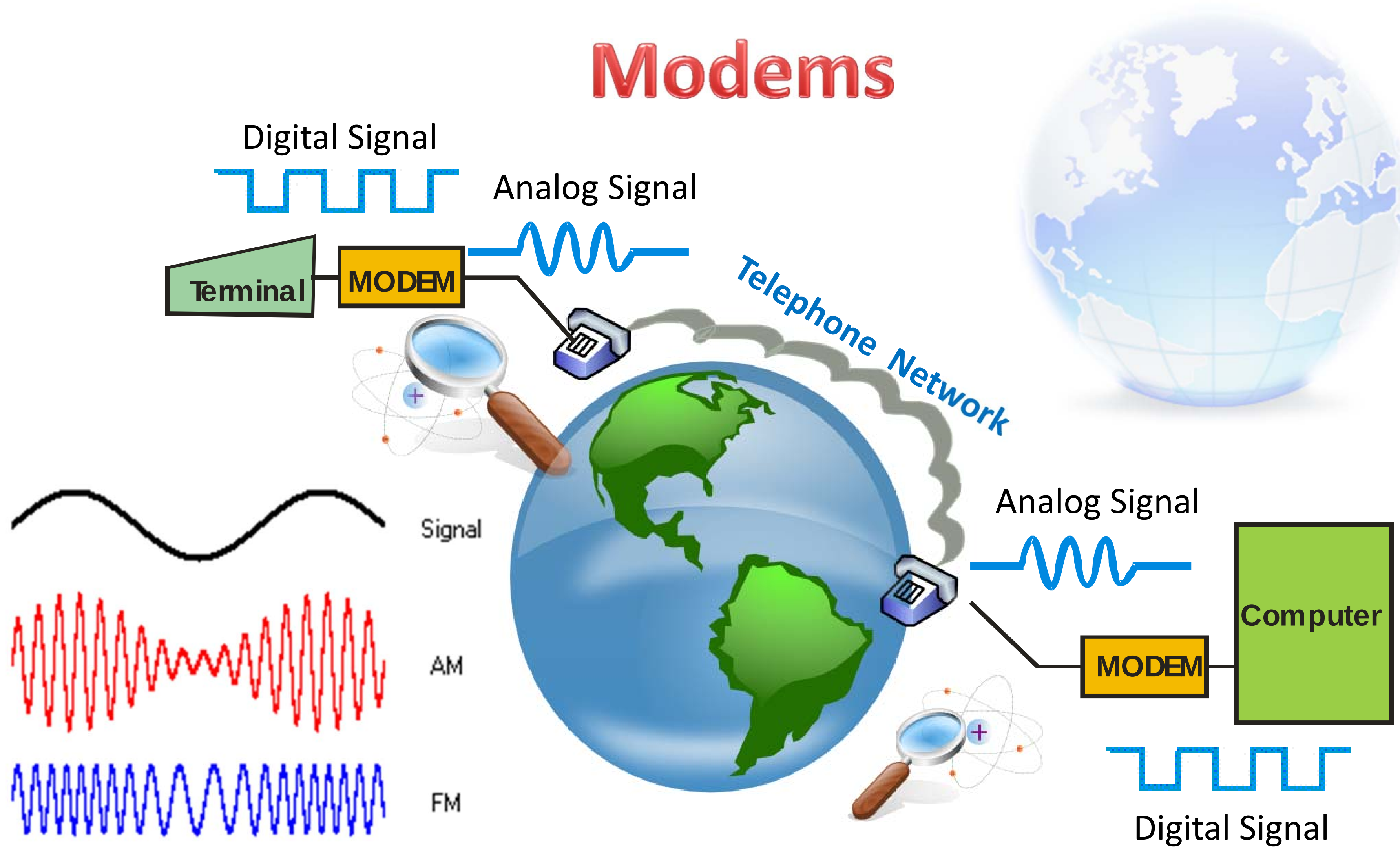
- Mass-produced modems in the United States began as part of NORAD's SAGE air-defense system in 1958, connecting terminals at various airbases, radar sites, and command-and-control centers in the U.S. and Canada.

- SAGE modems were essentially commercial acoustically coupled Bell 101, 110 baud modems.

- Modem: Acronym formed from two words. Modulator and Demodulator
  Modulator and Demodulator 😐 Mod Dem 😐 Modem

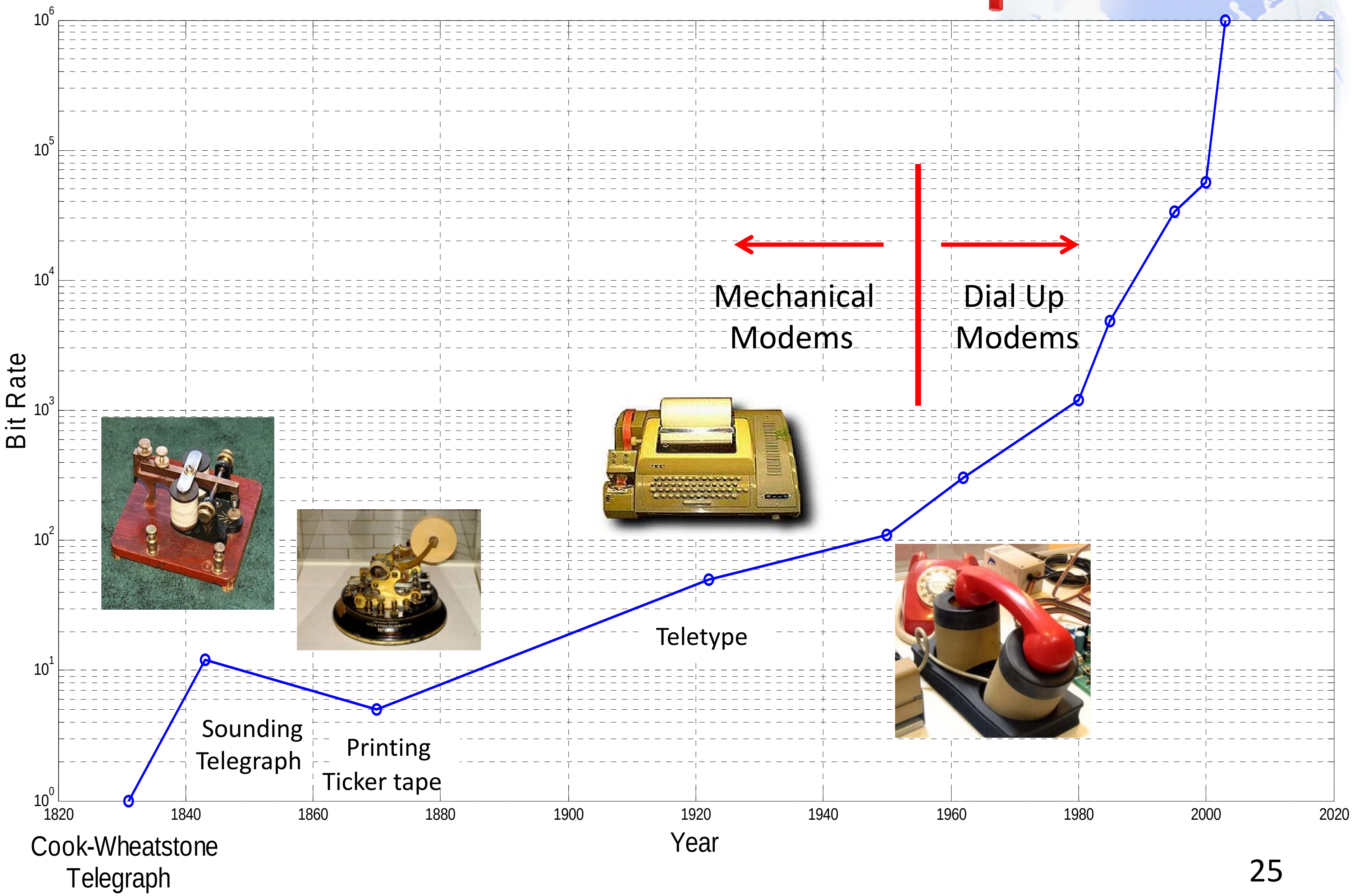
Norad: North American Aerospace Defense Command
SAGE: Semi-Automatic Ground Environment

Modems



Modems are the interface between a computer and the telephone line.

Wire-Line Modem Speeds



Communication at a Distance by Electromagnetic Radiation, (Radio or Wireless)

1894 Guglielmo Marconi improves wireless telegraphy.

1902 Guglielmo Marconi transmits radio signals across the Atlantic Ocean.

1914 First cross continental telephone call made.

1916 First radios with tuners to select different stations.

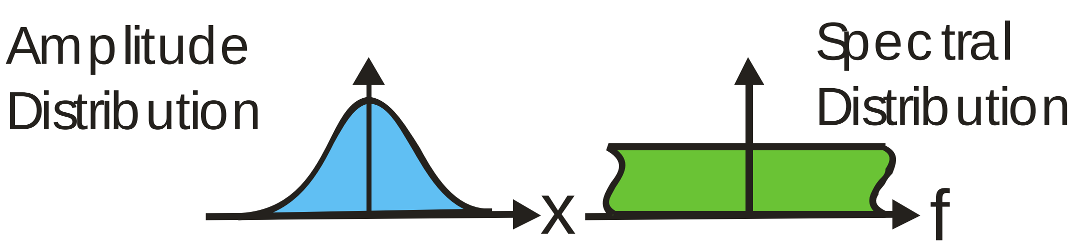
1930 First television broadcasts in the United States.

Russian Astrophysicist Iosif Shklovski Commented:

"For a few decades after invention of the first radio-amplifier the total level of radio-emission from earth increased millions of times in comparison with the normal level of emission of a 300 Kelvin-degree planet. For the shortest time the Earth became #1 source of the radio-emission in the solar system "

It means that, if someone is looking through a radio-telescope at the Solar system from another part of our galaxy, he would register the radio explosion that looks like the birth of a new star on the Earth planet.

The Basic Communication System



The Wireless Channel

The Wireless Channel Propagates Wave Shape Energy Between Remote Locations

Radio Waves are Not Constrained in Space and Share the Medium with Others

Our **First Model** of the Channel is:

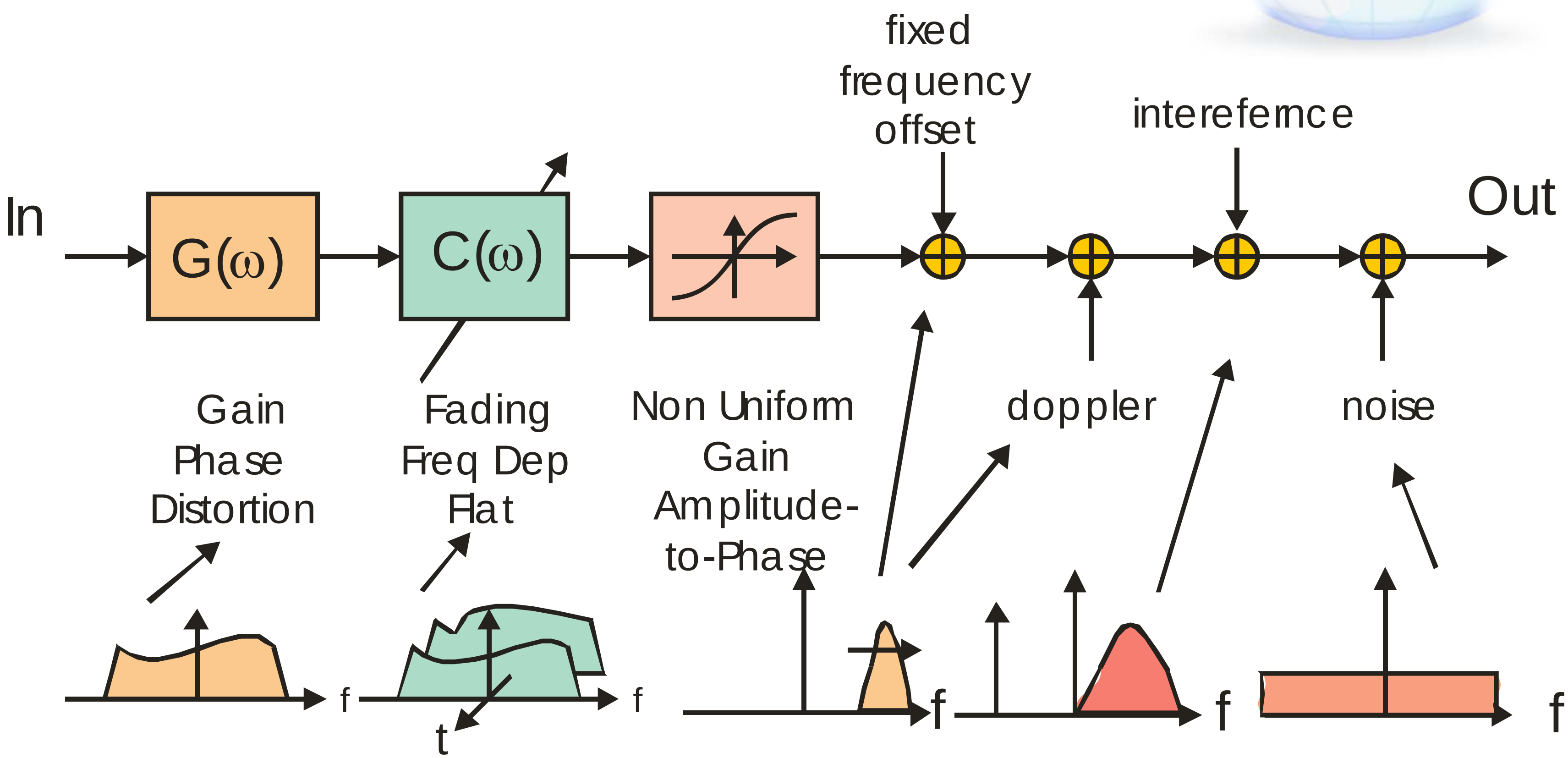
Linear, Time Invariant, with White, Gaussian, Additive Noise

If we Include Transmitter and Receiver in the Channel Model we find

Our **Second Model** of the Channel is:

Non Linear, Time Varying, with Non White, Non Gaussian, Additive Noise

More Inclusive Channel Impairments



Modern Physical Layer Modem Recipe: Add these Ingredients, Stir, Bake for 20 Minutes at 300°. Let Cool! Enjoy your Modem!

- **First Tier Processing: Modulation and Demodulation**
  - Shaping Filters
  - Interpolation
  - Spectral Translation
  - Signal Conversion

DSP Genie-1

- **Second Tier Processing: Parameter Estimation**
  - Carrier Frequency and Phase Synchronization
  - Timing Frequency and Phase Synchronization
  - Automatic Gain Control
  - SNR Estimate

DSP Genie-2

DSP Genie-3

- **Third Tier Processing: Channel and Hardware (Dirty RF)**
  - Equalization
  - I-Q Balance
  - DC-Cancel
  - Peak-to-Average Ratio (PAPR) Control
  - Predistortion
  - Interference Suppression
  - Intrusion Suppression
  - Power Amplifier Linearization

DSP Genie-4

DSP Genie-5

Modem Ingredients

- Signal Strength Indicator
- Log Amplifier
- Signal Presence (Squelch)
- Overdrive Protection
- Automatic Gain Control (AGC)
- Logarithm and Exponentiation
- Amplitude Demodulation
- Frequency Demodulation
- Phase Demodulation
- Carrier Frequency & Phase Recovery Phase Locked Loop
- Symbol Timing Frequency & Phase Recovery Phase Locked Loop
- ATAN (Nobody Does This!)
- Comparator
- Delay
- DC Cancel
- I-Q Gain and Phase Balance
- Interleaved ADC Gain and Timing Balance
- Predistortion
- Peak-to-Average Power Ratio Control
- Interference Suppression
- Intrusion Suppression
- Power Amplifier Linearization
- Signal-to-Noise Ratio Estimate (Nobody Does This!) (I'm Shocked!)
- Analog-to-Digital Converter (ADC)
- Digital-to-Analog Converter (DAC)
- Fast Fourier Transform (FFT)
- Interpolator (Sample Rate Change)
- Direct Digital Synthesizer (DDS)
- Channelize

Important Technology Developments

- Pupin Loading Coils
- Echo Cancellers
- Fixed Equalizers
- Adaptive Equalizers
- Phase Locked Loops
- μ-Processors
- A-to-D Converters
- D-to-A Converters

Why Are There So Many Modulation Options?

- Analog Modulation
  - AM, Amplitude Modulation
  - SSB, Single Sideband Modulation
  - VSB, Vestigial Sideband Modulation
  - QAM, Quadrature AM
  - FM, Frequency Modulation
  - PM, Phase Modulation
  - Space Modulation
    (ILS Instrument Landing System)

- Spread Spectrum Modulation (SS)
  - CSS, Chirp Spread Spectrum
  - DSSS, Direct-Sequence Spread Spectrum
  - FHSS, Frequency-Hopping Spread Spectrum
  - PWM, Pulse-Width Modulation
  - PCM, Pulse-Code Modulation

- Digital Modulation
  - OOK, On-Off Keying
  - FSK, Frequency Shift Keying
  - DTMF, Dual-Tone Multi-Frequency
  - MFSK, Multiple Frequency Shift Keying
  - ASK, Amplitude Shift Keying
  - PSK, Phase Shift Keying
  - BPSK, Binary PSK
  - QPSK, Quadrature PSK
  - OQPSK, Offset PSK
  - π/4-QPSK,
  - DQPSK, Differential QPSK
  - DPSK, Differential PSK
  - QAM, Quadrature Amplitude Modulation
  - MSK, Minimum (Phase) Shift Keying
  - GMSK, Gaussian MSK
  - CPM, Continuous Phase Modulation
  - PPM, Pulse Position Modulation
  - TCM, Trellis Coded Modulation
  - OFDM, Orthogonal Frequency Division Multiplex
  - SC-OFDM, Single Carrier OFDM

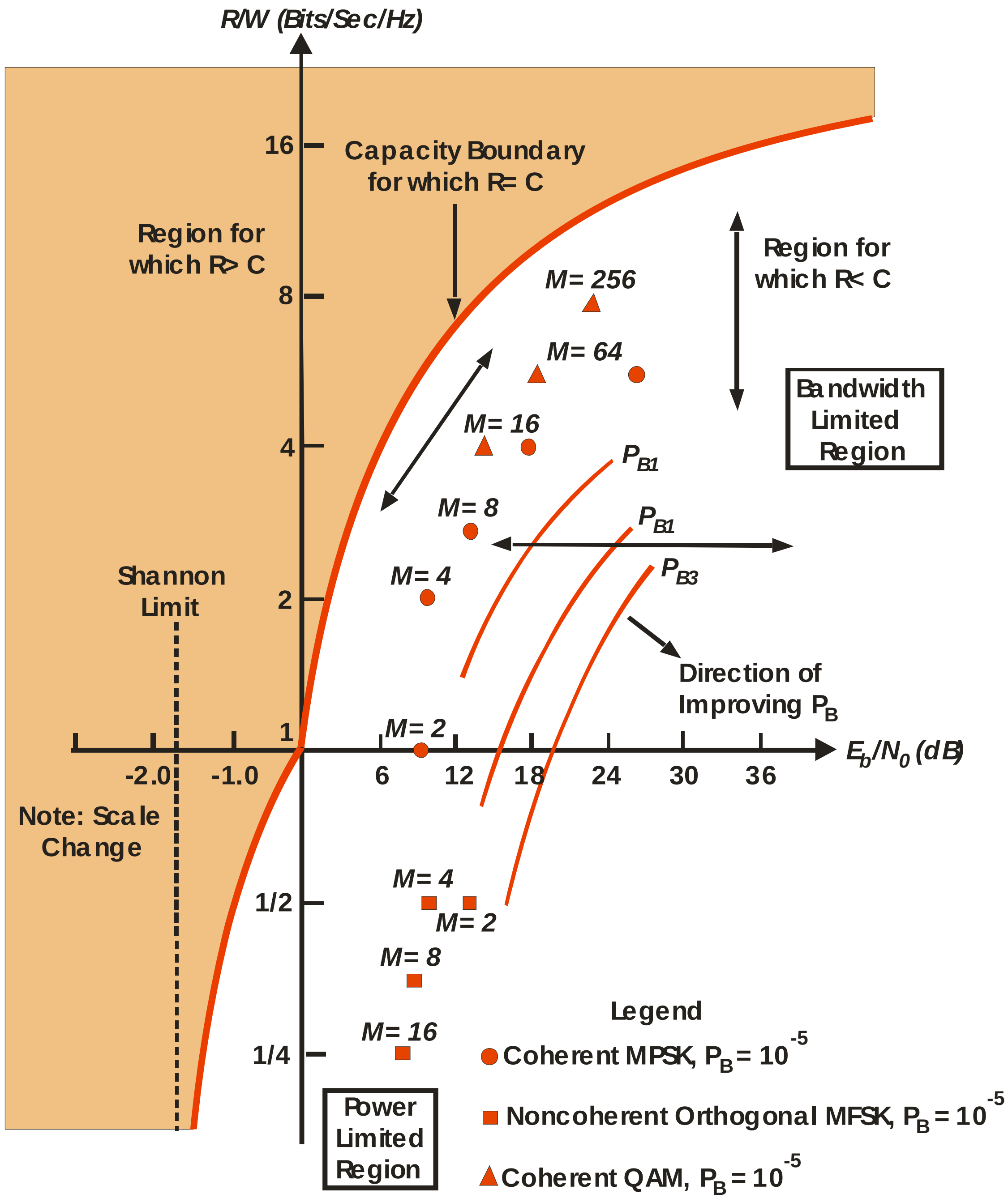
Reasonable Goals

- Maximize transmission Bit Rate
- Minimize probability of bit error
- Minimize system Bandwidth
- Minimize Size, Weight, & Power
- Maximize system utilization
- Minimize system complexity
- Minimize cost

Boundary Conditions

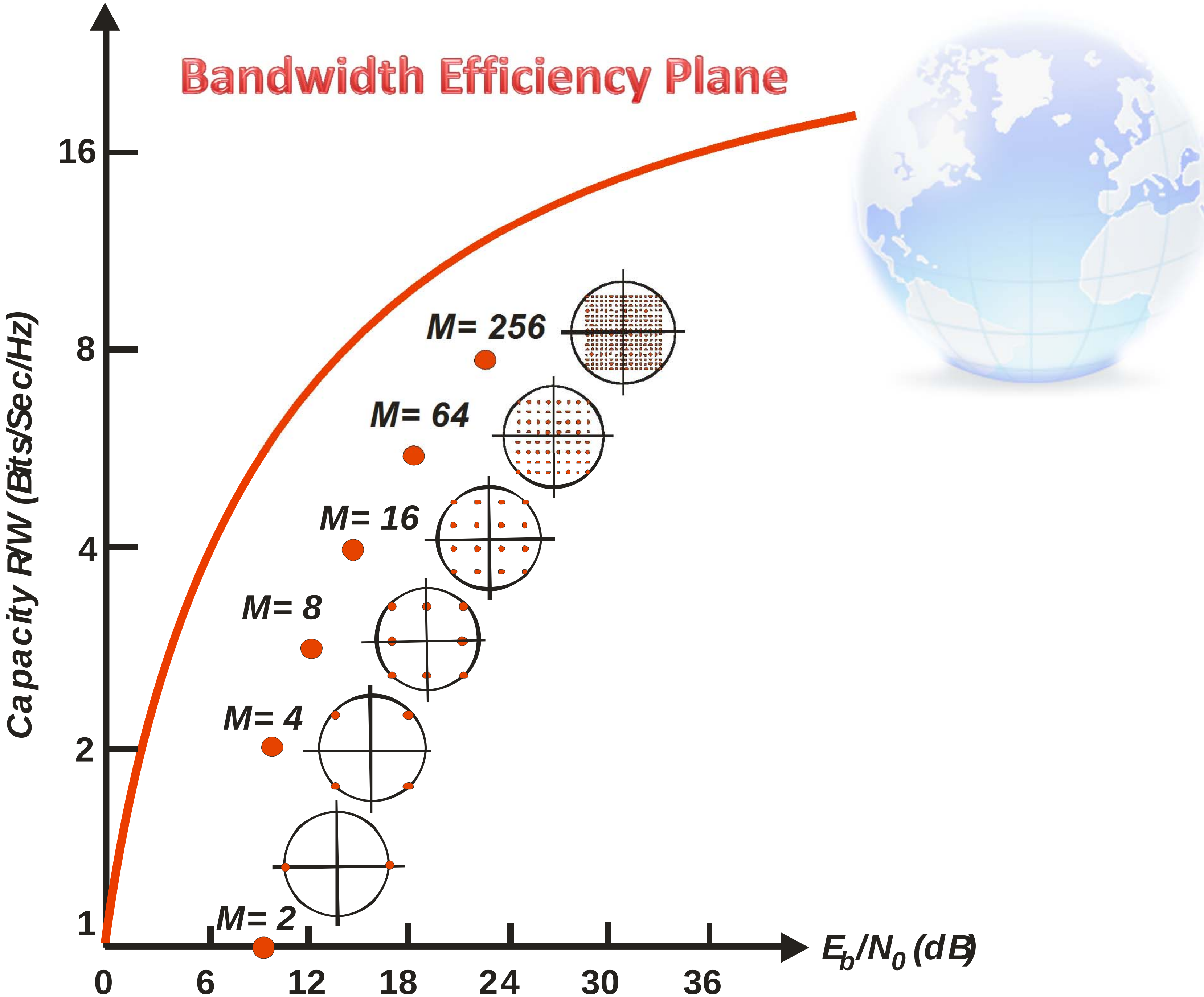
- Nyquist Bandwidth Requirement
- Shannon-Hartley Capacity Theorem
- Technology Limitations
- Regulatory and Treaty Limitations
- Deployment Restrictions

  (Laws of Physics, Antenna Placement, Satellite orbits, Etc.)



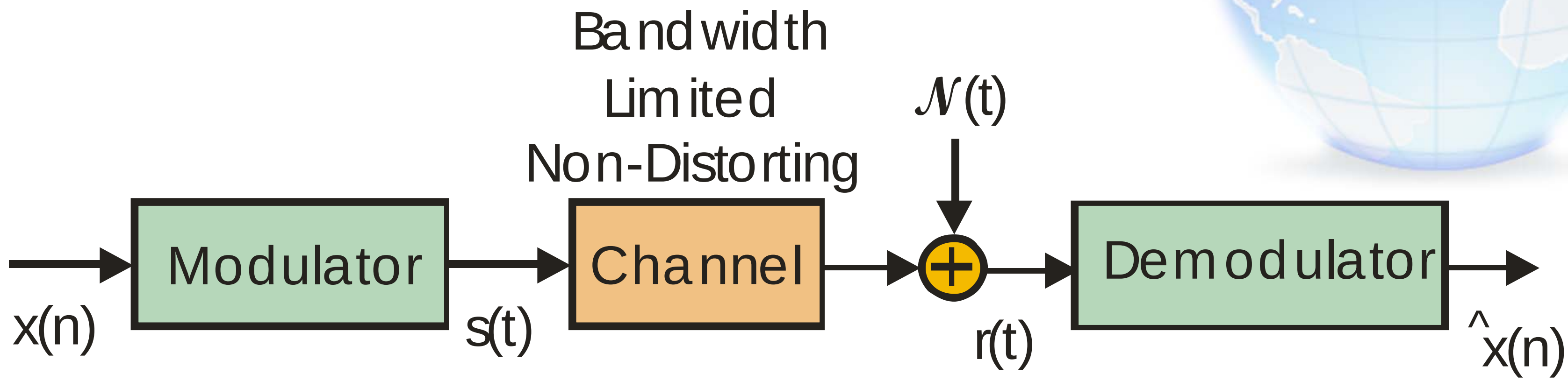
Bandwidth Efficiency Plane

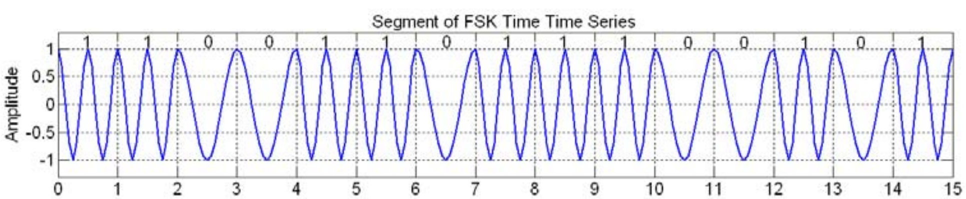
Complements of Bernard Sklar

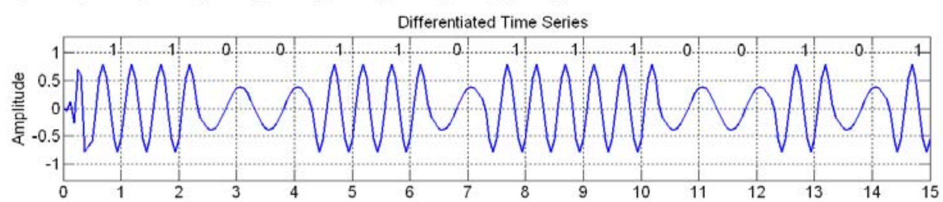


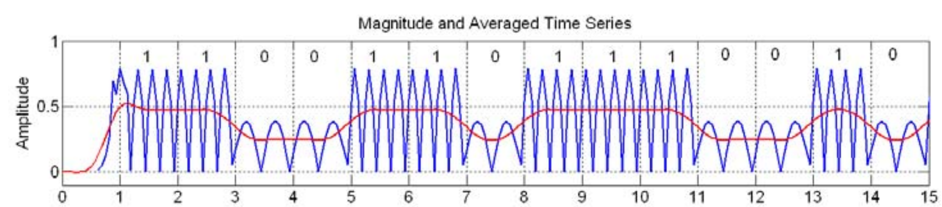
Bandwidth Efficiency Plane
Capacity R/W (Bits/Sec/Hz)
16
8
4
2
1
M= 256
M= 64
M= 16
M= 8
M= 4
M= 2
0
6
12
18
24
30
36
E_b/N_0 (dB)

FSK Modulator-Channel-AWGN-Demodulator

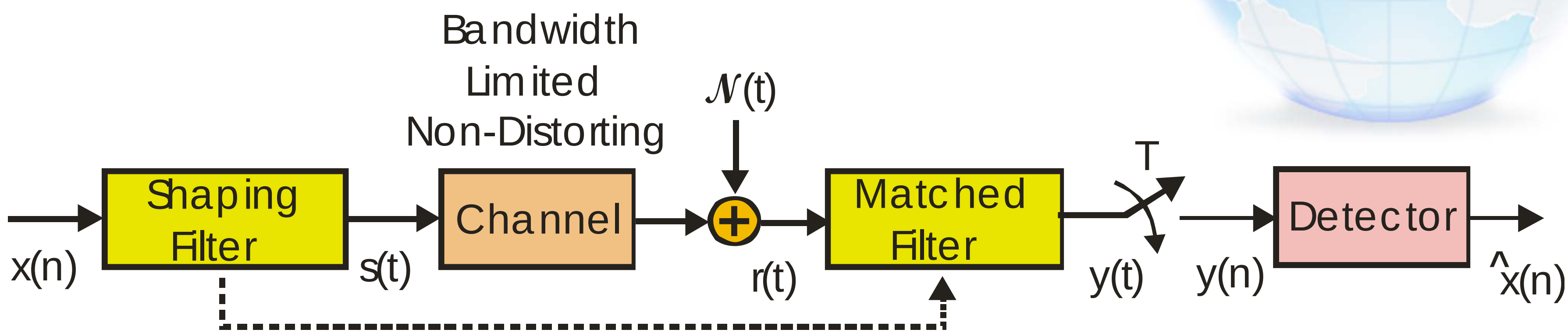


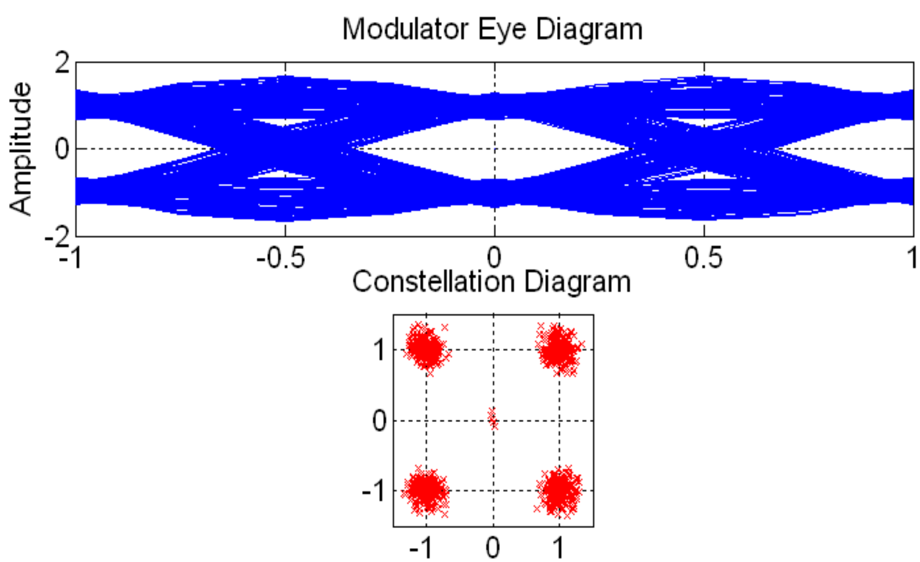


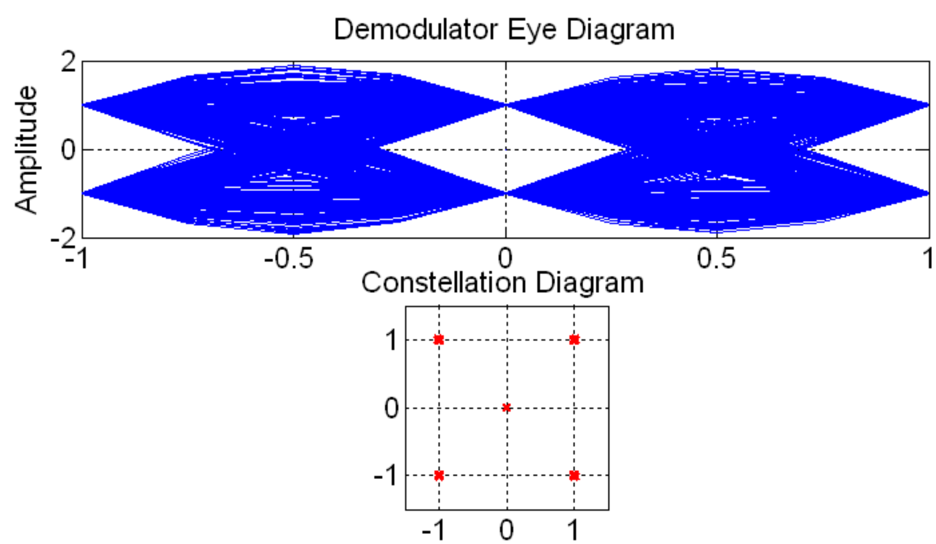




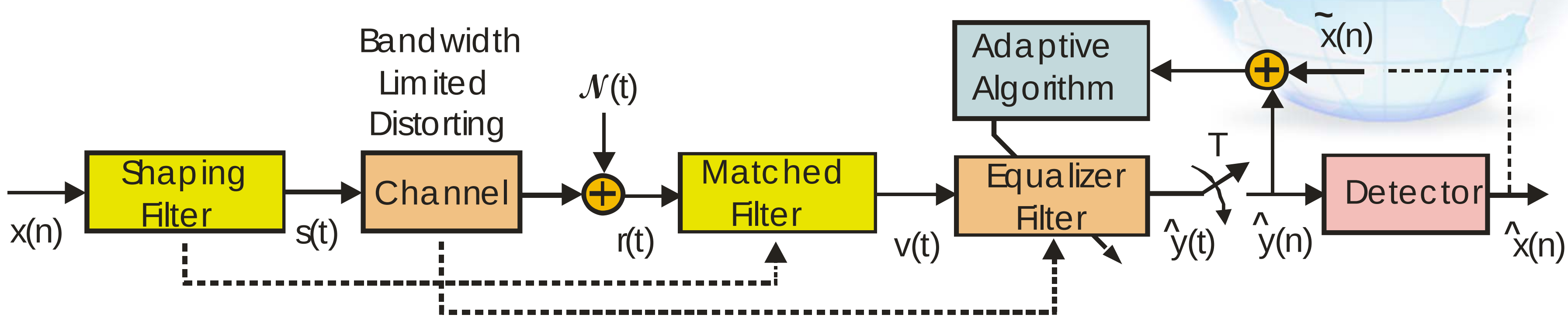
Shaping Filter in Modulator, Matched Filter in Demodulator

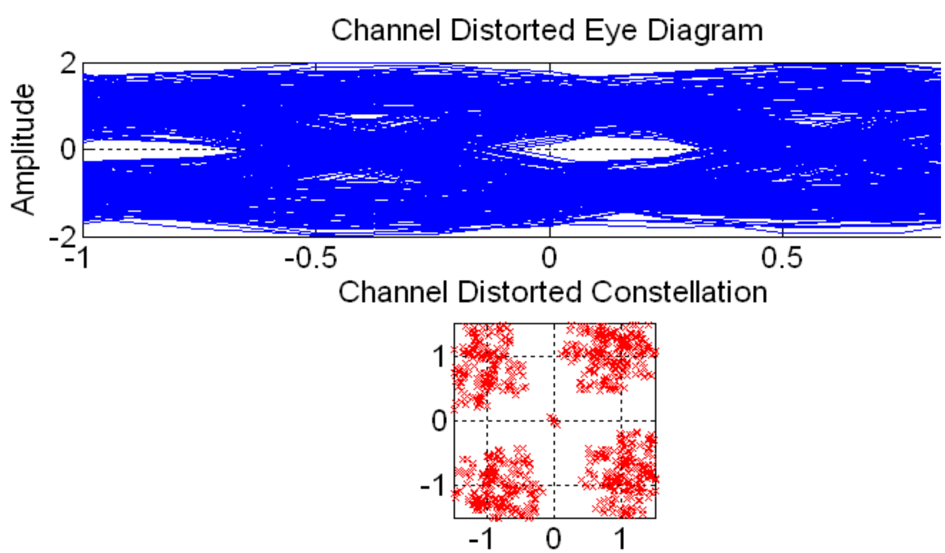


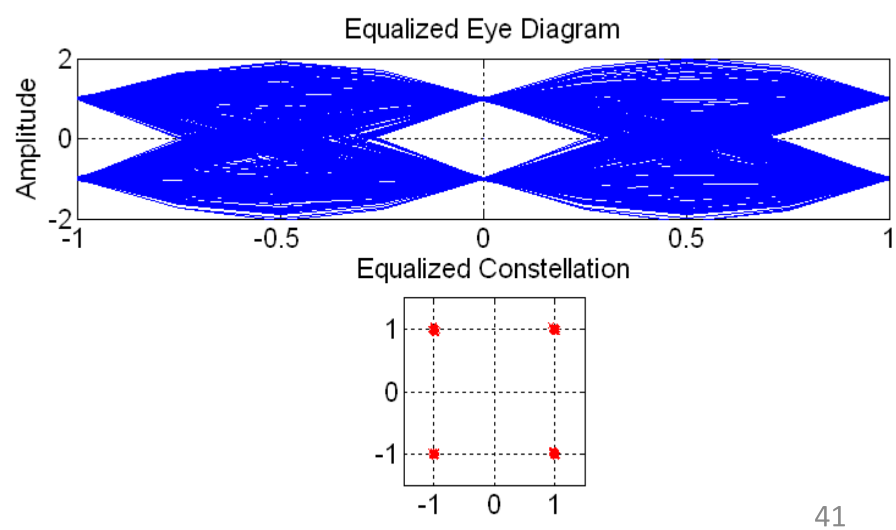




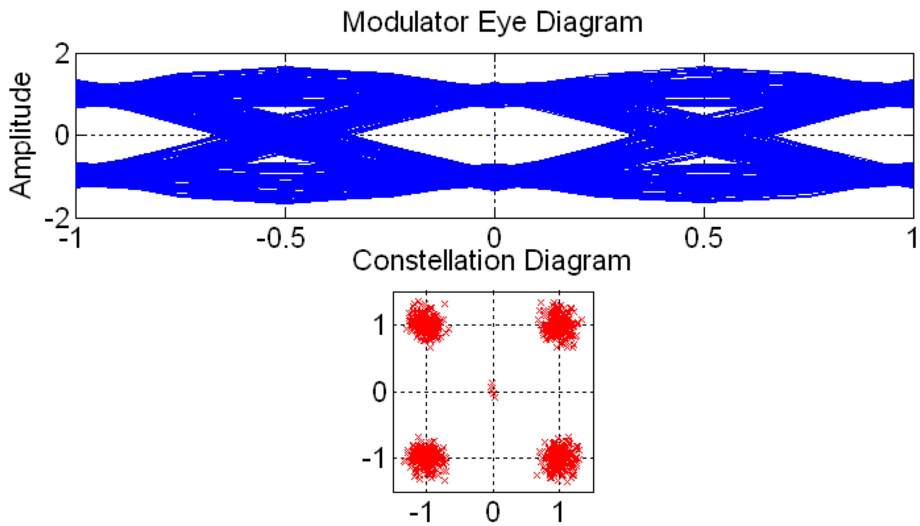
Distorted Output of Channel and Output of Channel Equalizer

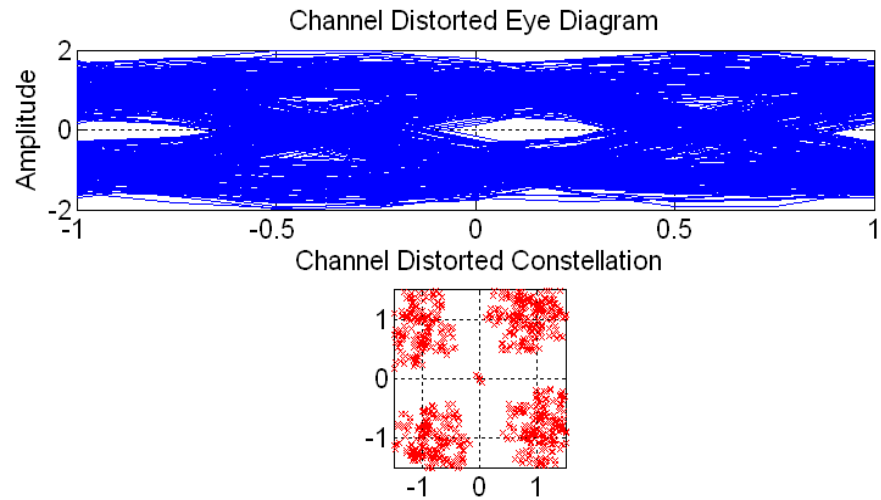


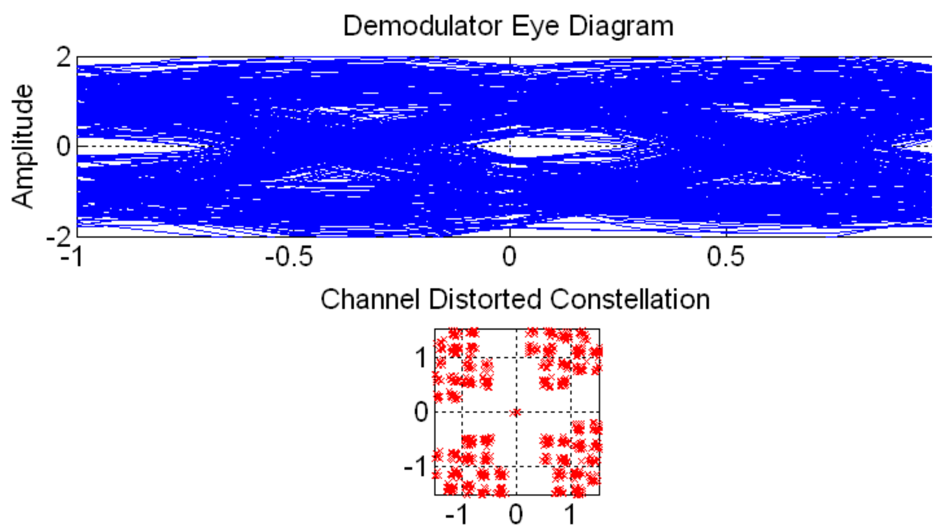


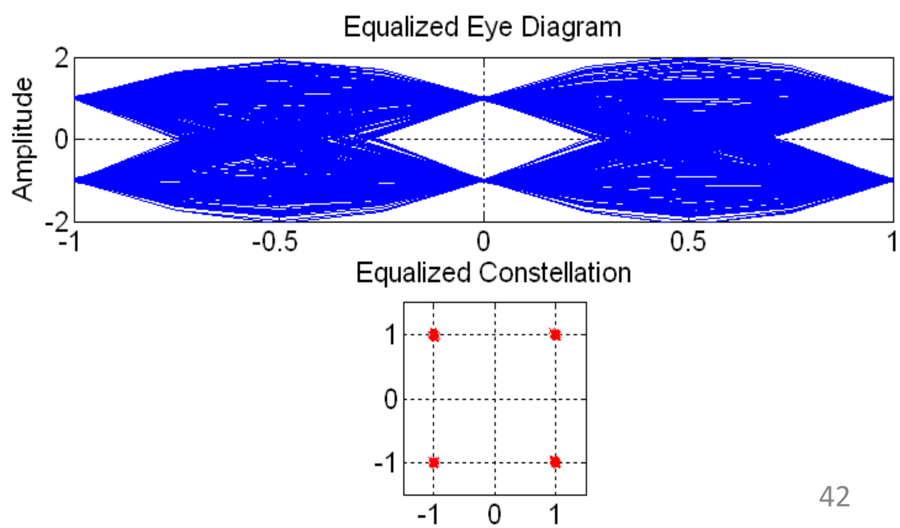


Eye Diagrams: Channel Input and Output
Matched Filter and Equalizer Outputs



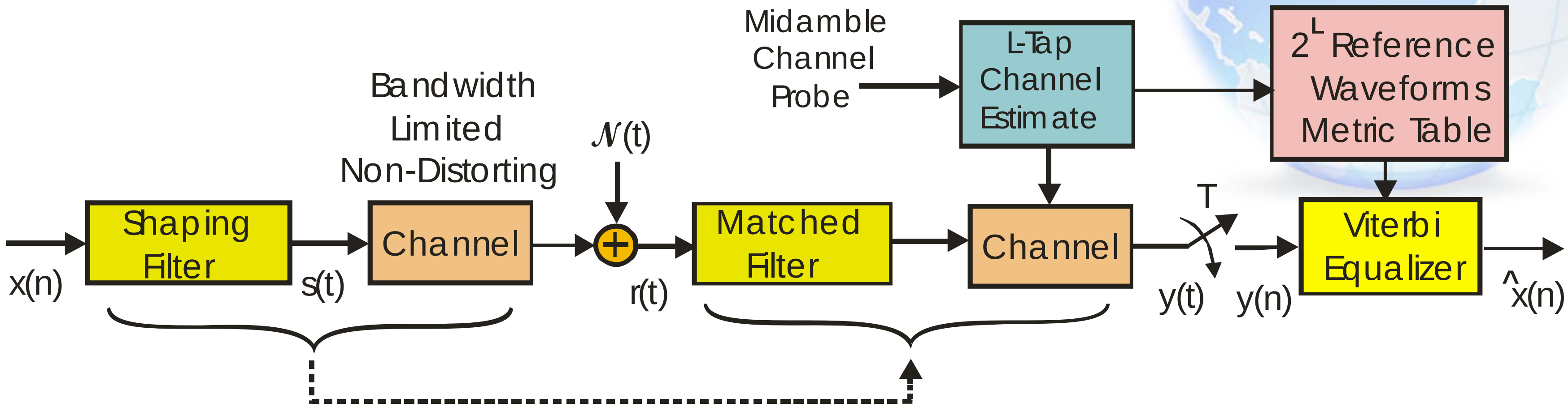


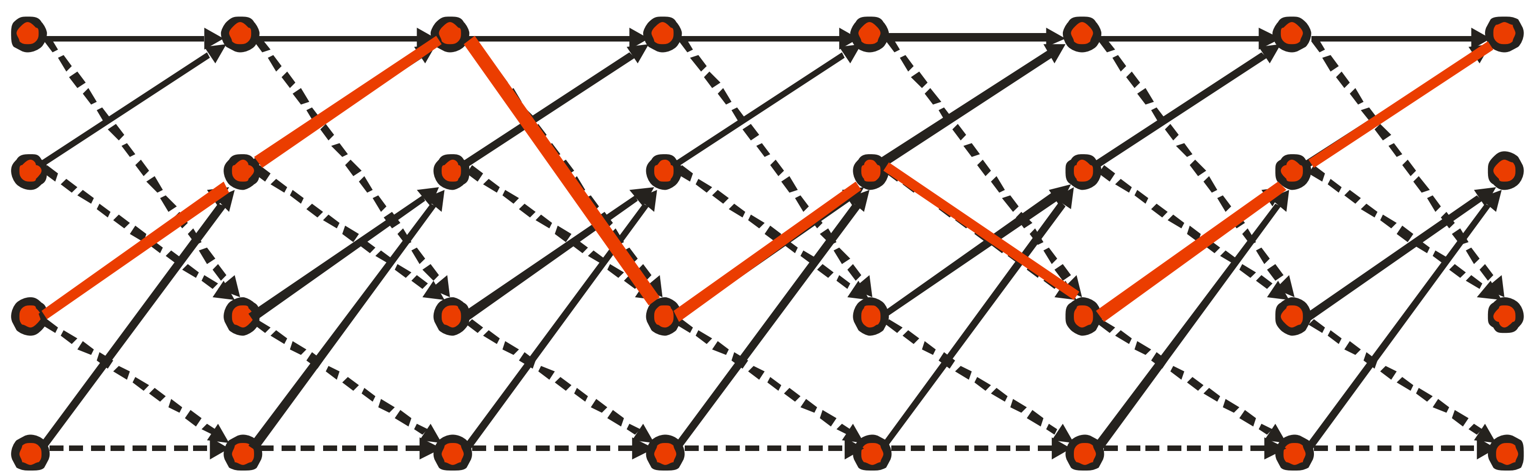




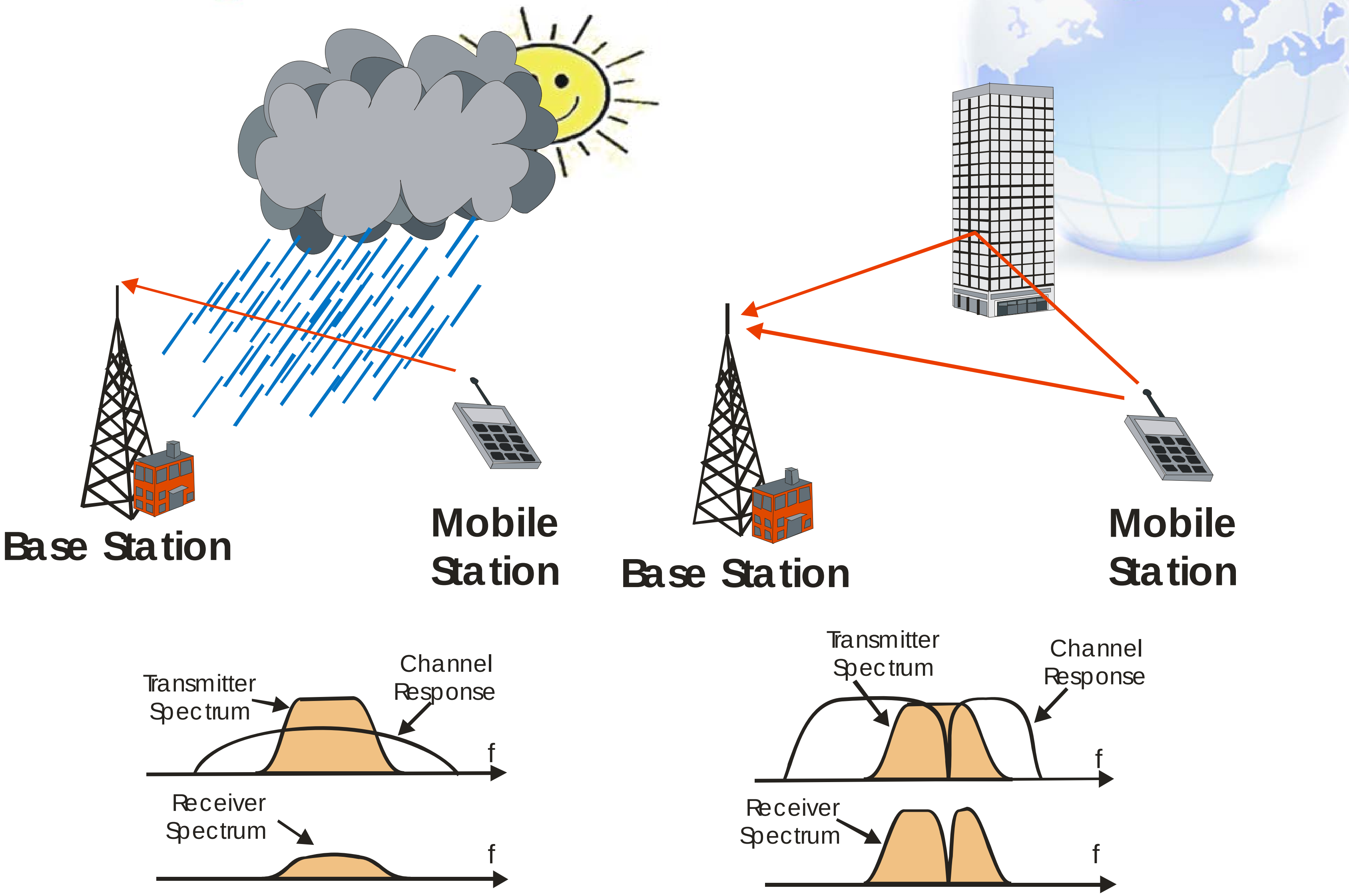
Viterbi Equalizer

Maximum Likelihood Estimate of Data Sequence





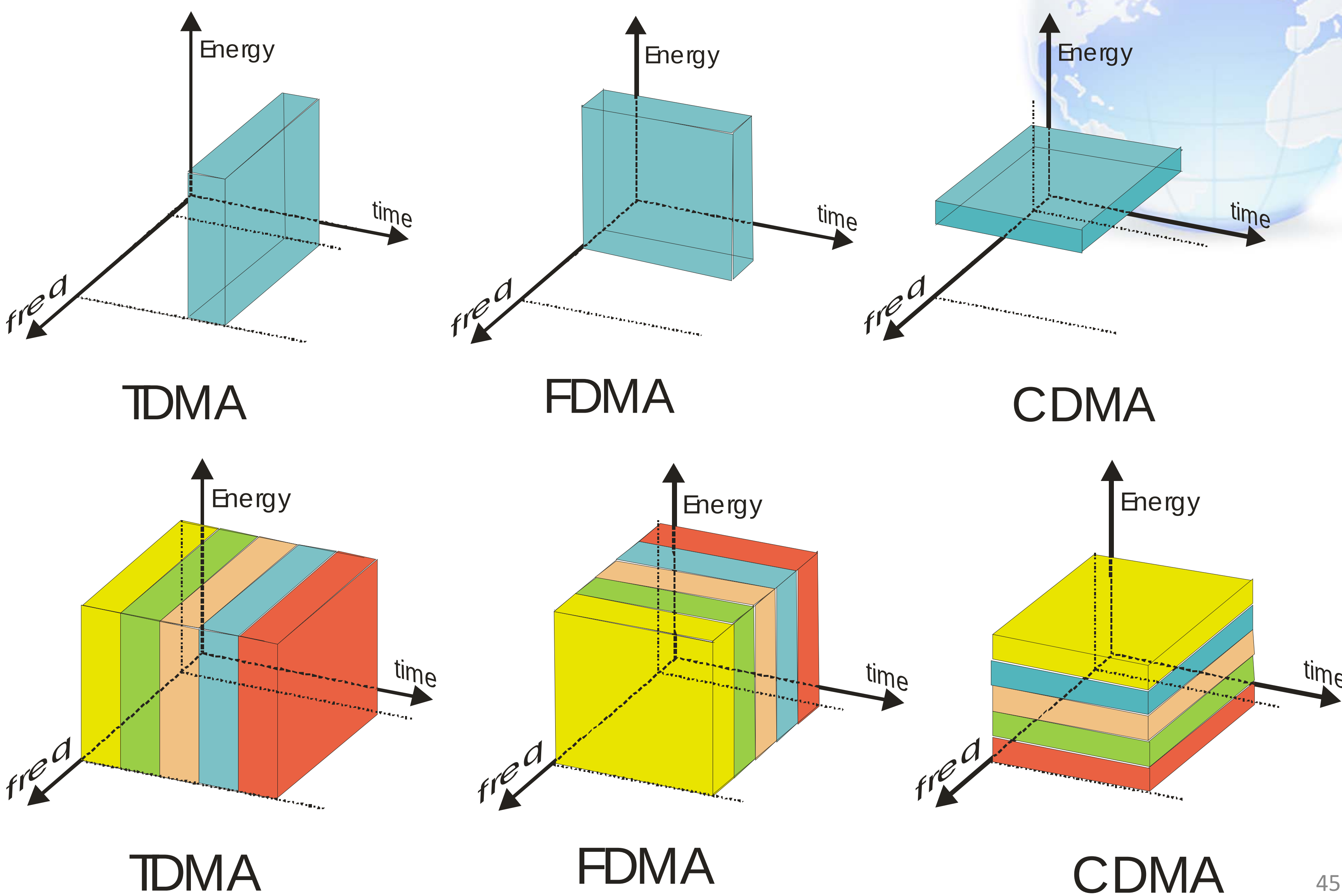
Flat Fading and Frequency Selective Fading



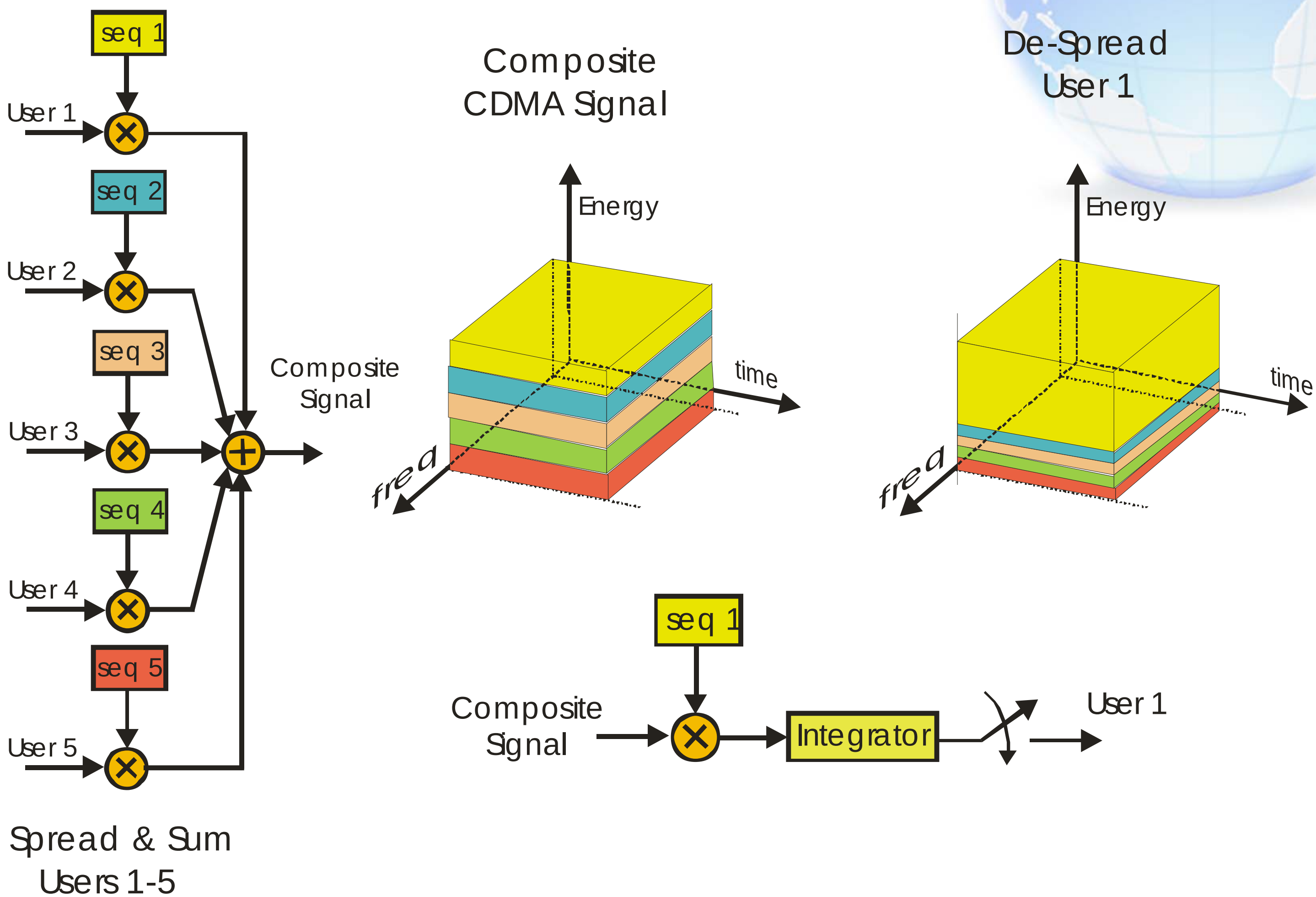
Flat Fading

Frequency Selective Fading

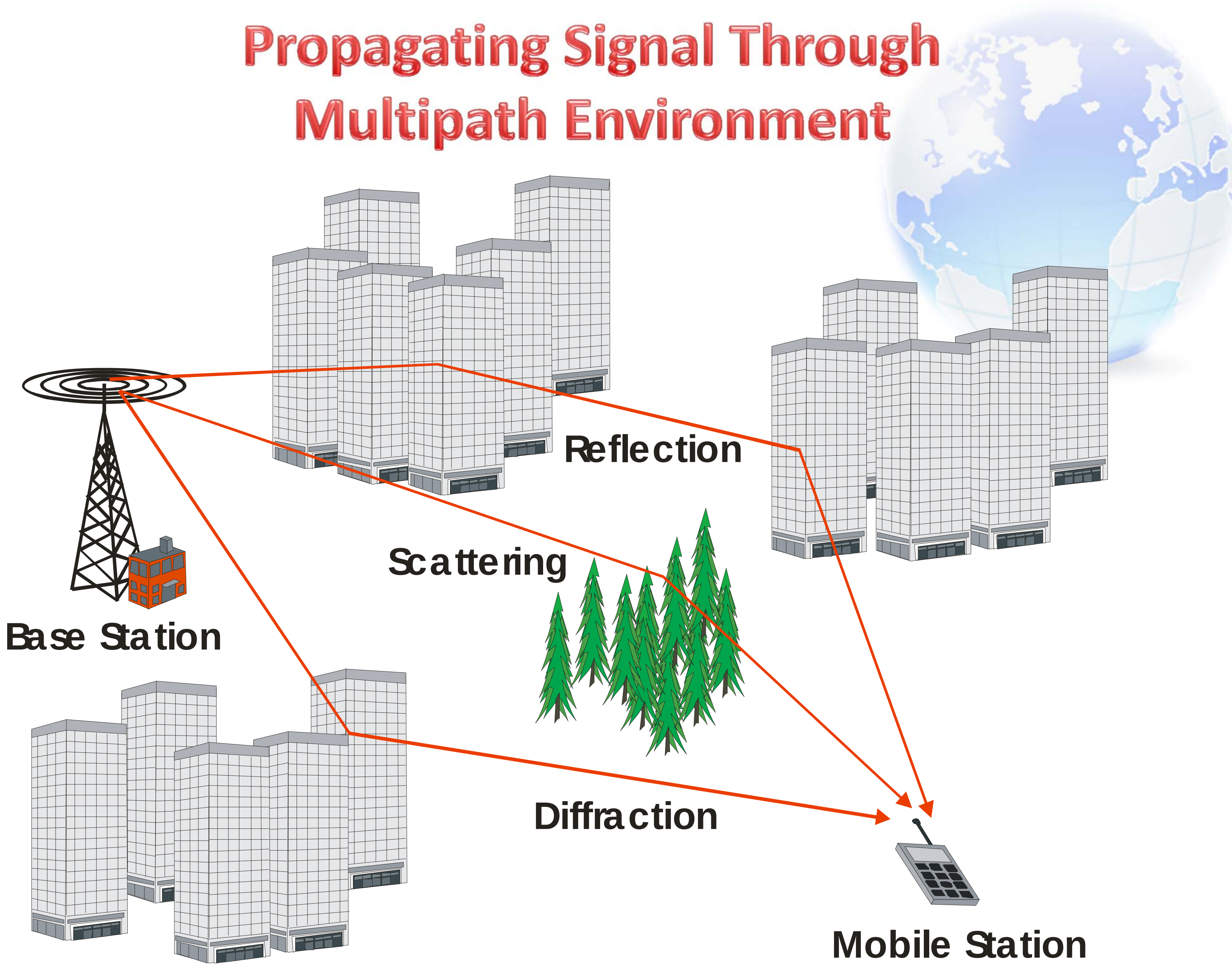
Share Time-Bandwidth Resources Among Multiple Users



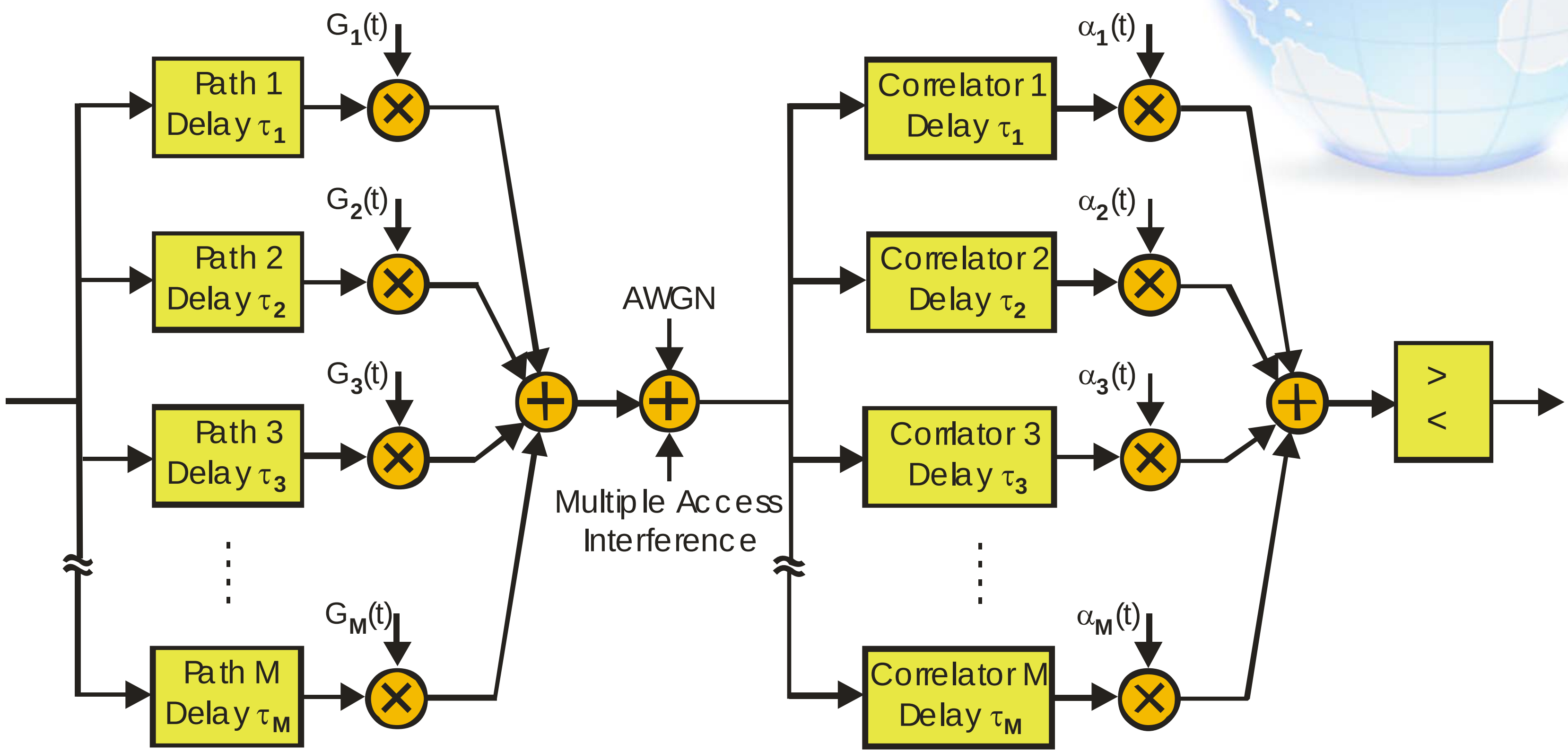
CDMA:
Direct Sequence Spread Spectrum, DS-SS



Propagating Signal Through Multipath Environment



Multipath Channel Model and Rake Receiver Correlators aligned with Multipath Signals



Channel Model

Rake Receiver

Modulation Evolution

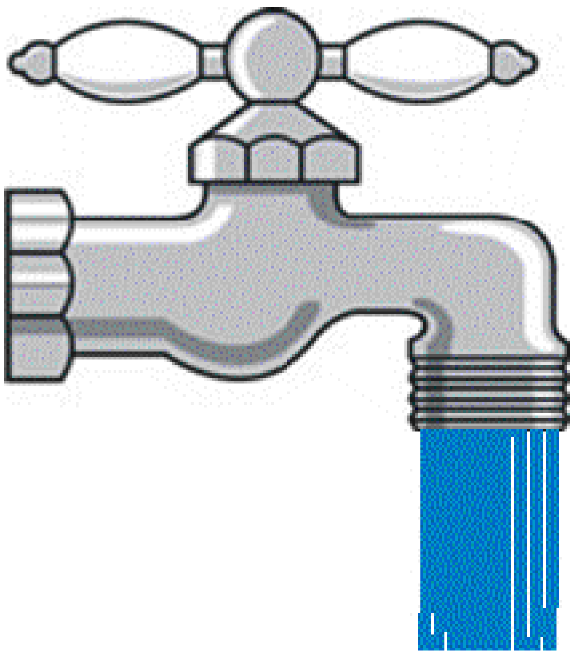
- **QAM** Shaping Filters Minimize Bandwidth to Share Channel Resource
- Channel Distortion, Combated by Channel Inversion by **Tapped Delay Line Filter**

- **GSM** Probe Channel, Learn T-Tap Impulse Response, Fold Impulse Response into MF
- Form List of 2^L Possible Sequences from Channel Impulse Response and MF
- Build Metric Table and Determine Maximum Likelihood Sequence with **Viterbi Decoder**

- **CDMA** Increased Modulation Bandwidth Offers Frequency Diversity
- Wide Bandwidth Signals have Narrow Main Lobe Correlation Width
- Narrow Correlation Width Permits Temporal Resolution of Multipath Components
- Multipath Spreading Combated in **Rake Receiver:**
  Channel Inversion by Time Aligned and Phase Coherent Sum of
  Multiple Correlator Outputs

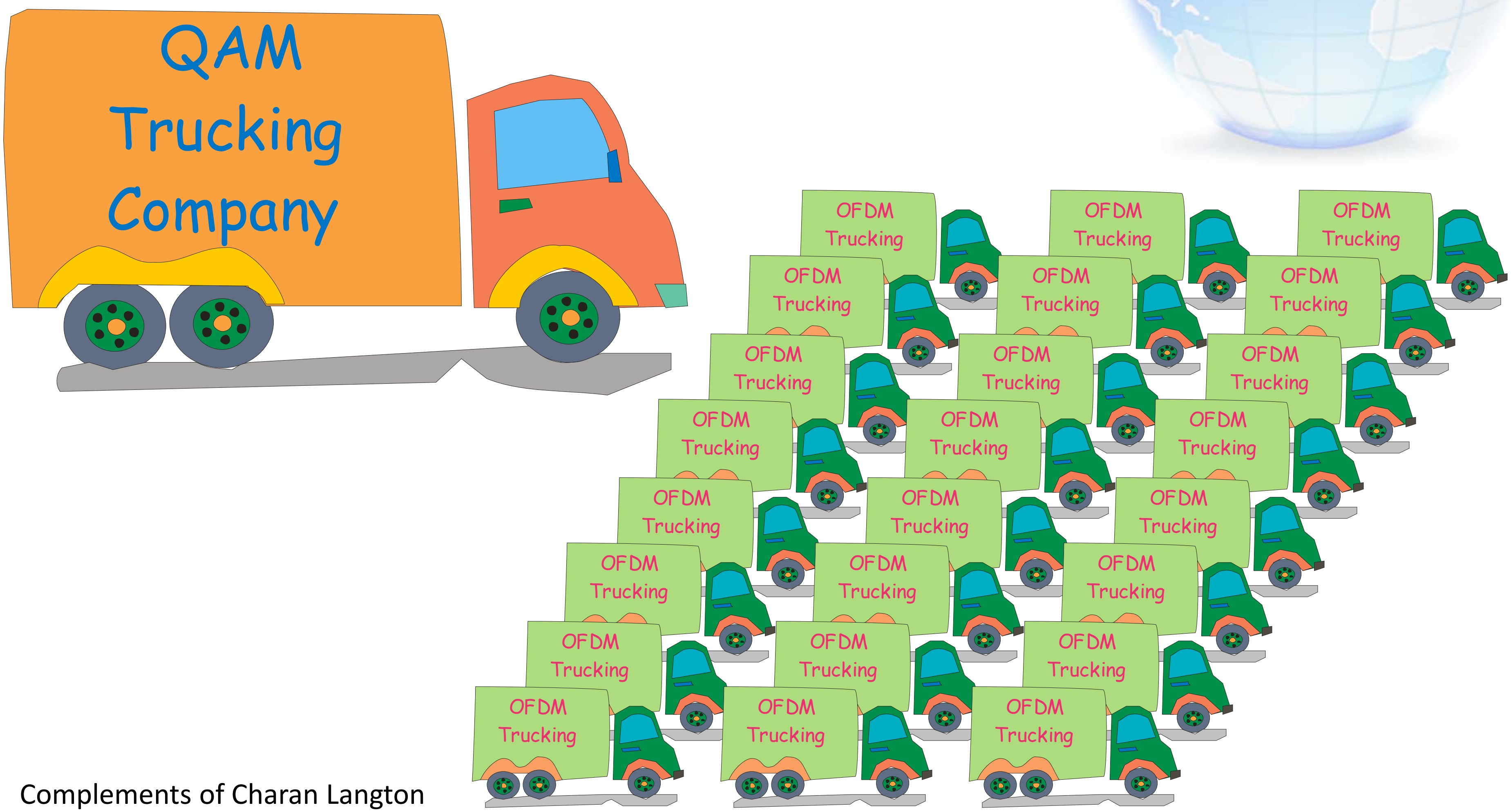
- **OFDM** Increased Bandwidth for Higher Data Rate (Without Spreading)
- Wider BW Channels Offer More Channel Distortion
- Rather than Increase Bandwidth, Reduce Bandwidth by Partitioning Available Bandwidth
  into Multiple Narrowband, Extended Time Duration, Sub-Channels
- Discrete Fourier Transform (DFT) Modulation and Demodulation
  Channel Inversion by **Frequency Domain Equalizer**

QAM One Wide Band Pipe
OFDM Many Parallel Narrow Band Pipes



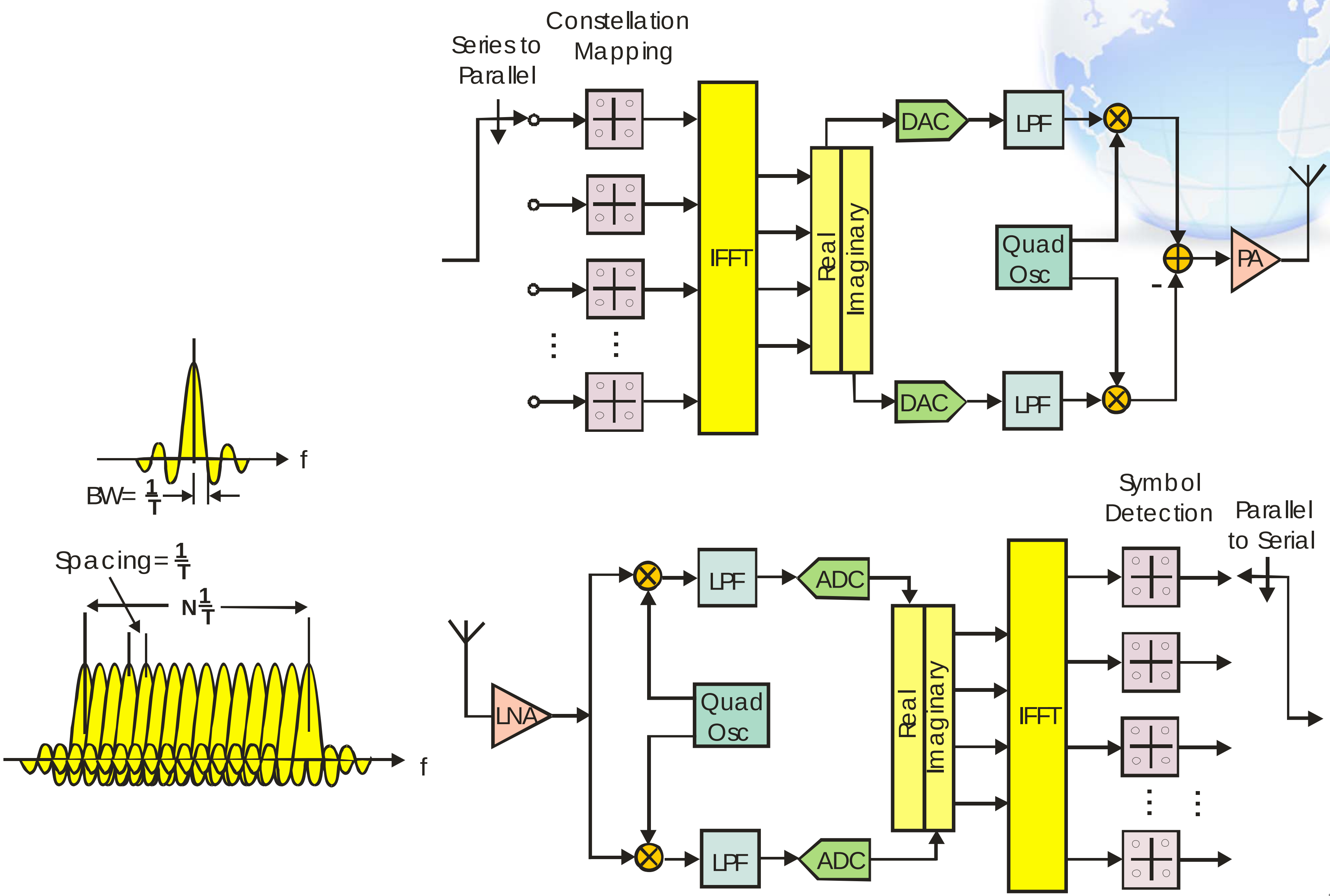
Complements of Charan Langton
Loral Space Systems,
www.complxtoreal.com

QAM: One Big Delivery Vehicle
OFDM: Many Small Delivery Vehicles

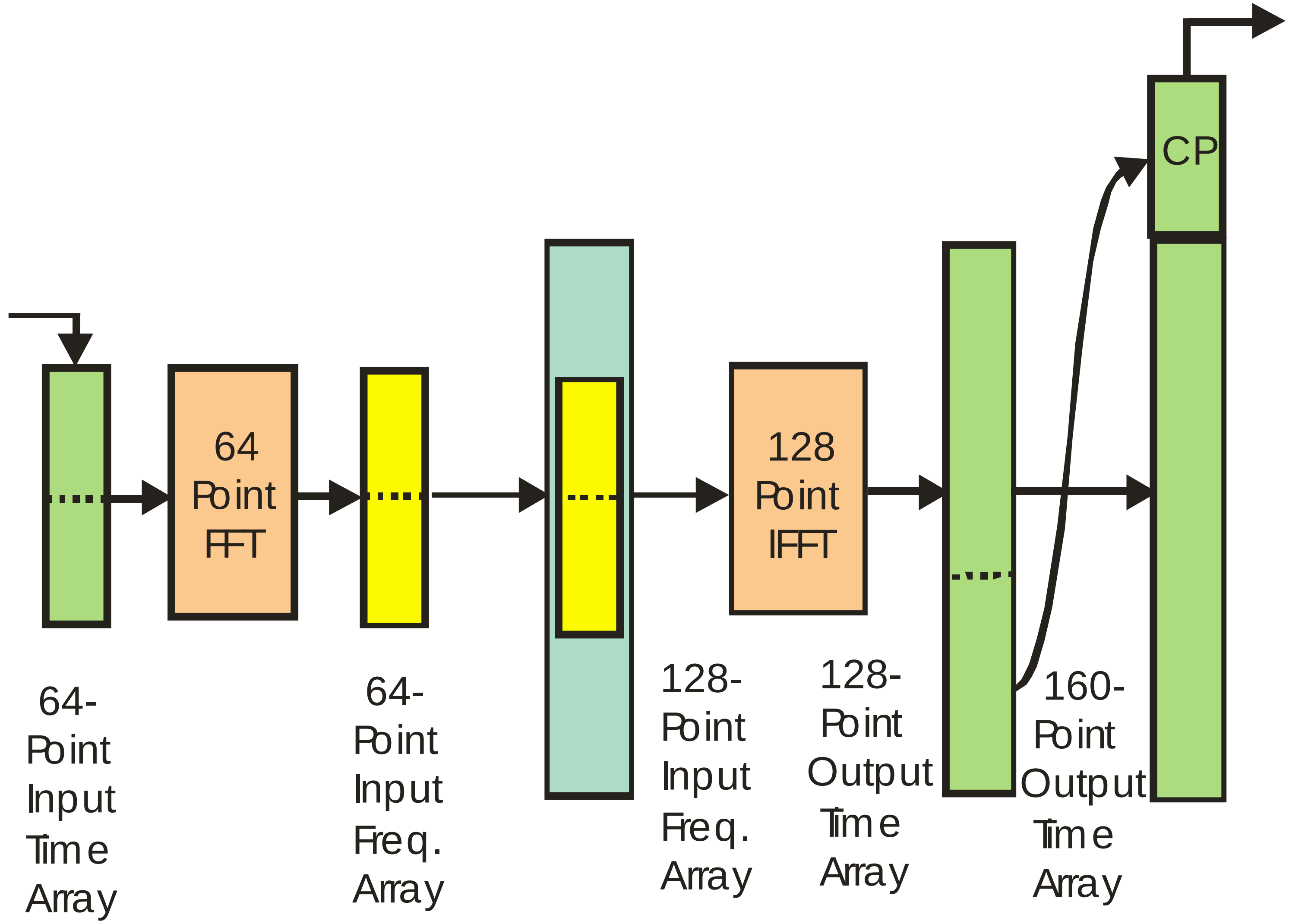


Complements of Charan Langton
Loral Space Systems,
www.complxtoreal.com

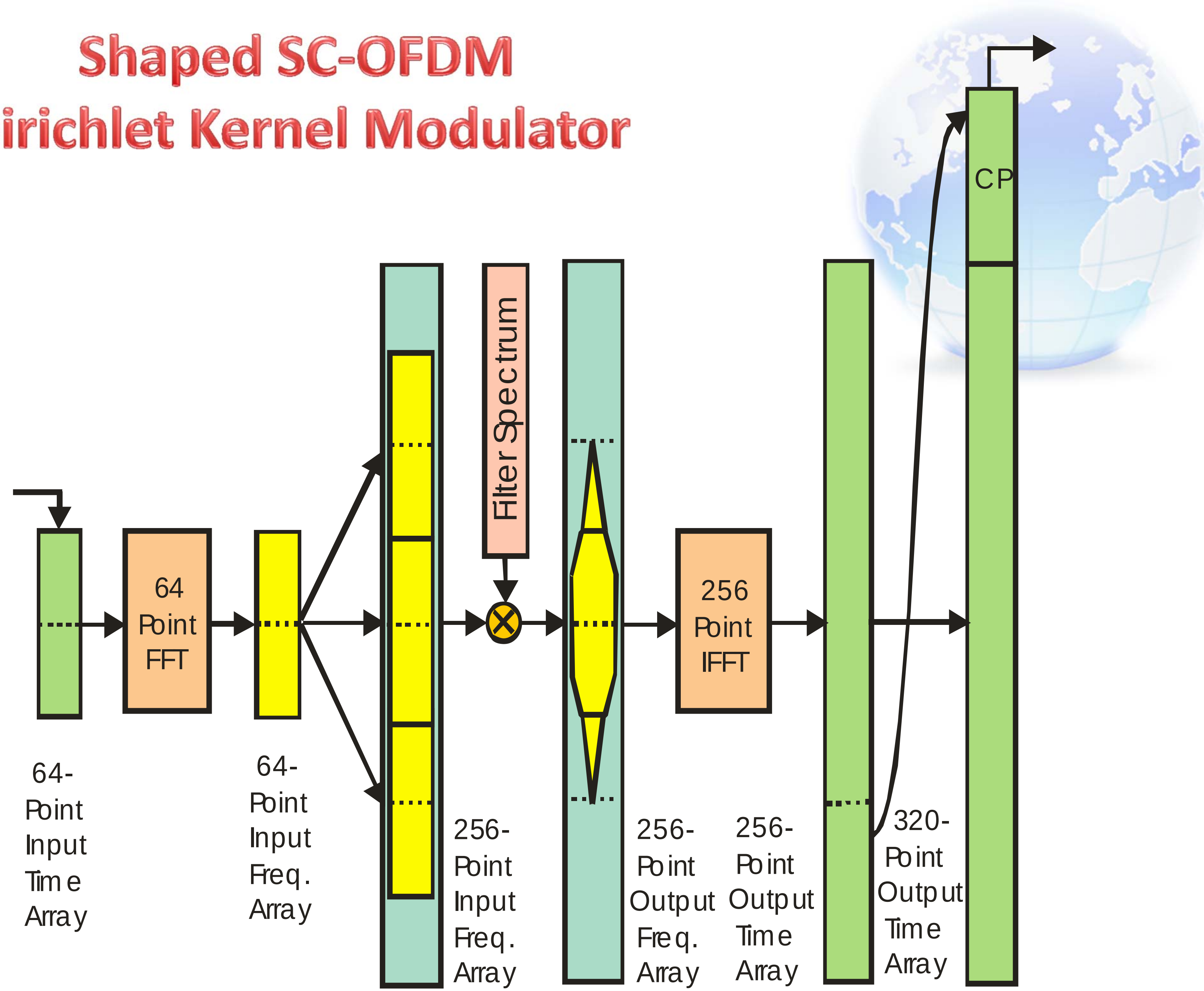
OFDM Modulator and Demodulator



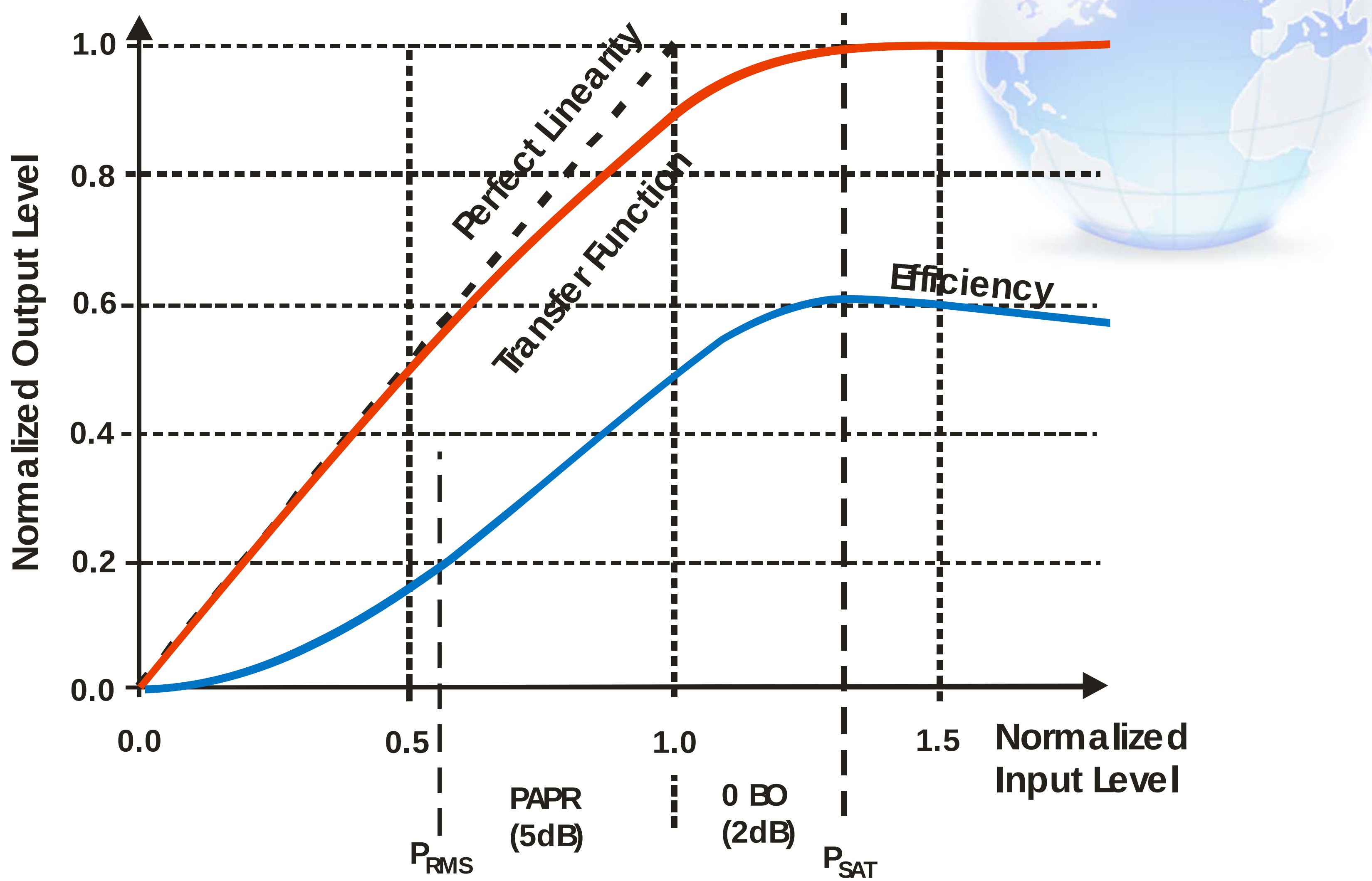
Unshaped SC-OFDM Dirichlet Kernel Modulator



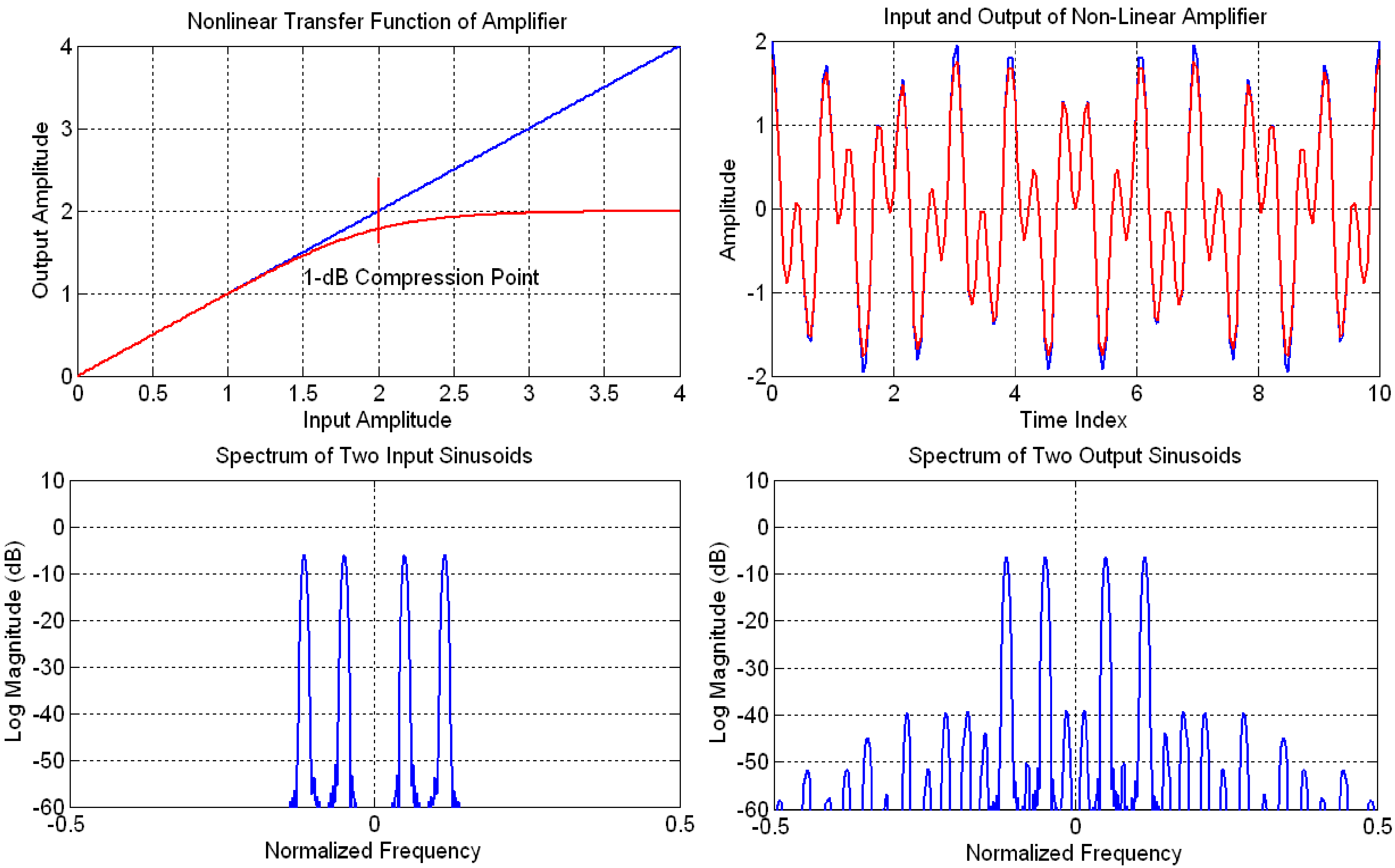
Shaped SC-OFDM
Dirichlet Kernel Modulator



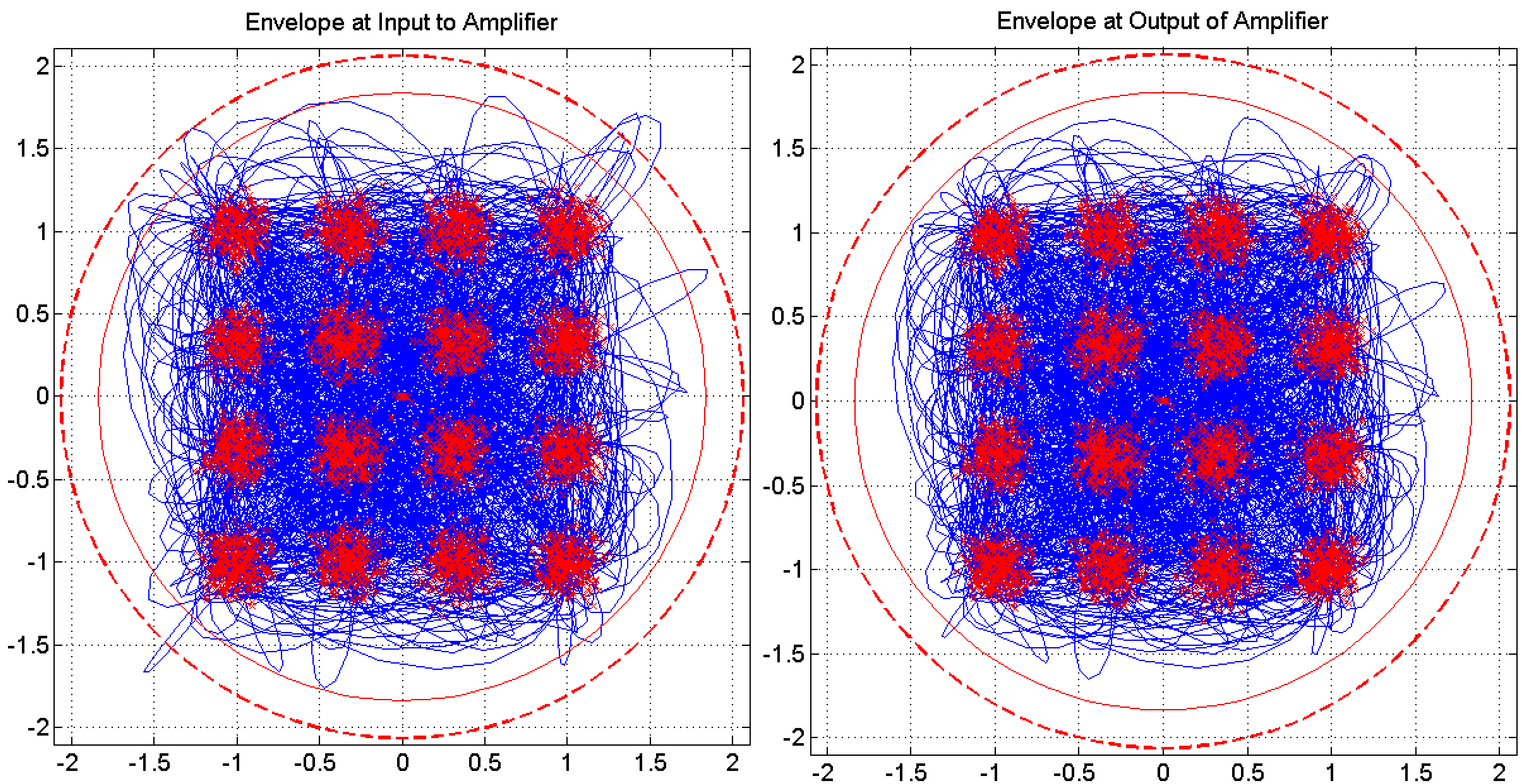
Power Amplifier Efficiency



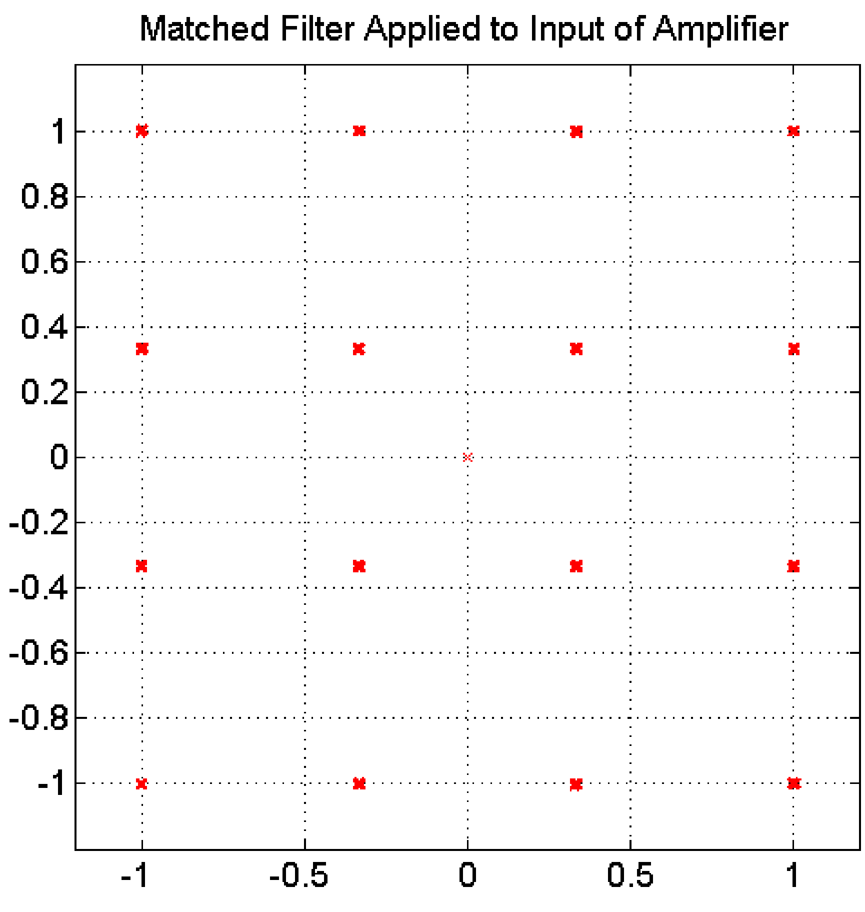
Spectral Re-Growth Due to Power Amplifier Non-Linearity
In-band and Out-of-Band Contributions

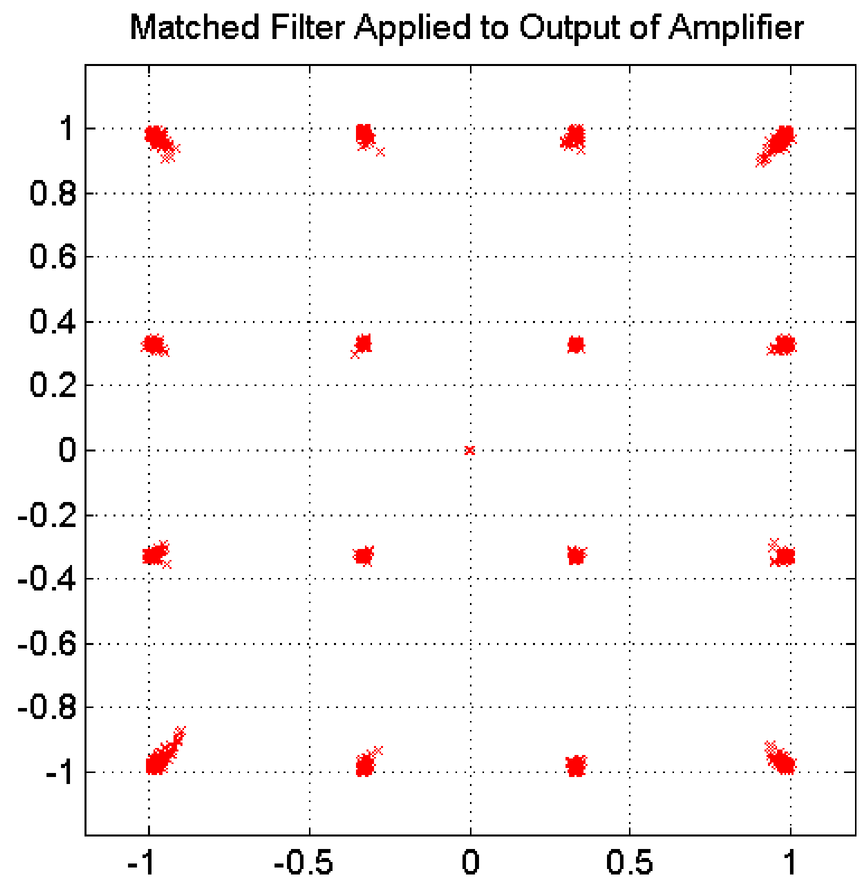


16-QAM Input and Output Envelopes. Saturation and 1-dB Compression Circles

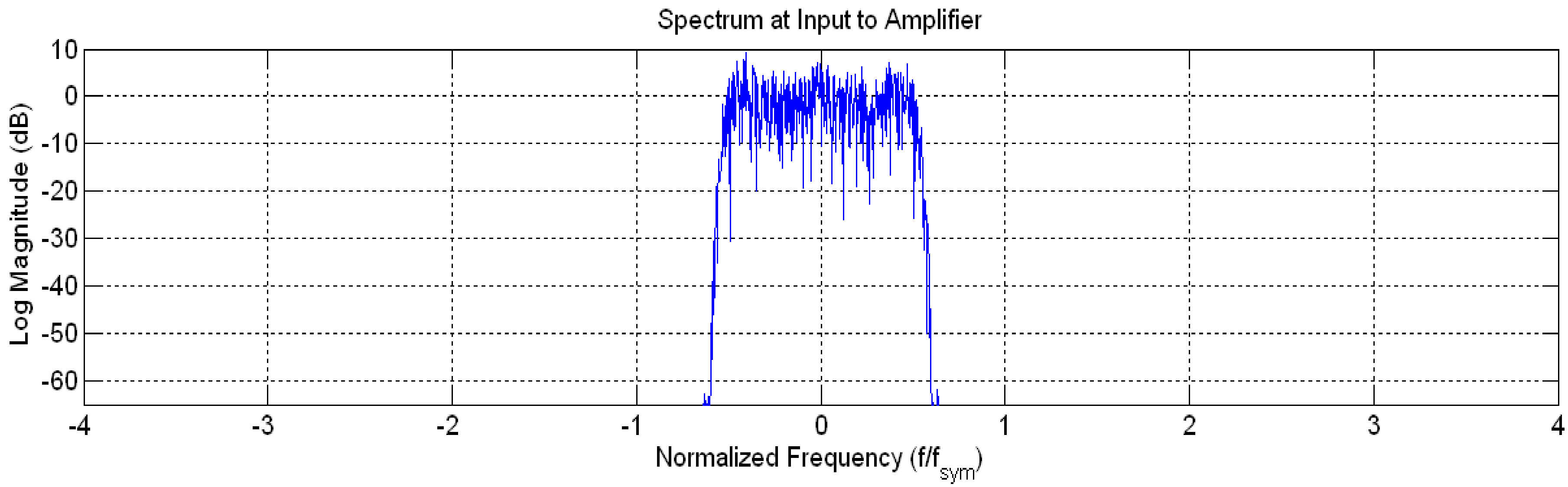


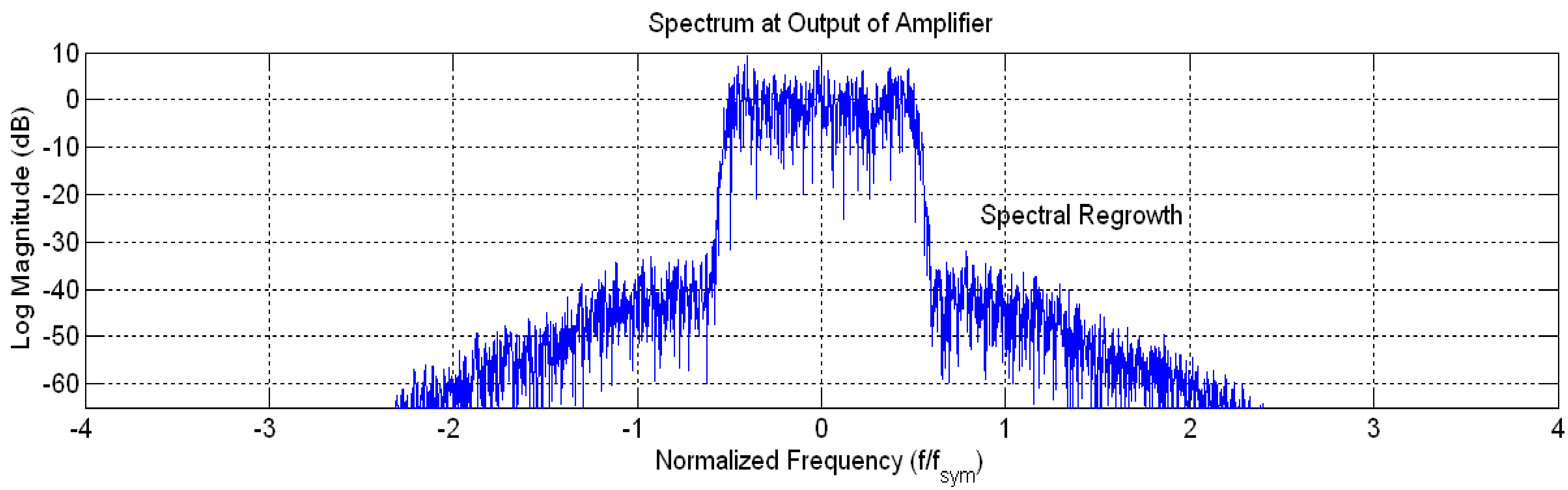
Limiting Amplifier Effect on Received QAM Constellation



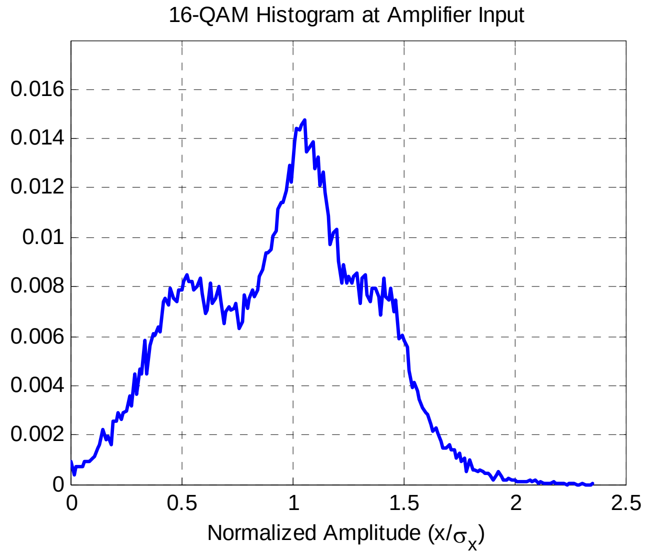


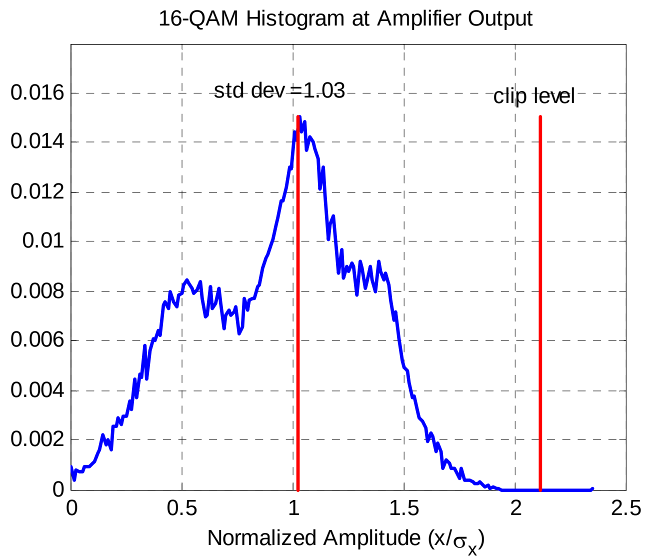
Limiting Amplifier Effect on Signal Spectra

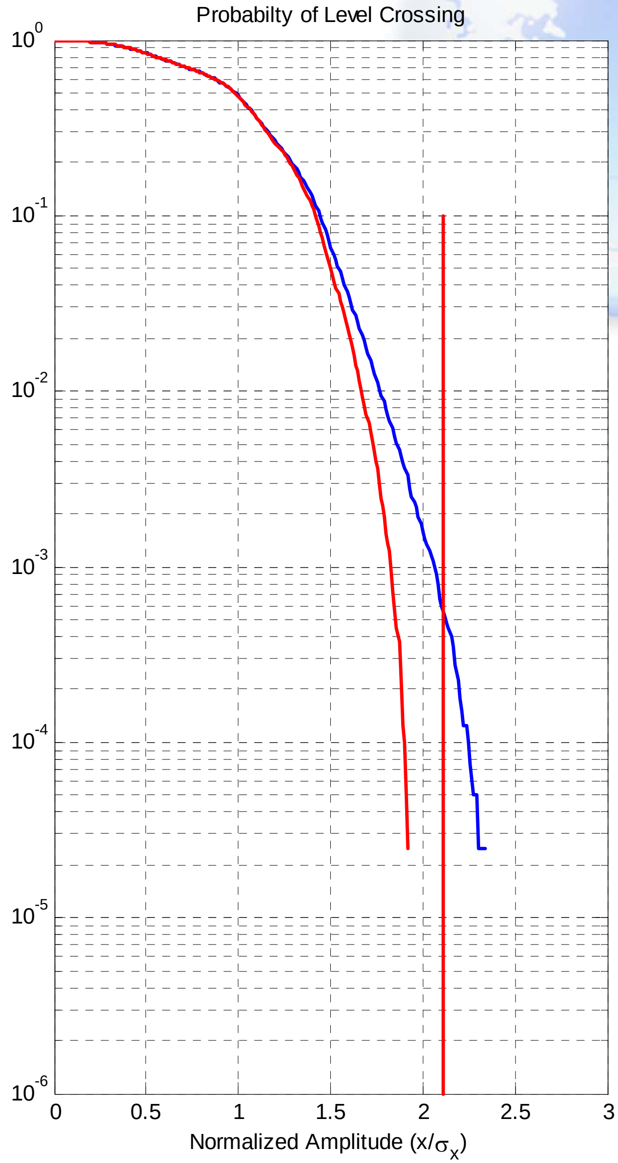




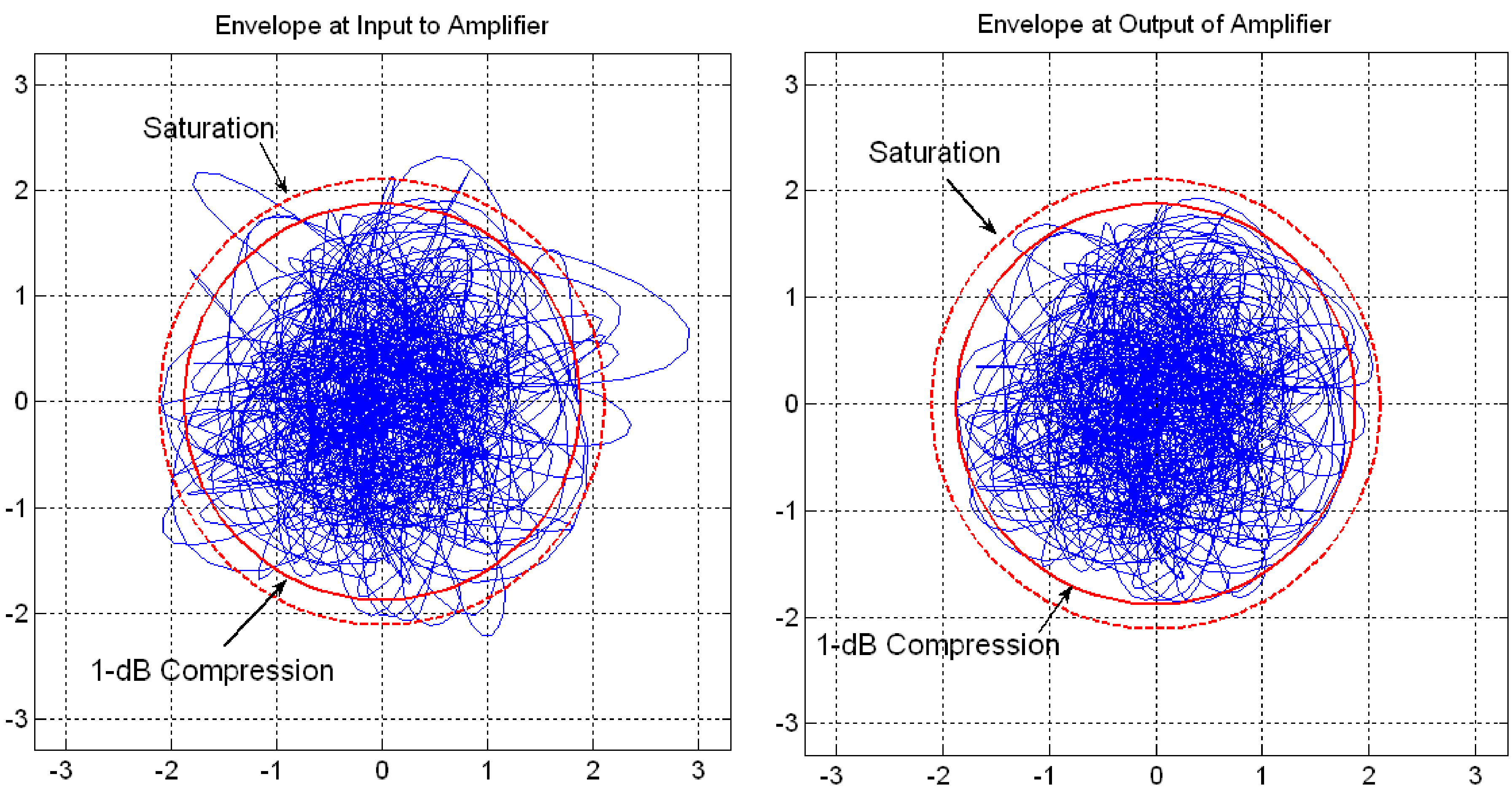
16-QAM (α=0.2) Envelope Statistics



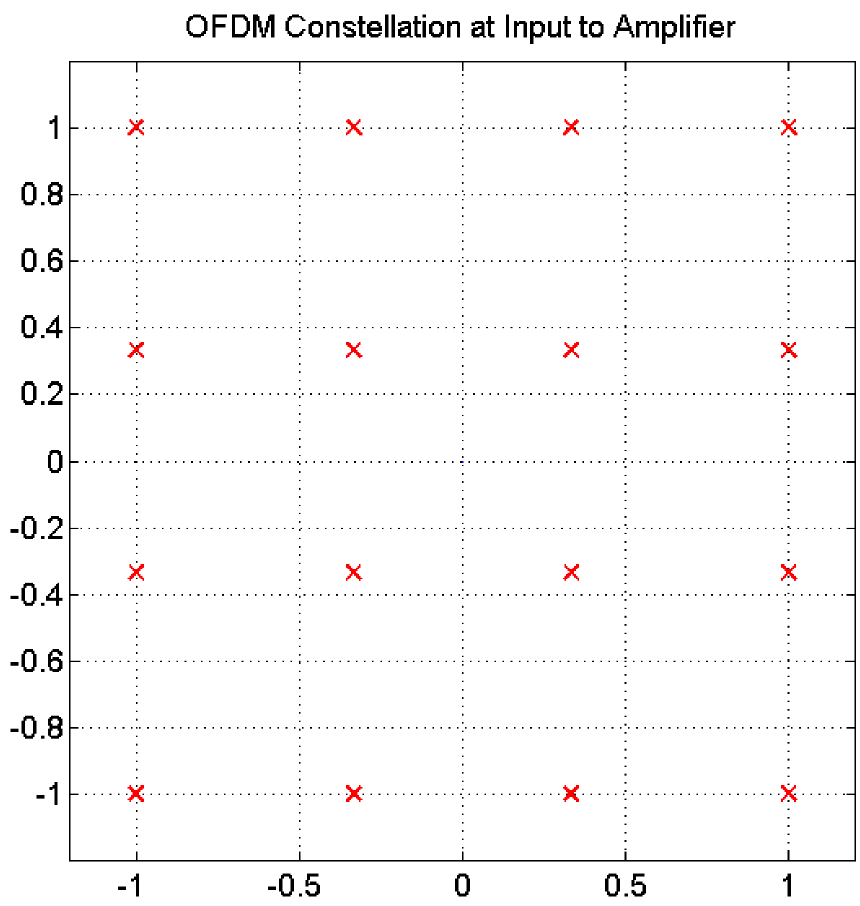


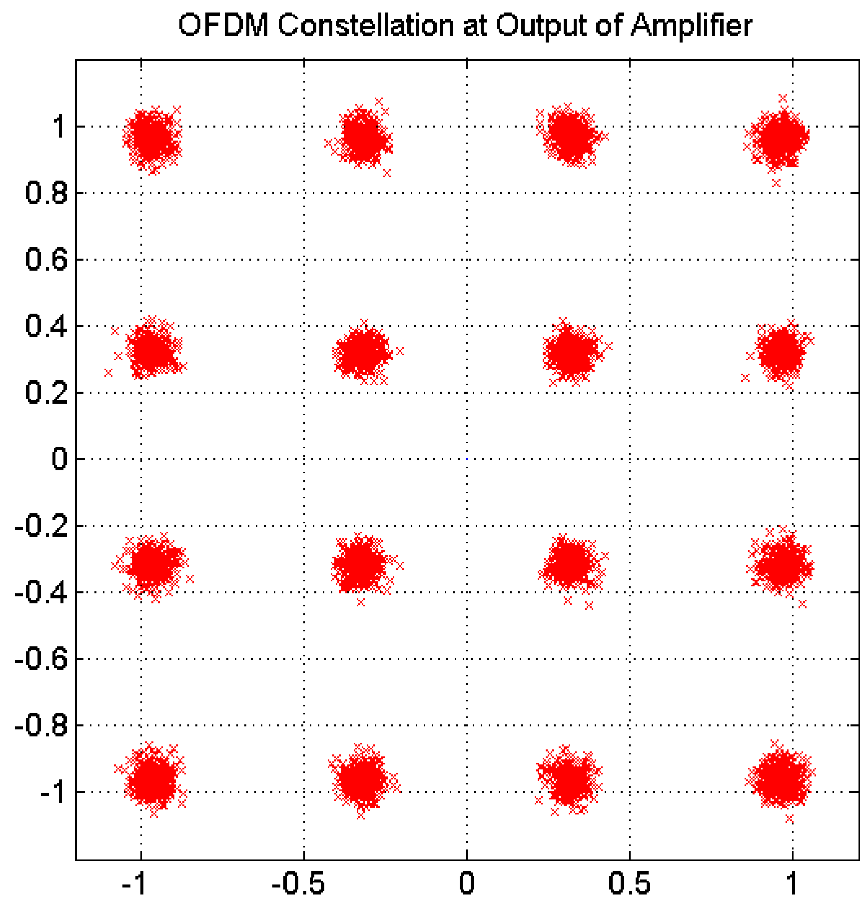


OFDM Input and Output Envelopes: Saturation and 1-dB Compression Circles

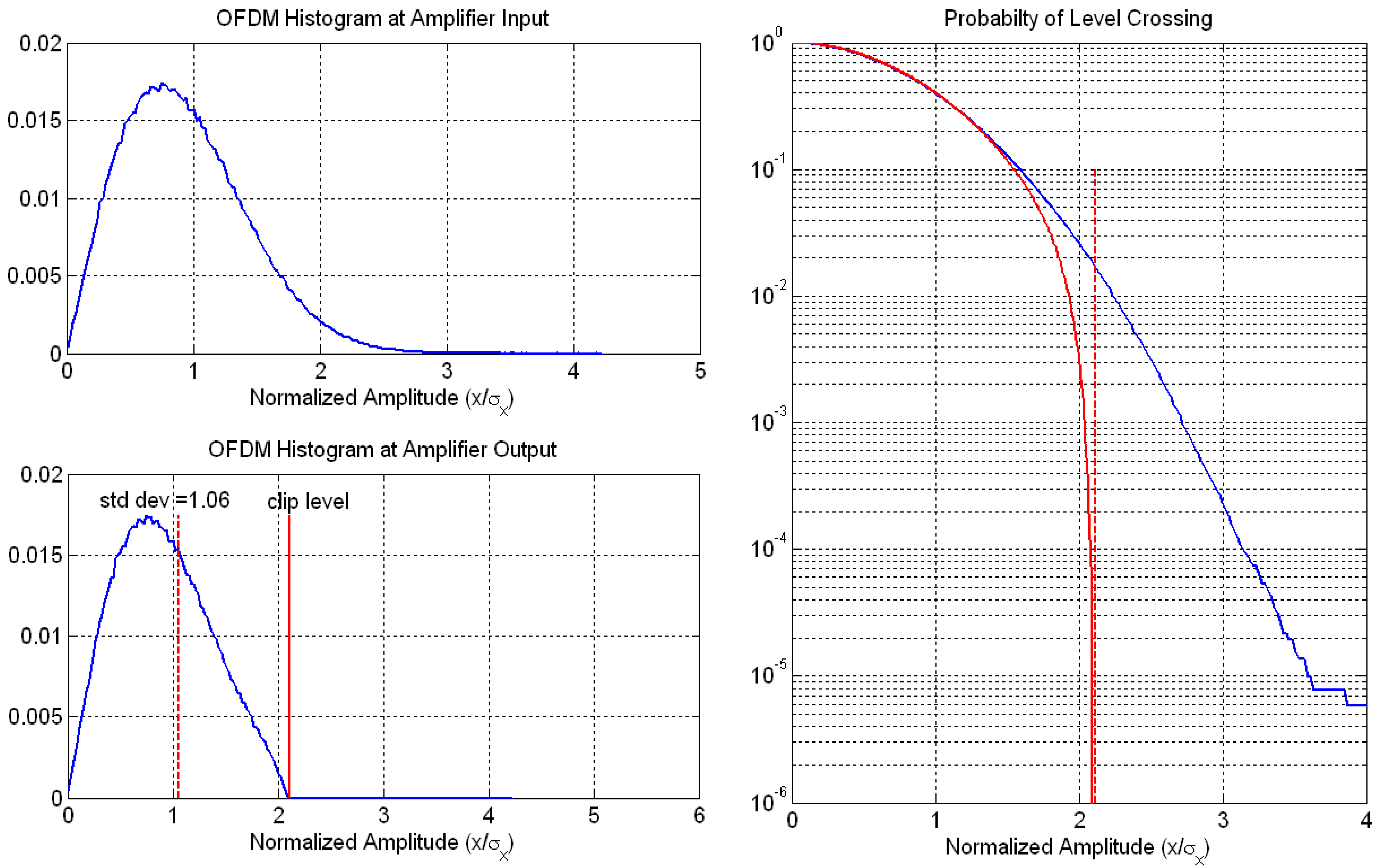


Limiting Amplifier Effect on OFDM Constellation

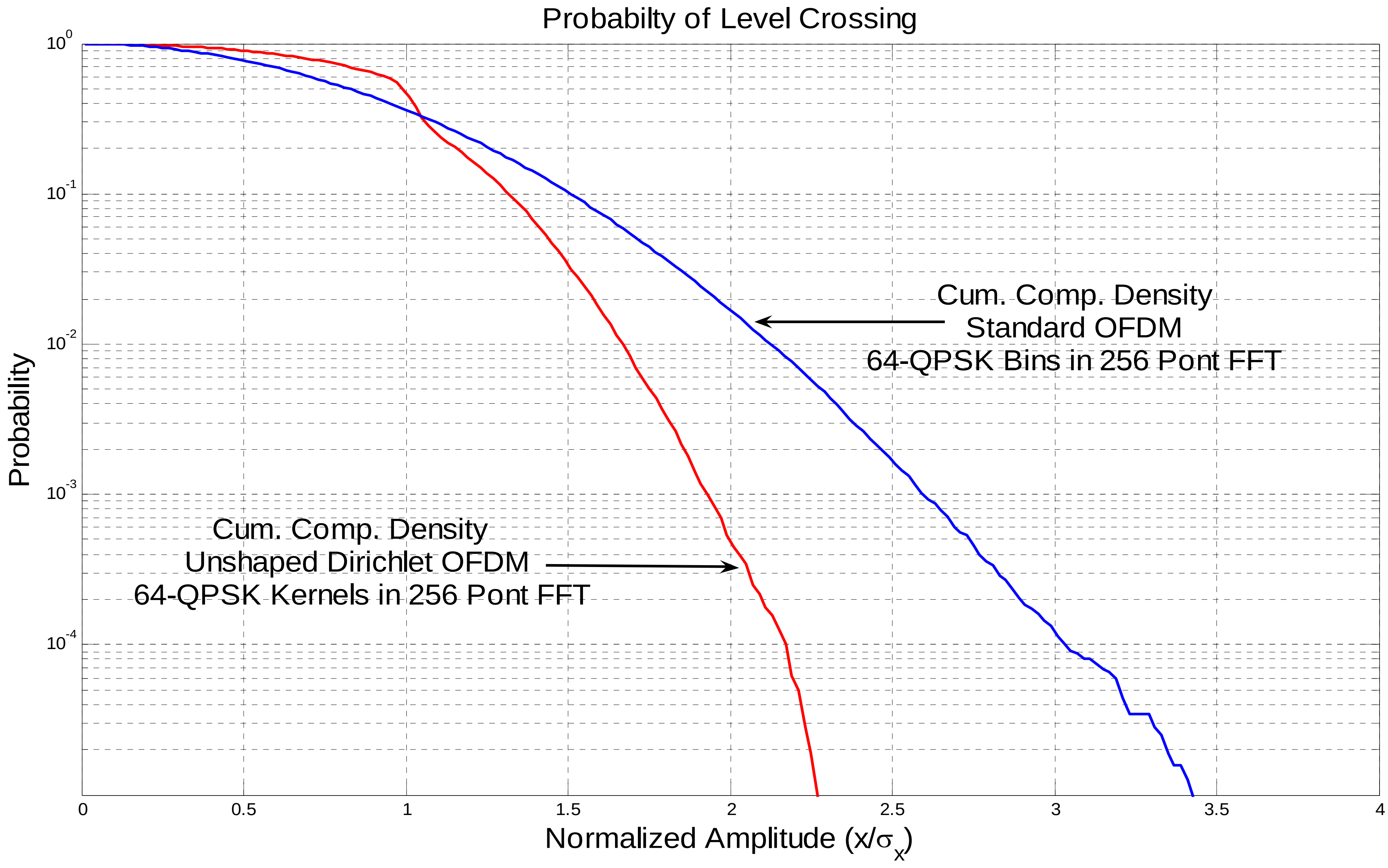




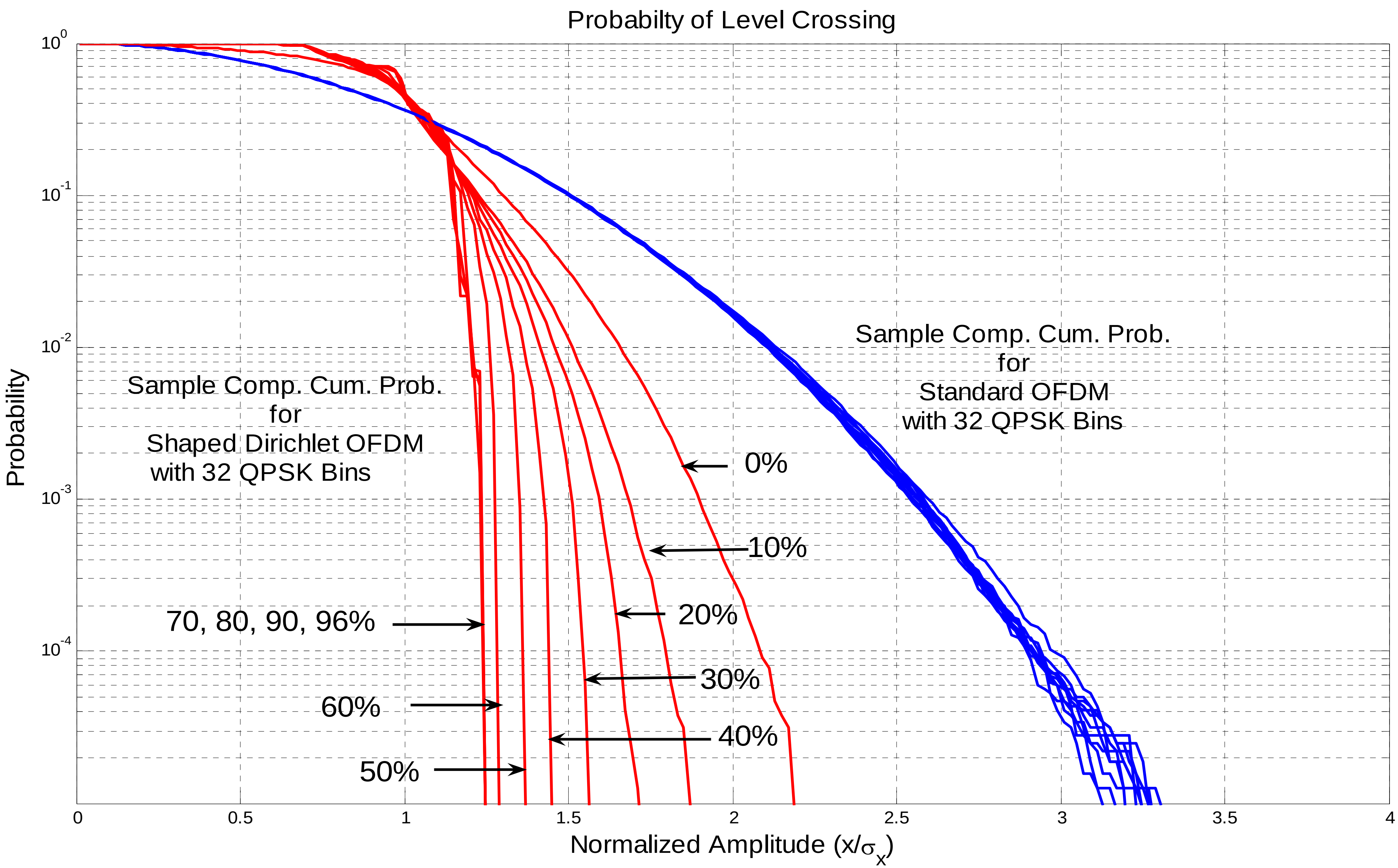
OFDM Envelope Statistics



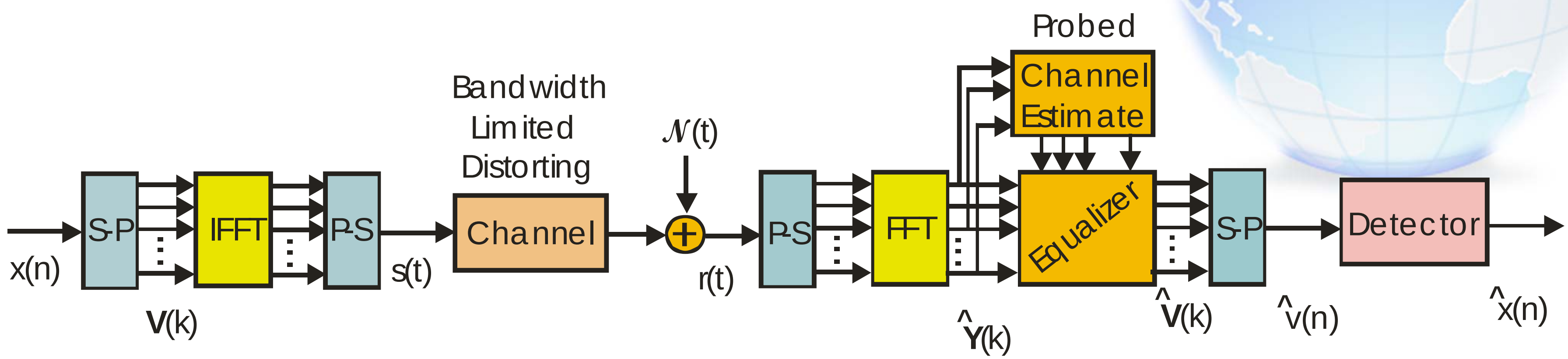
Complementary Cumulative Density Functions for Standard OFDM and SC-OFDM

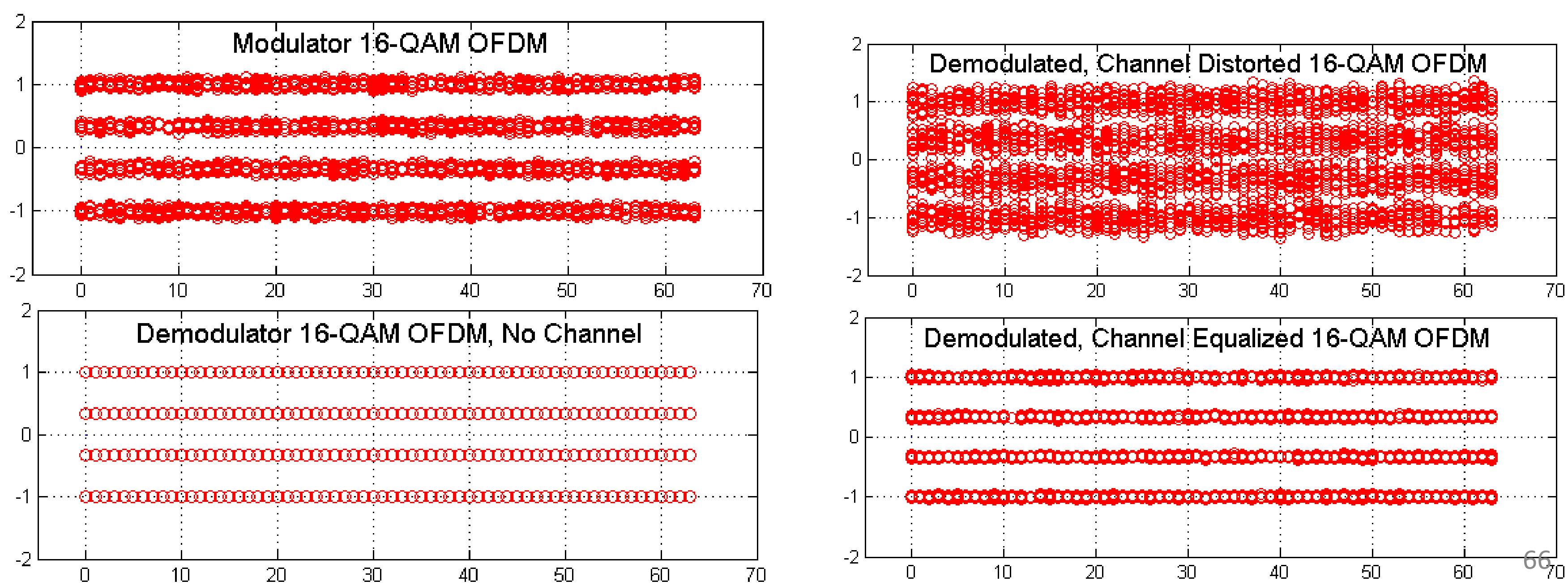


PAPR: OFDM, SC-OFDM, Shaped SC-OFDM

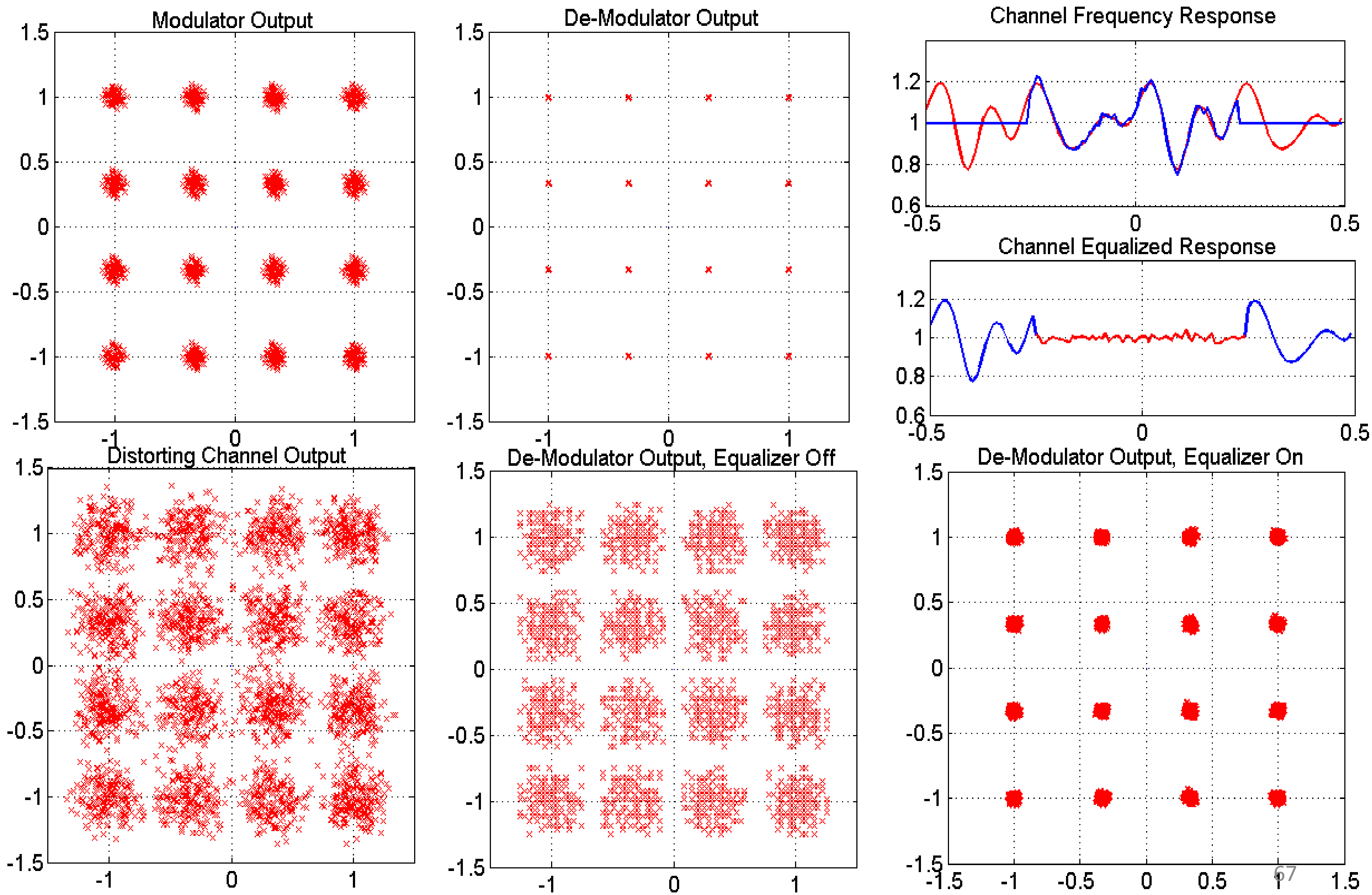


Orthogonal Frequency Division Multiplexing
Frequency Domain Equalization



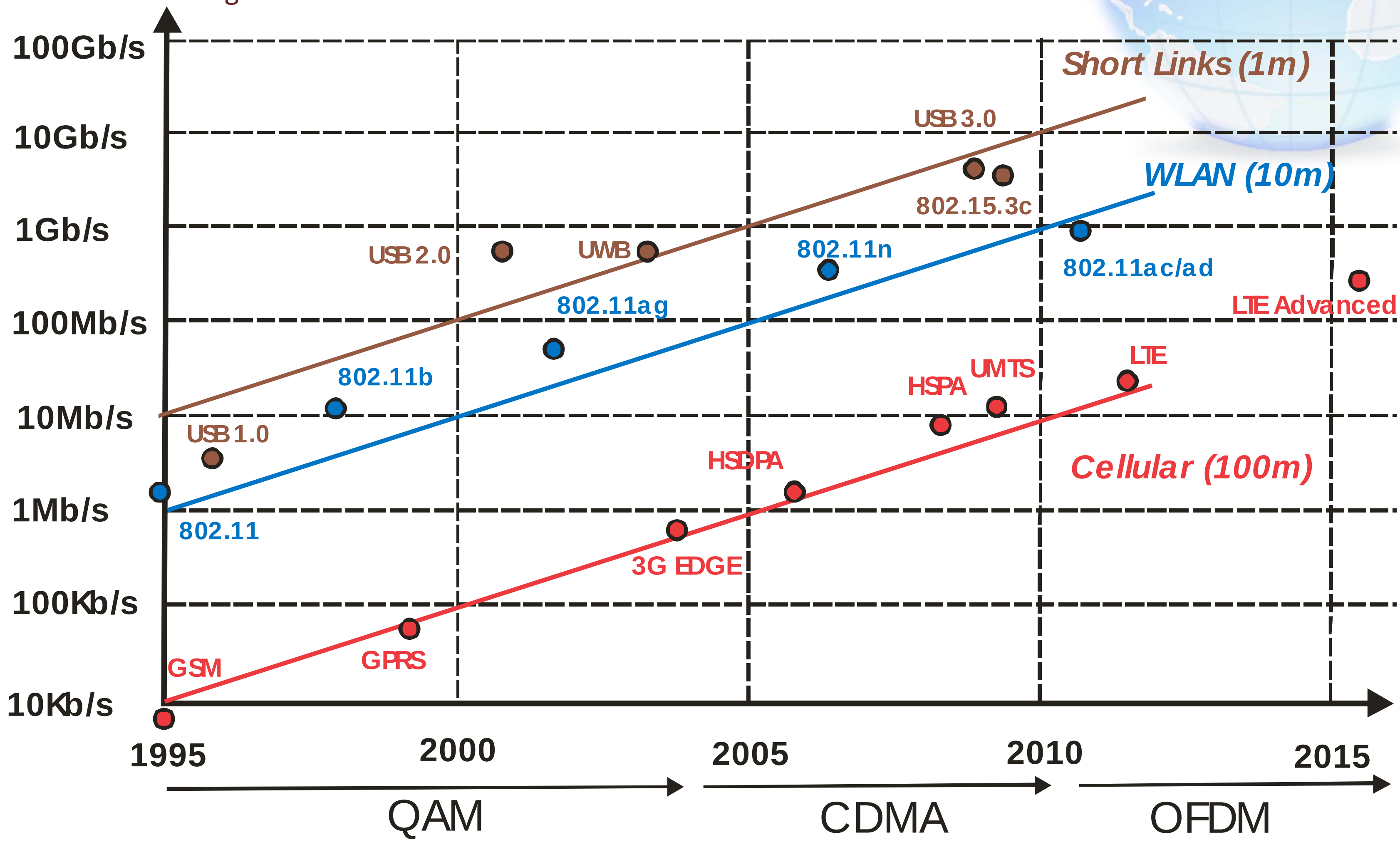


OFDM Frequency Domain Equalization



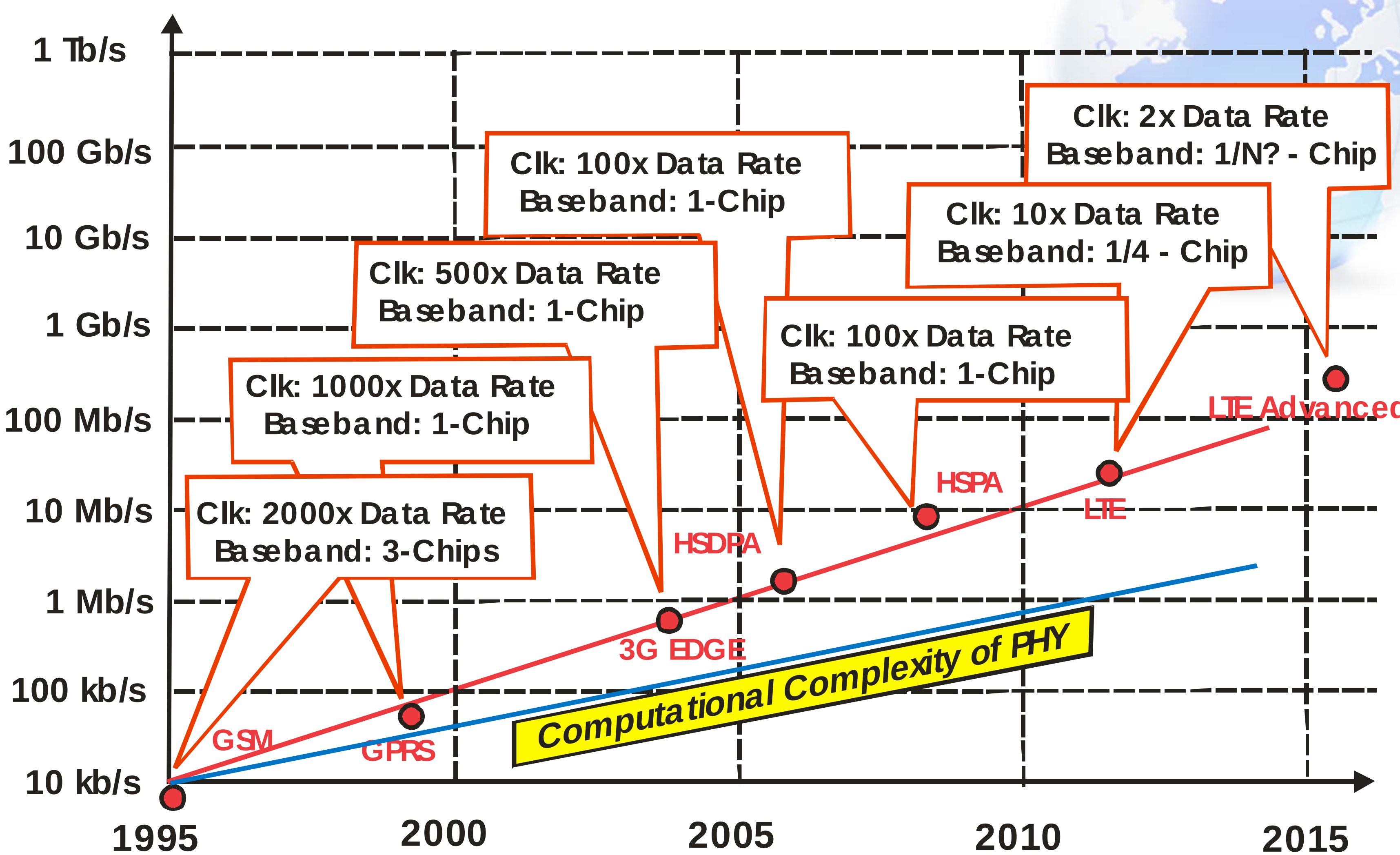
GSM: Groupe Spécial Mobile
GPRS: General Packet Radio Service
EDGE: Enhanced Data Rates for GSM Evolution
HSDPA: High Speed Downlink Packet Access
HSPA: High Speed Packet Access
UMTS: Universal Mobile Telecommunications System
LTE: Long Term Evolution

Evolving Data Rates



Gerhard Fettweis, TU Dresden

Physical Layer Complexity



Gerhard Fettweis, TU Dresden

Receiver Complexity Reduction

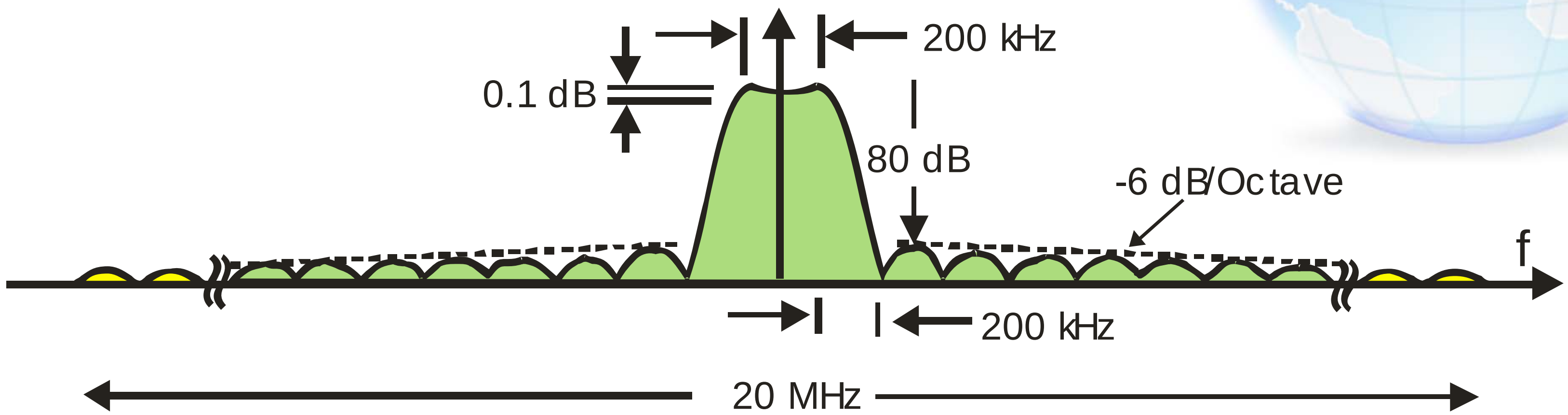
2G: MLSE
Equalizer Complexity
Grows Exponentially
With Length of Echoes!!

3G: RAKE
Receiver Complexity
Grows Linearly
With Number of Echoes!!

4G/LTE: OFDM
Receiver Complexity
Grows Logarithmically
With Length of Echoes!!

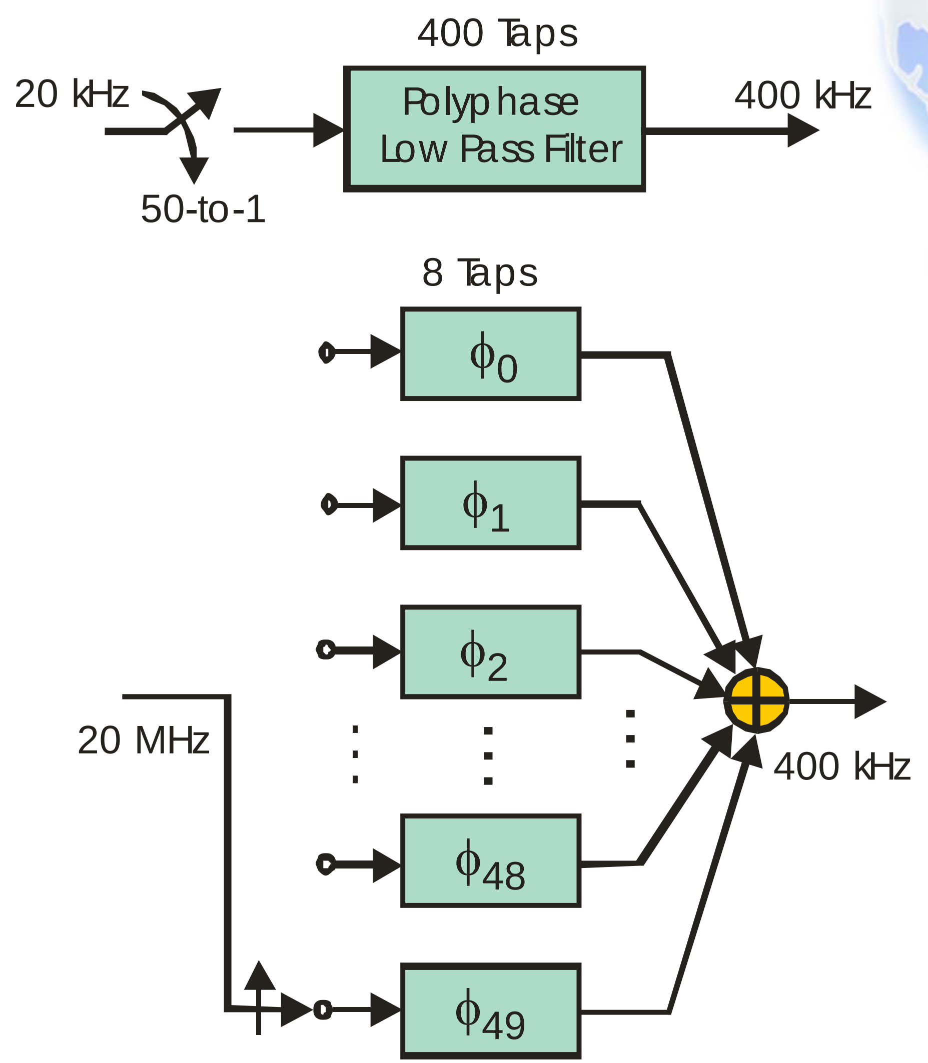

Hear ye...
More Than
Half Way
There!
Hold on!

Bad Mismatch: Sample Rate Large Compared to Transition Bandwidth

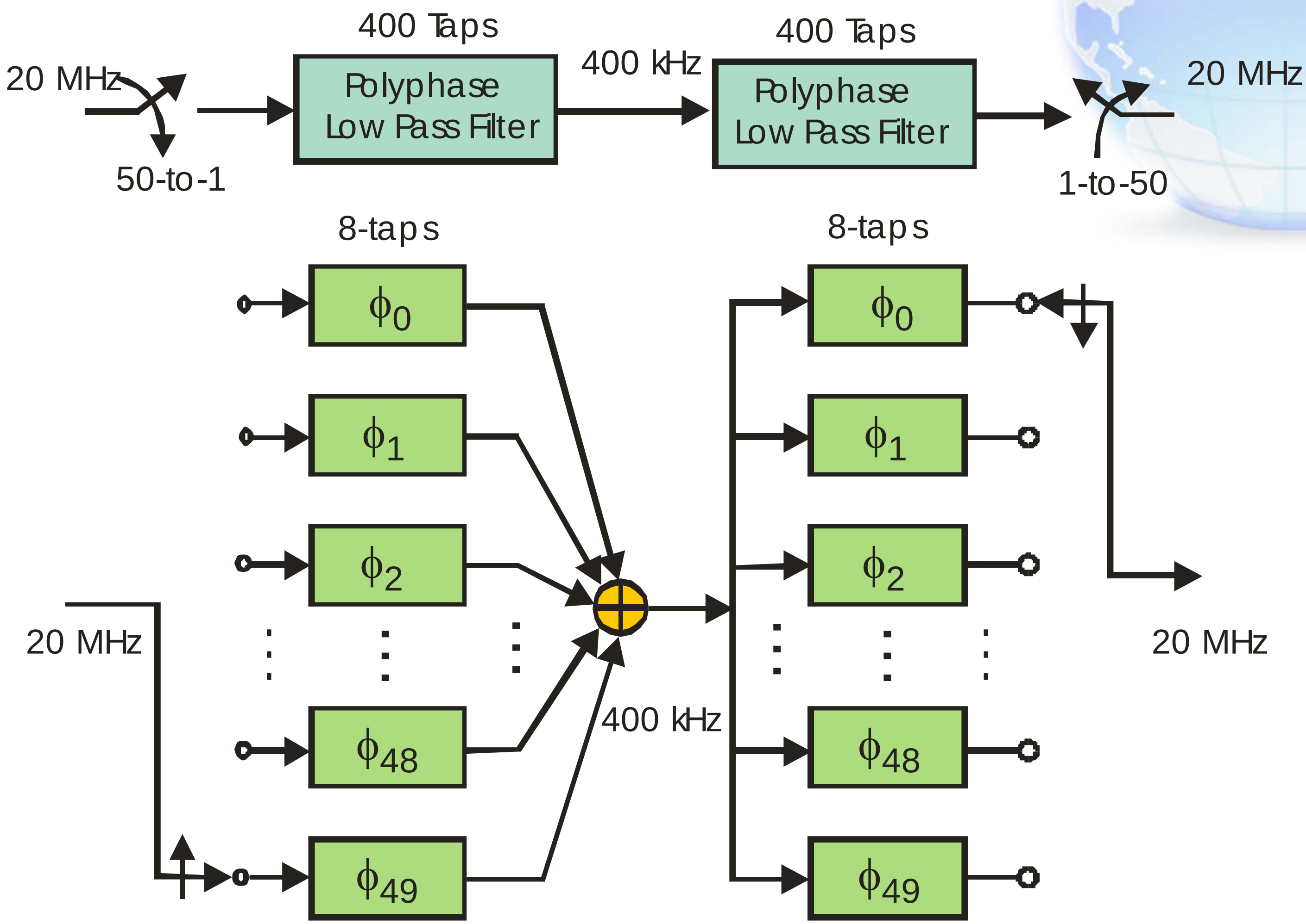


Nyquist Rate for Filter is 200 kHz + 200 kHz = 400 kHz or fs/50

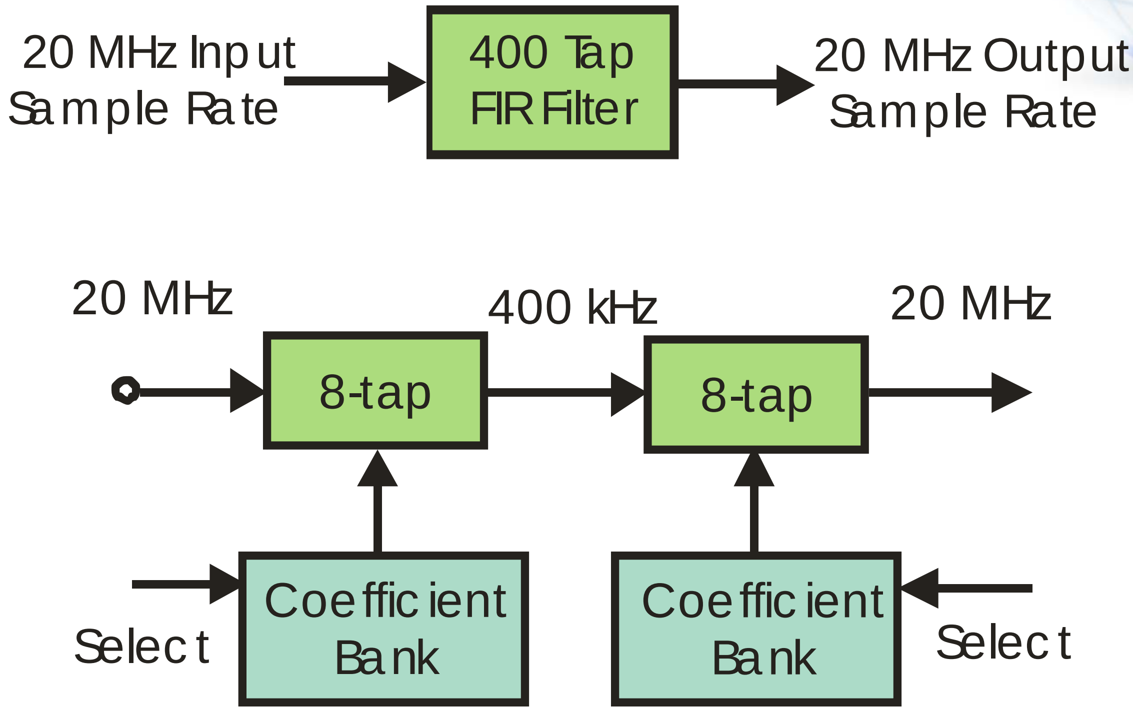
Polyphase Partition of Low-Pass Filter



Cascade Polyphase Filter
Down-Sampling and Up-Sampling

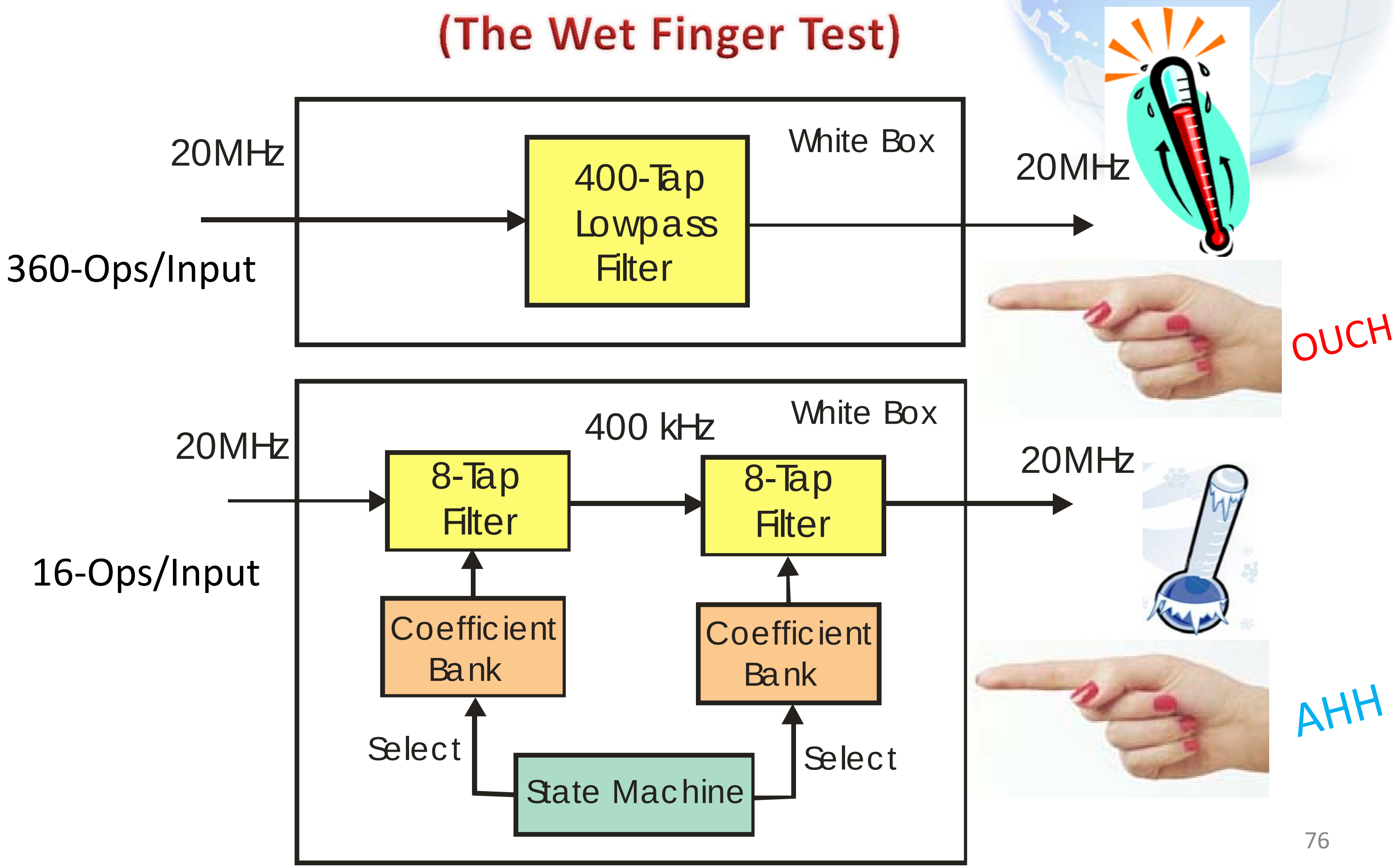


Efficient Polyphase Filter Implementation

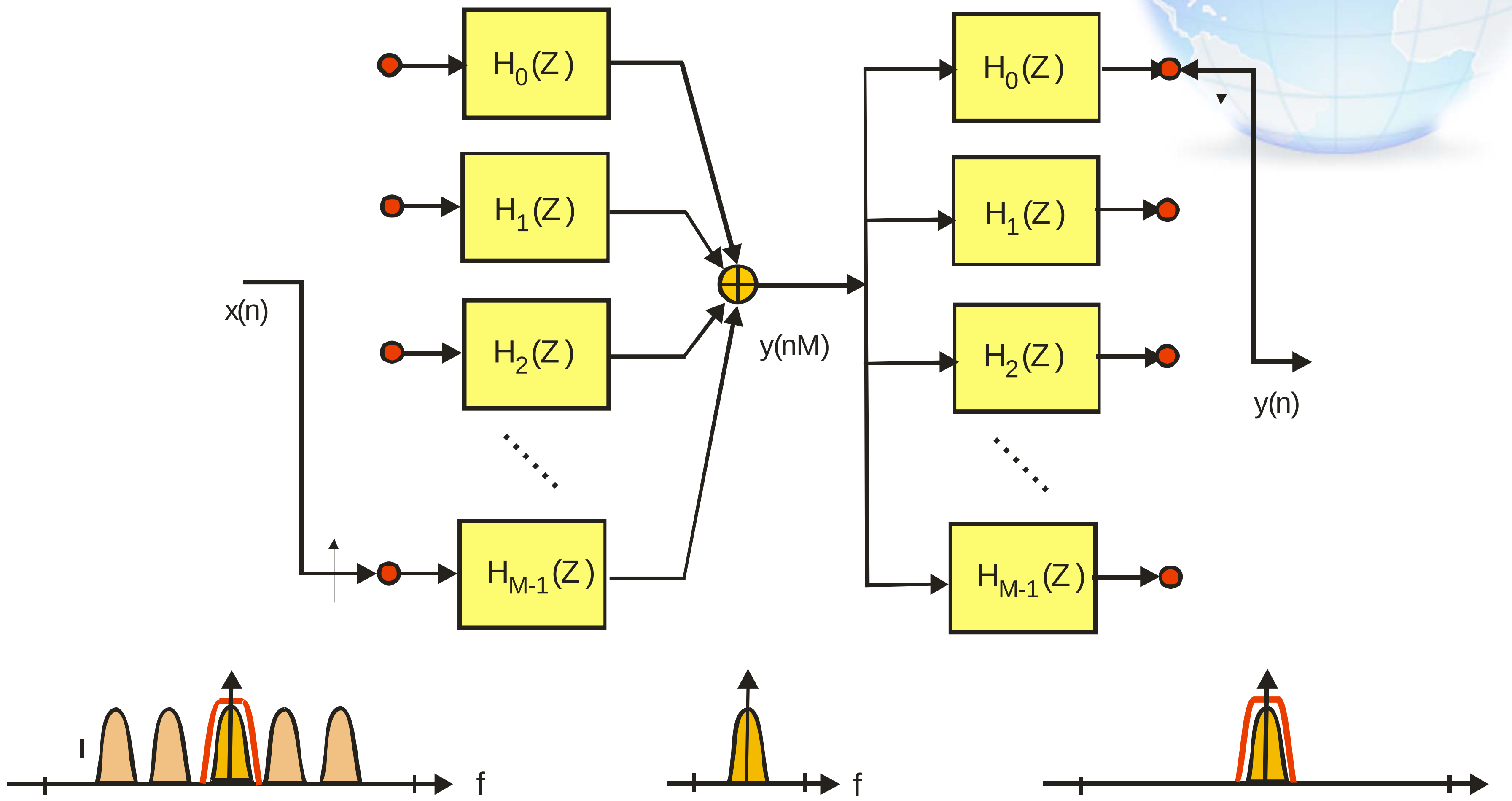


Two Processing in Boxes:
How can you tell which is which from outside box?

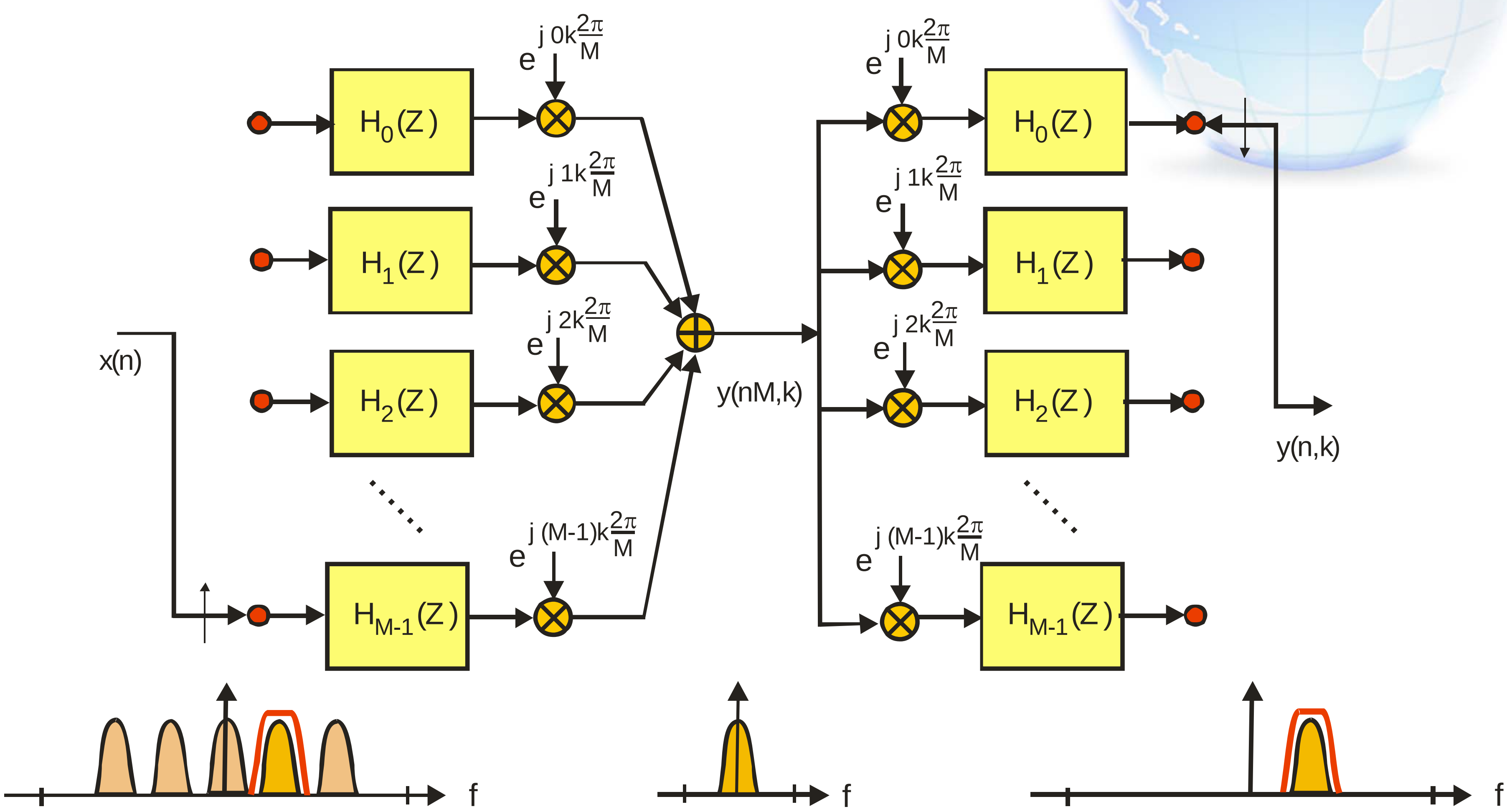
(The Wet Finger Test)



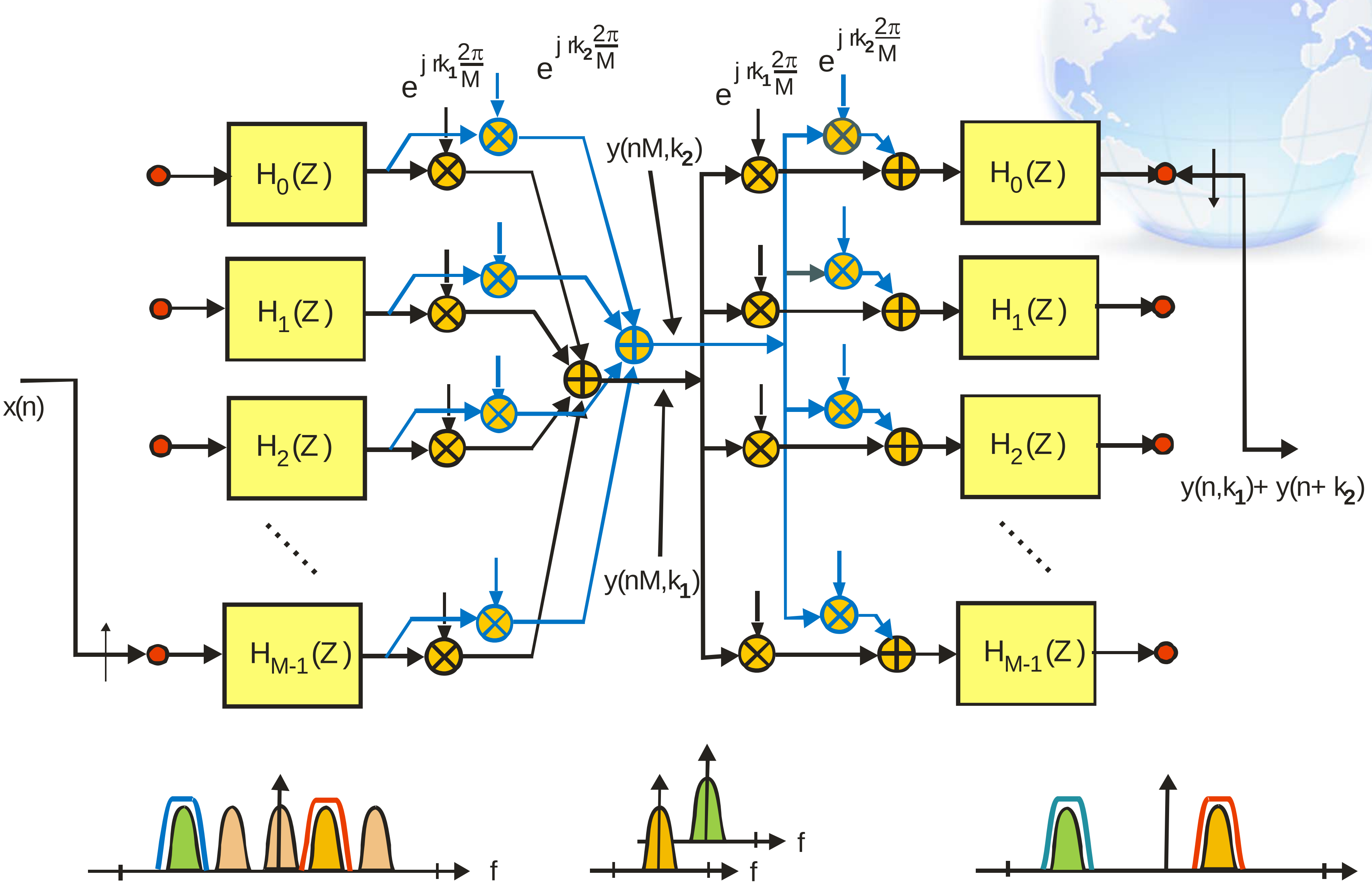
Polyphase Partition of Low-Pass Filter



Polyphase Partition of Band Pass Filter



Polyphase Partition of Two Band Pass Filters



Workload for Multiple M-Path Filters

- 1-Channel M-to-1 Down Sample
  - 1-Filter and M Complex Phase Rotators
- 2-Channels M-to-1 Down Sample
  - 1-Filter and 2M Complex Phase Rotators
- K-Channels M-to-1 Down Sample
  - 1-Filter and kM Complex Phase Rotators
- M-channels M-to-1 Down Sample (use FFT)
  - 1-Filter and $[\log_2(M)/2]M$ Complex Phase Rotators

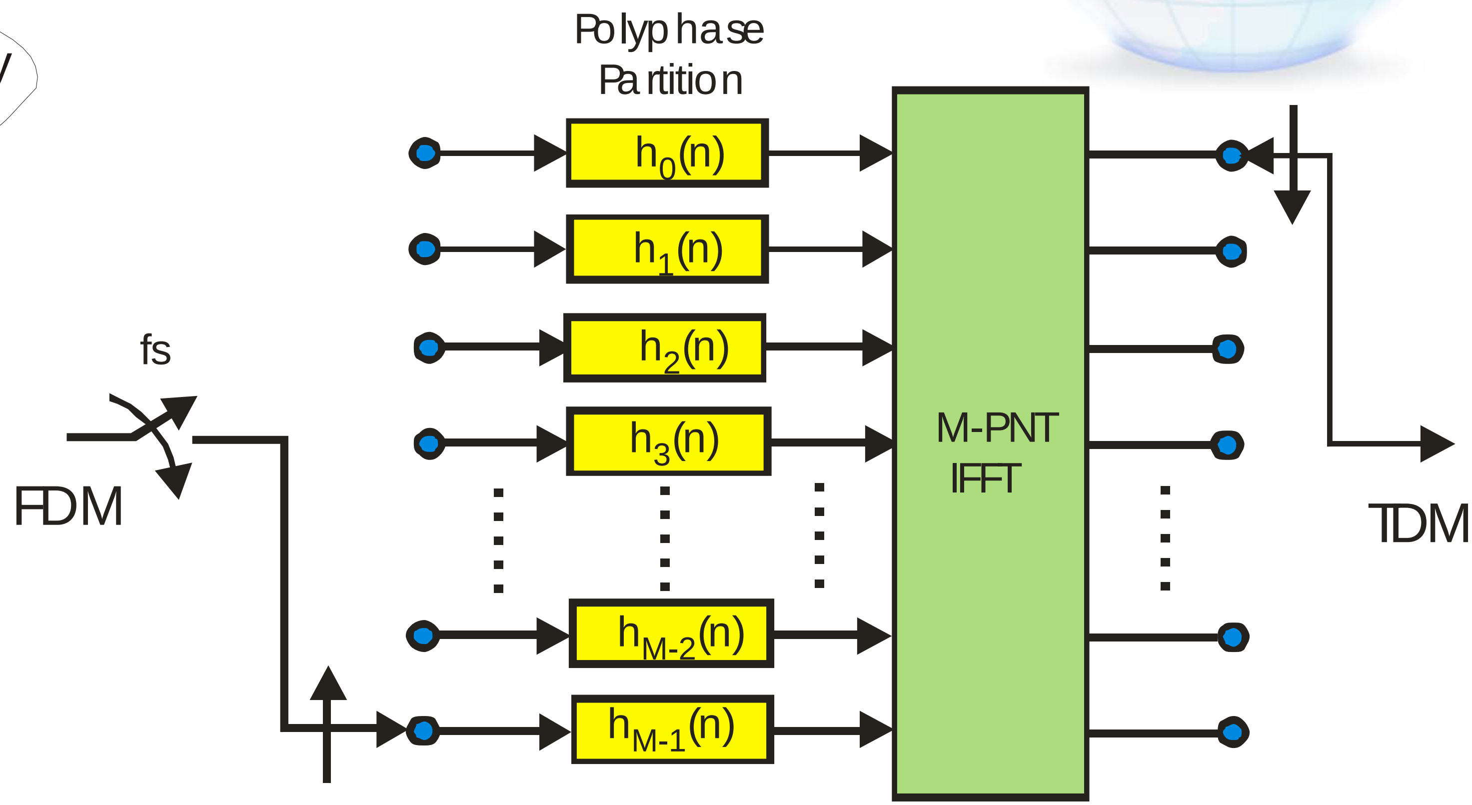
When $k > \text{Log}_2(M)/2$ Build all channels and discard the channels you don't need!

IF M=16, $\text{Log}_2(16)/2 = 2$: thus if you want 2 or more, Build them all!

IF M=128, $\text{Log}_2(128)/2 = 3.5$: thus if you want 4 or more, Build them all!

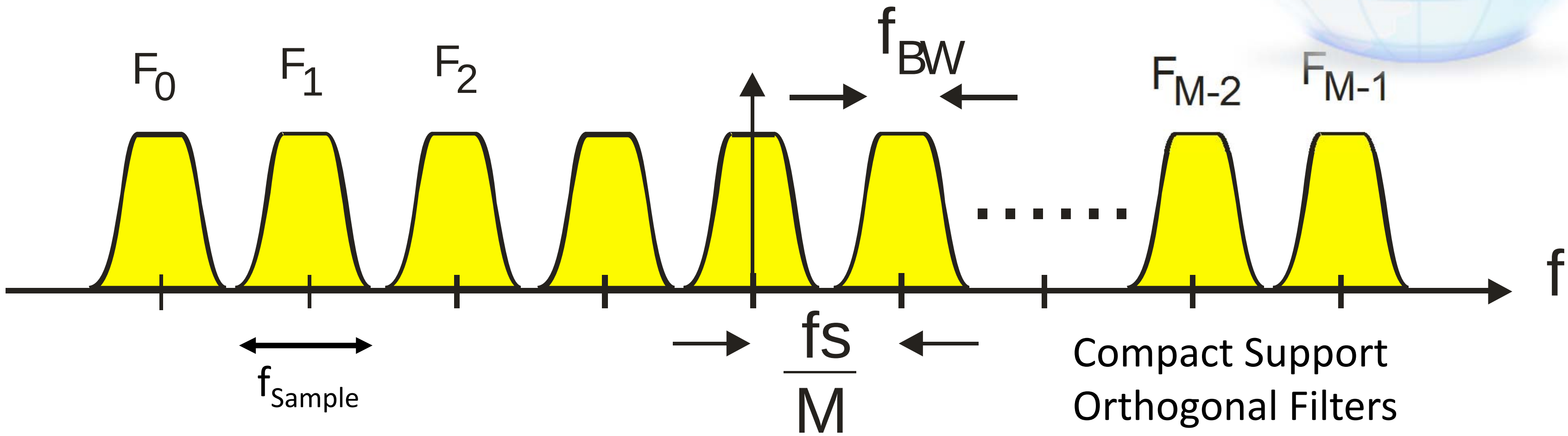
IF M=1024, $\text{Log}_2(1024)/2 = 5$: thus if you want 5 or more, Build them all!

M-Channel Channelizer: Resampled M-Path Narrowband Filter
M-Channels Alias to Baseband: Phase Aligned Sums Separate Aliases: Work Performed at Low Output Rate Rather Than at High Input Rate. One Input Filter Services M-Output Channels

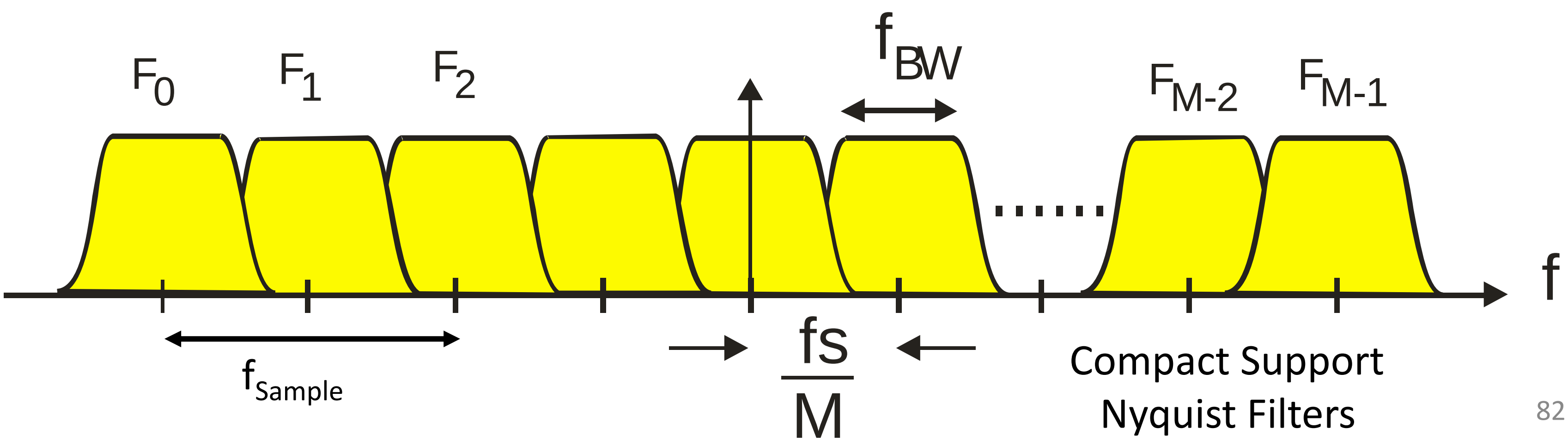


$h_r(n) = h(r + nM)$

Polyphase Channelizer: Bandwidth from Polyphase Filter, Spectral Spacing from IFFT, Sample Rate from Commutator

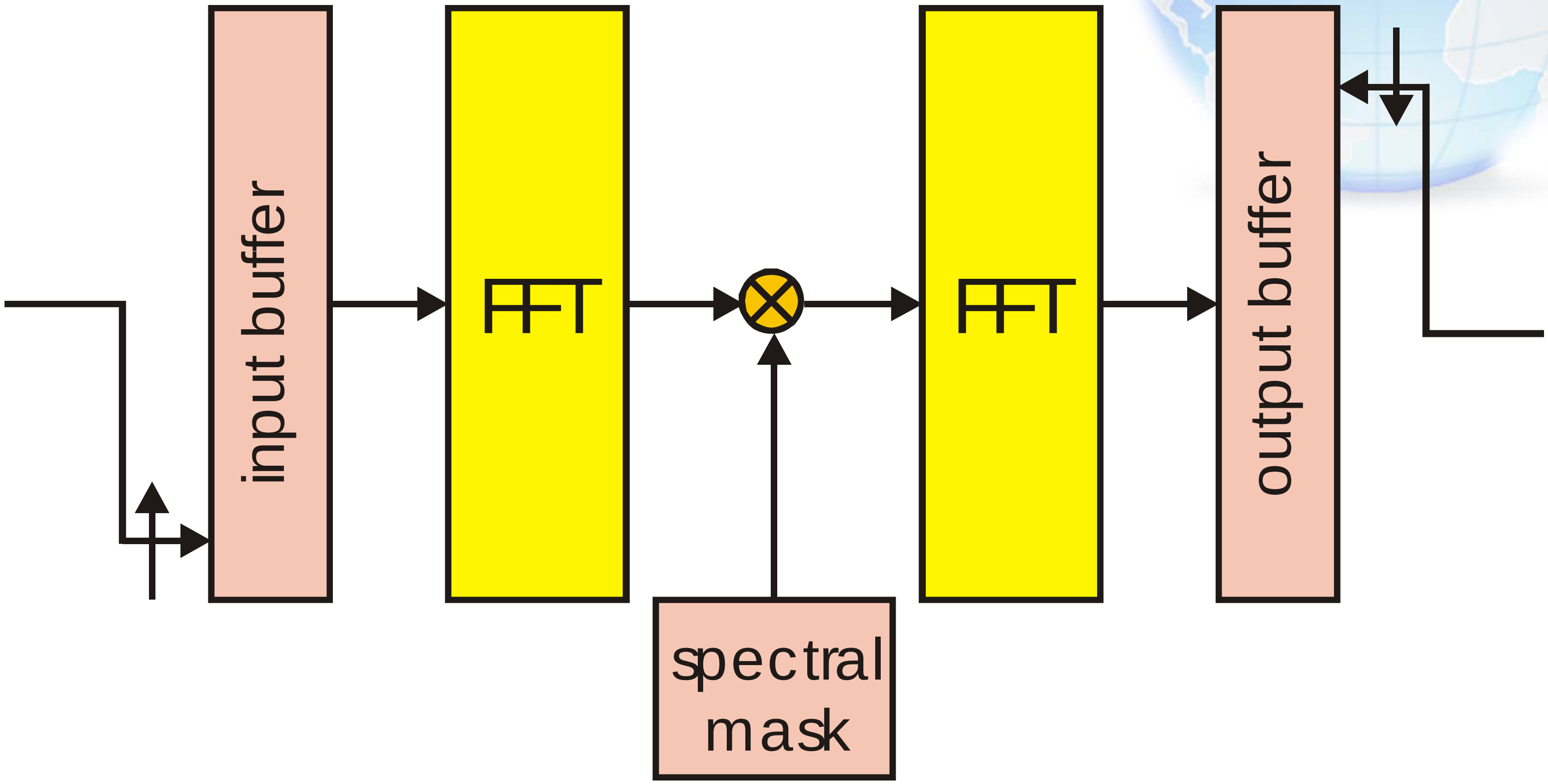


Compact Support Orthogonal Filters



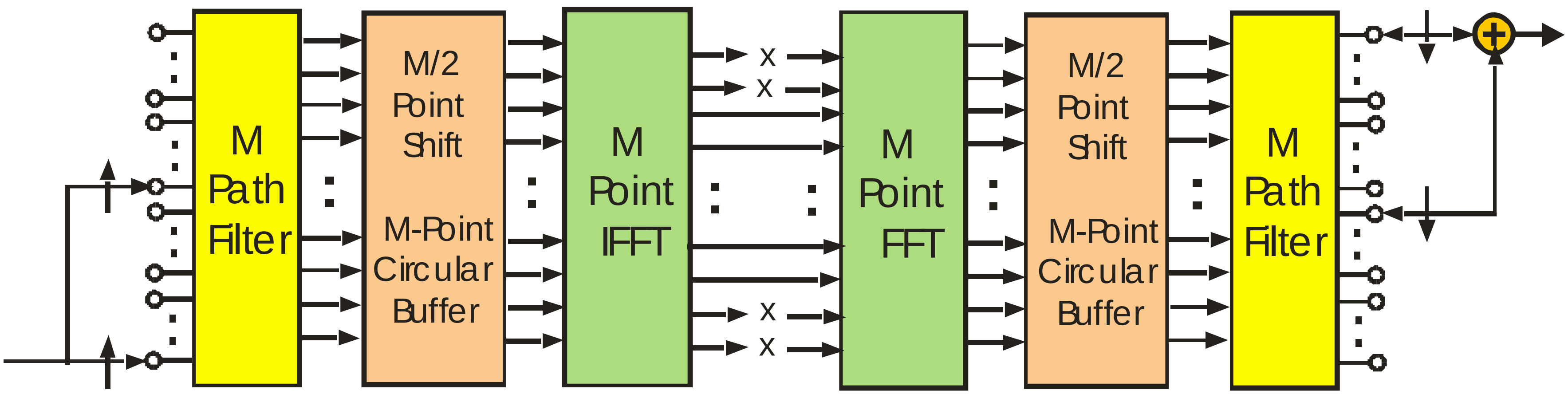
Compact Support Nyquist Filters

Indirect Convolution, Fast Filtering by Spectral Product
The Core Advantage of OFDM

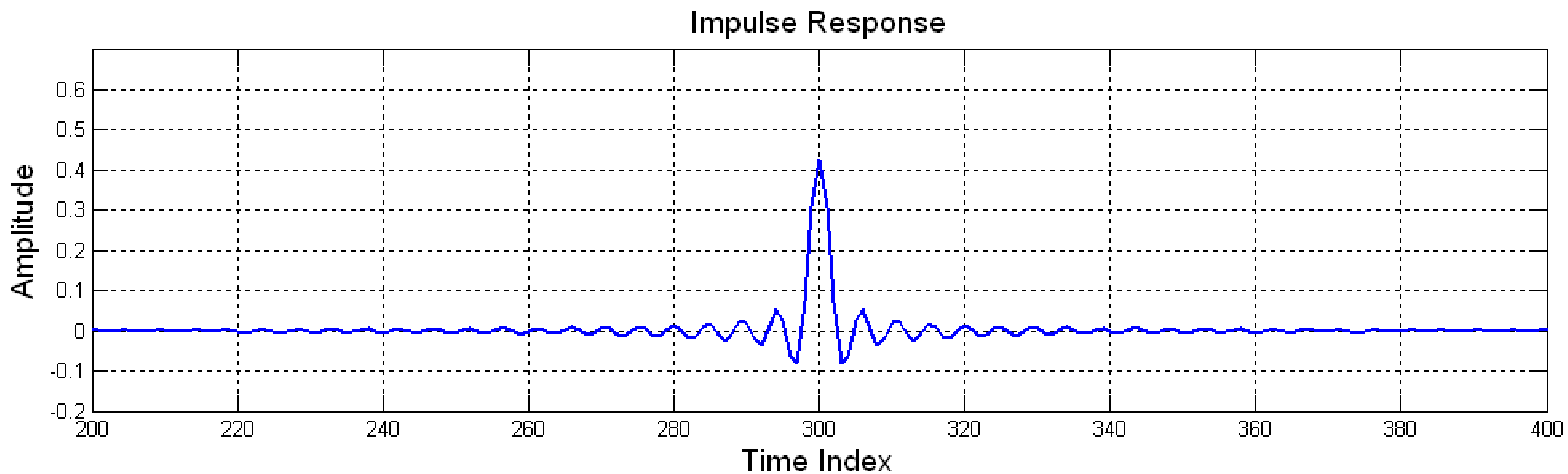


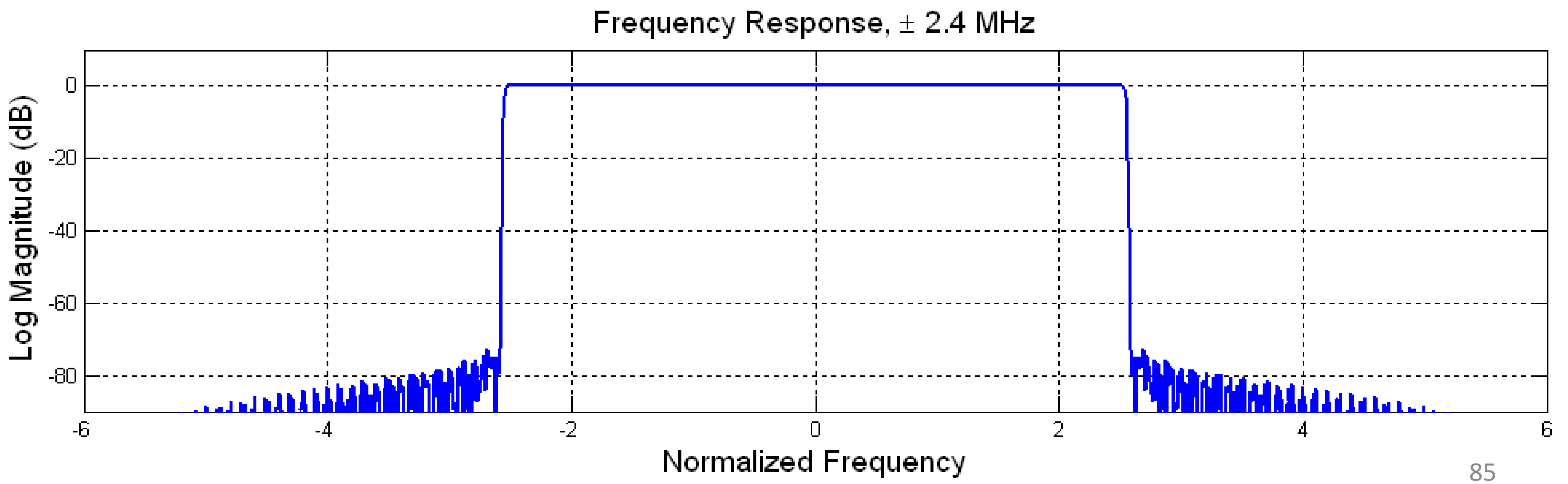
Block Processing Related Boundary Conditions.
Boundaries are Natural for OFDM Waveforms

Filtering in the Frequency Domain

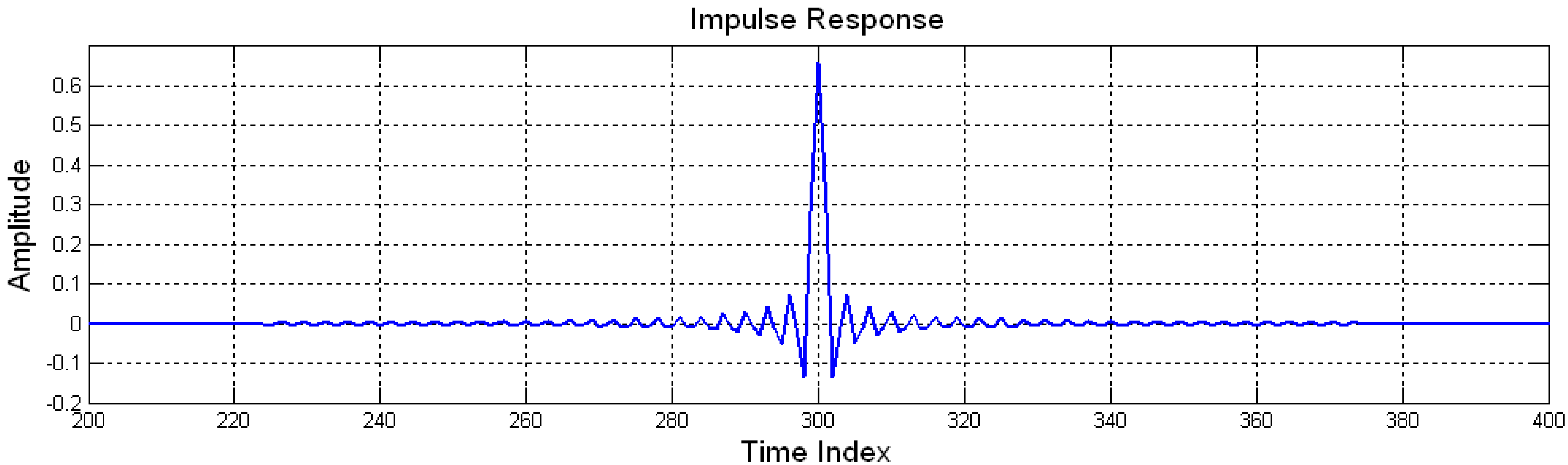


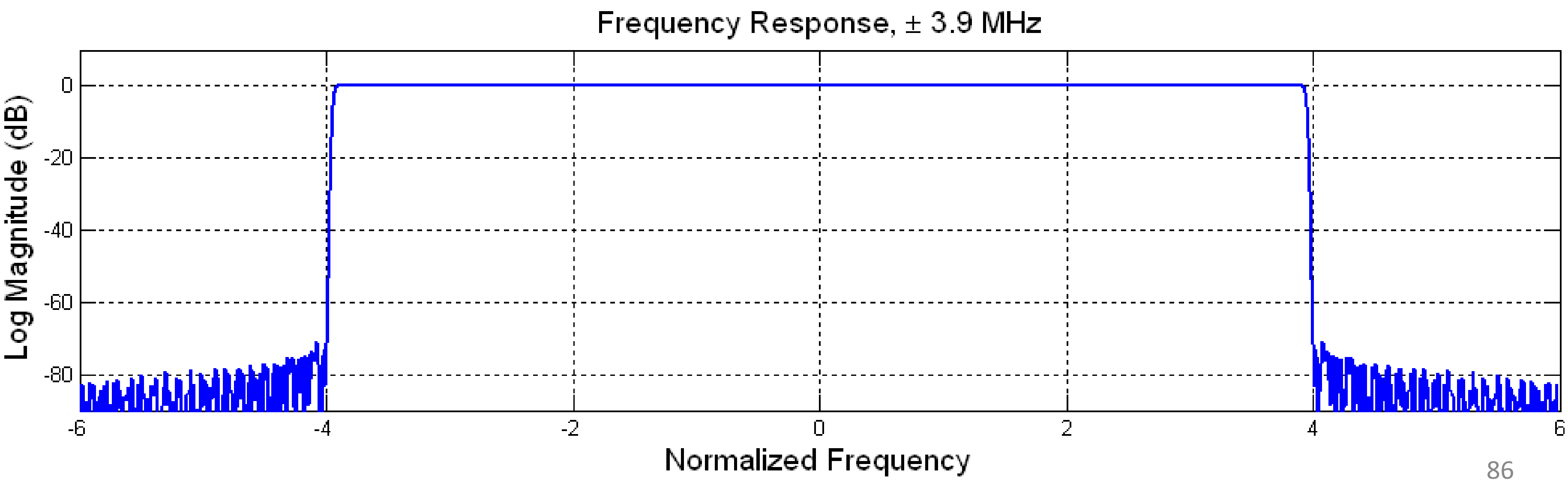
Impulse Response and Frequency Response
25-Enabled Ports: 2.4 MHz Bandwidth



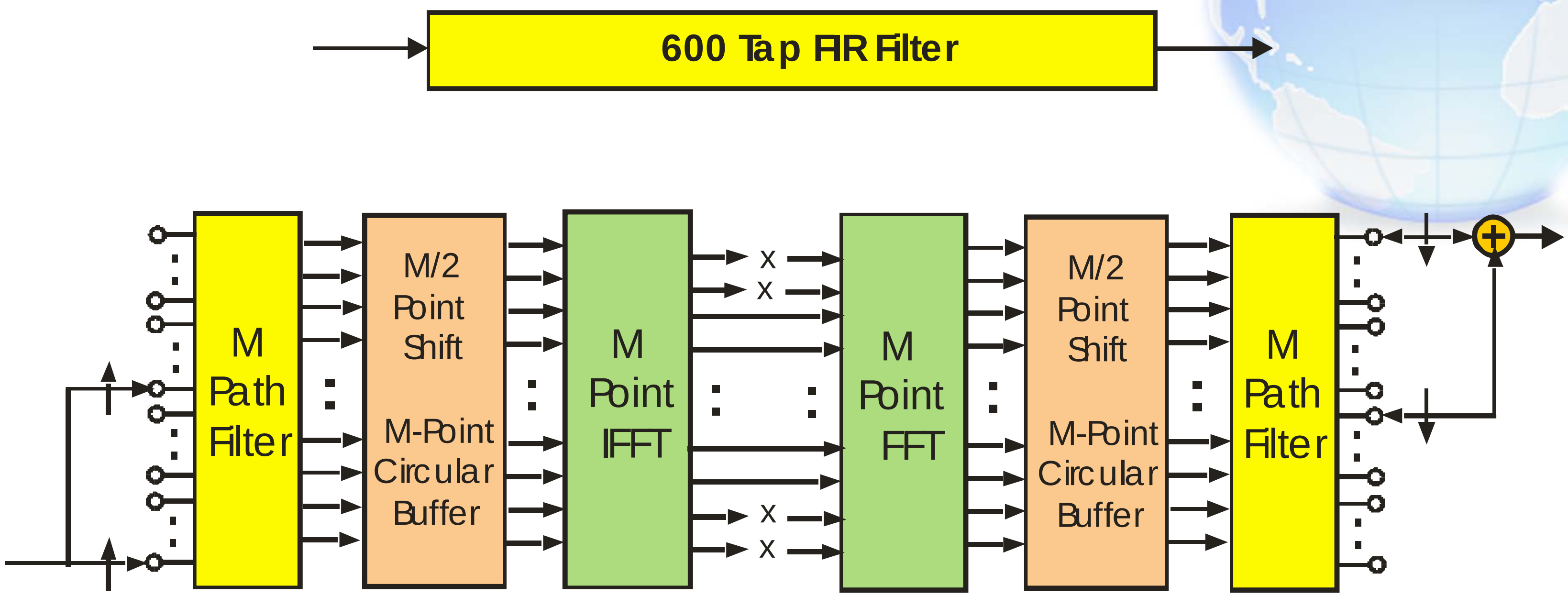


Impulse Response and Frequency Response 40-Enabled Ports: 3.9 MHz Bandwidth





Frequency Domain Filtering With Cascade M/2-to-1 Analysis and 1-to-M/2 Synthesis Channelizers



600 taps partitioned into 120 paths
5-Coefficients per path
10-Multiplies per input

120 Point FFT
3,5,8 prime factor FFT
288 Multiplies[(a)]
2.4-Multiples per input

120 Point FFT
3,5,8 prime factor FFT
288 Multiplies[(a)]
2.4-Multiples per output

600 taps partitioned into 120 paths
5-Coefficients per path
10-Multiplies per output

Direct Convolution: 600 Multiplies per input-output pair
Channelizer Convolution: 25 multiplies per input output pair
4.16% of Computational Effort, 95.8% Saving

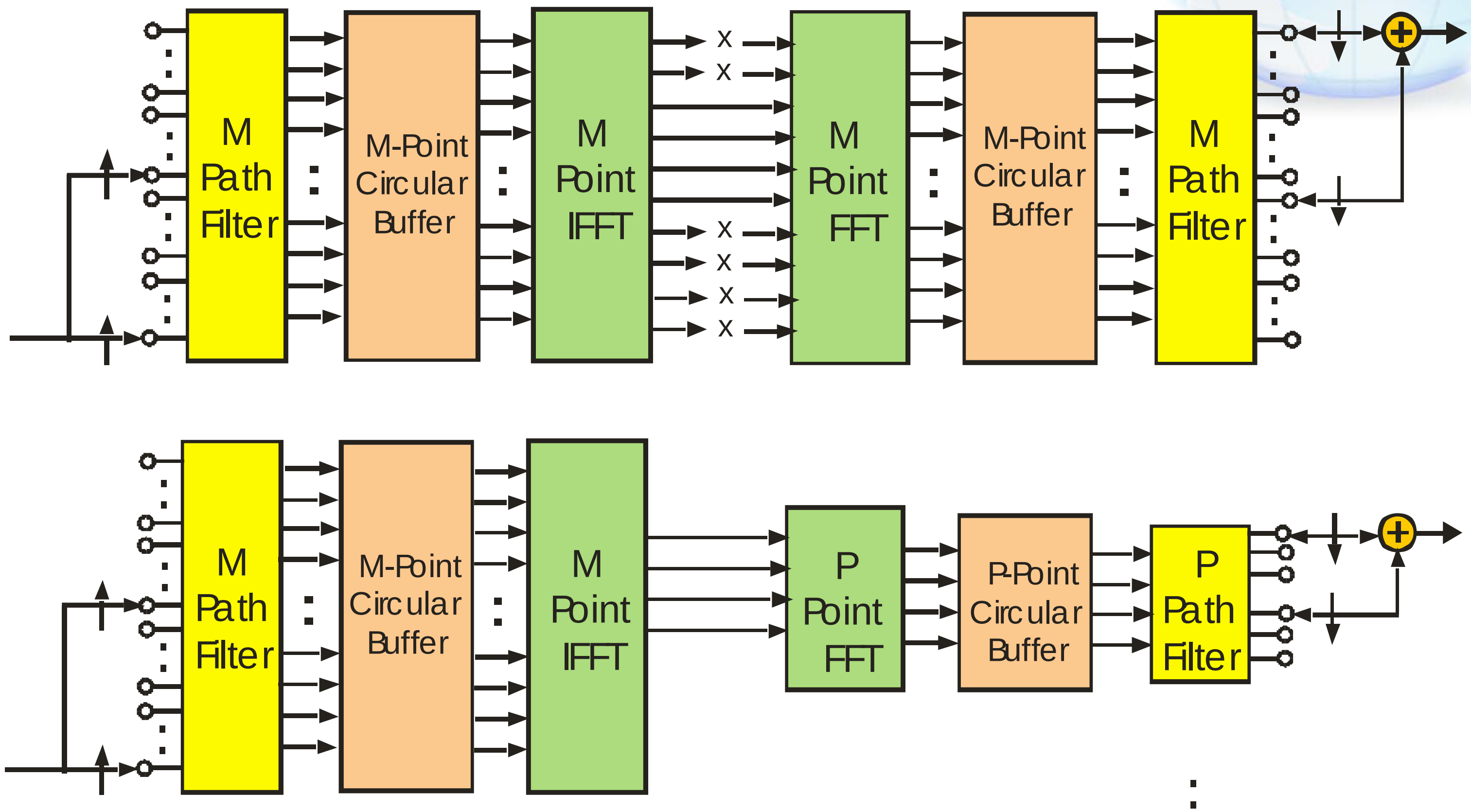
[(a)] Complex Input Samples

MATLAB DEMO-3

vary_bw_channelizer_120_3a

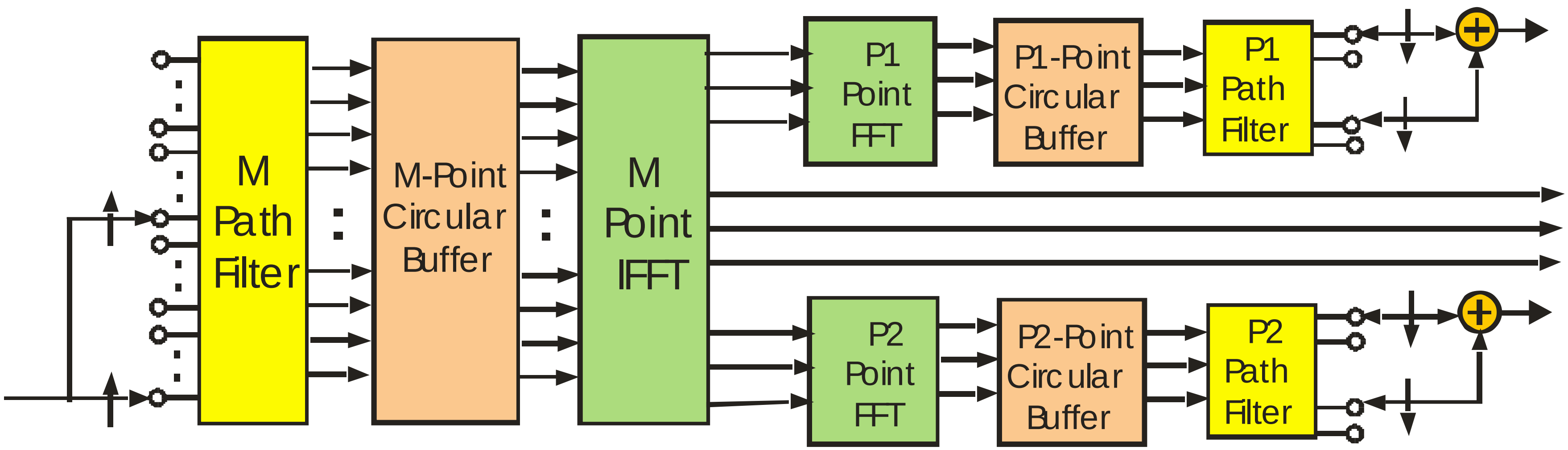
Mixed, Arbitrary Bandwidth Channelizers

Change Bandwidth With Mask
Change Sample Rate With Transform



Reassemble Decomposed Broadband Signals Using Short Synthesis Filters Formed by Multiple Channel Analysis Channelizer

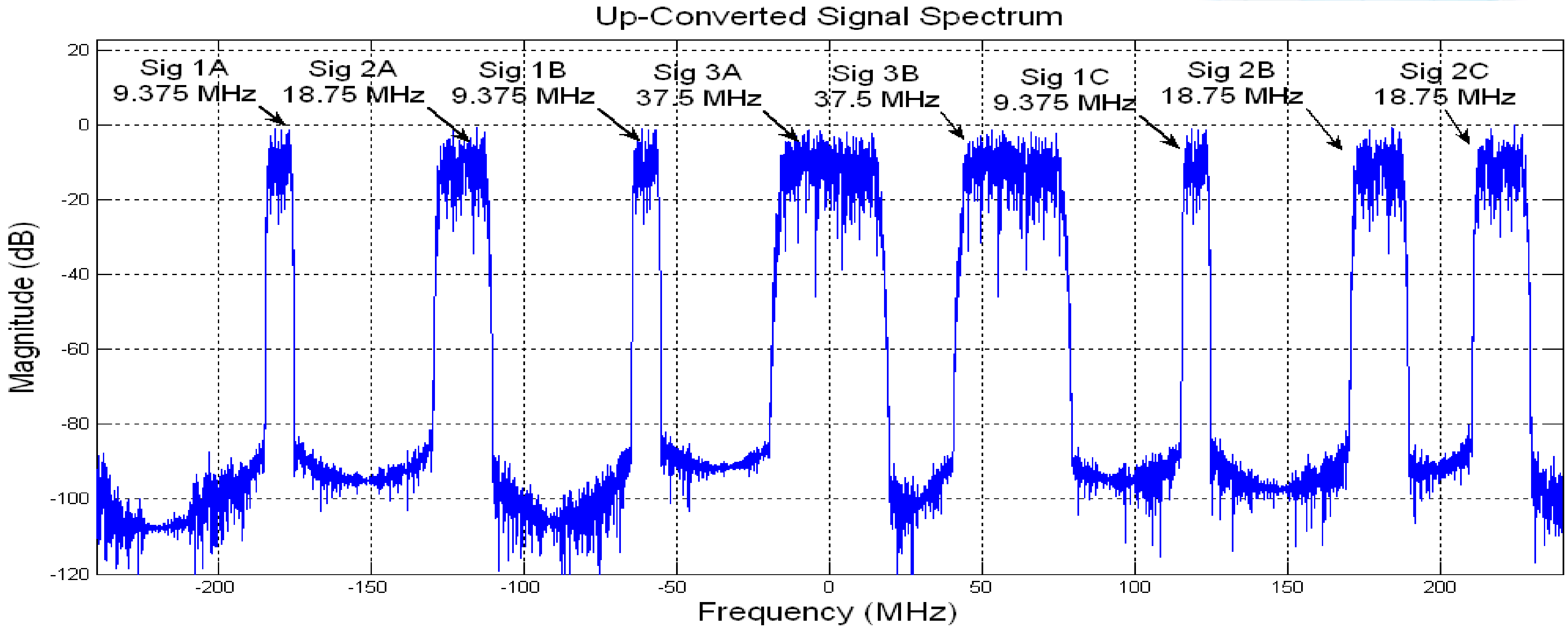
Synthesizer



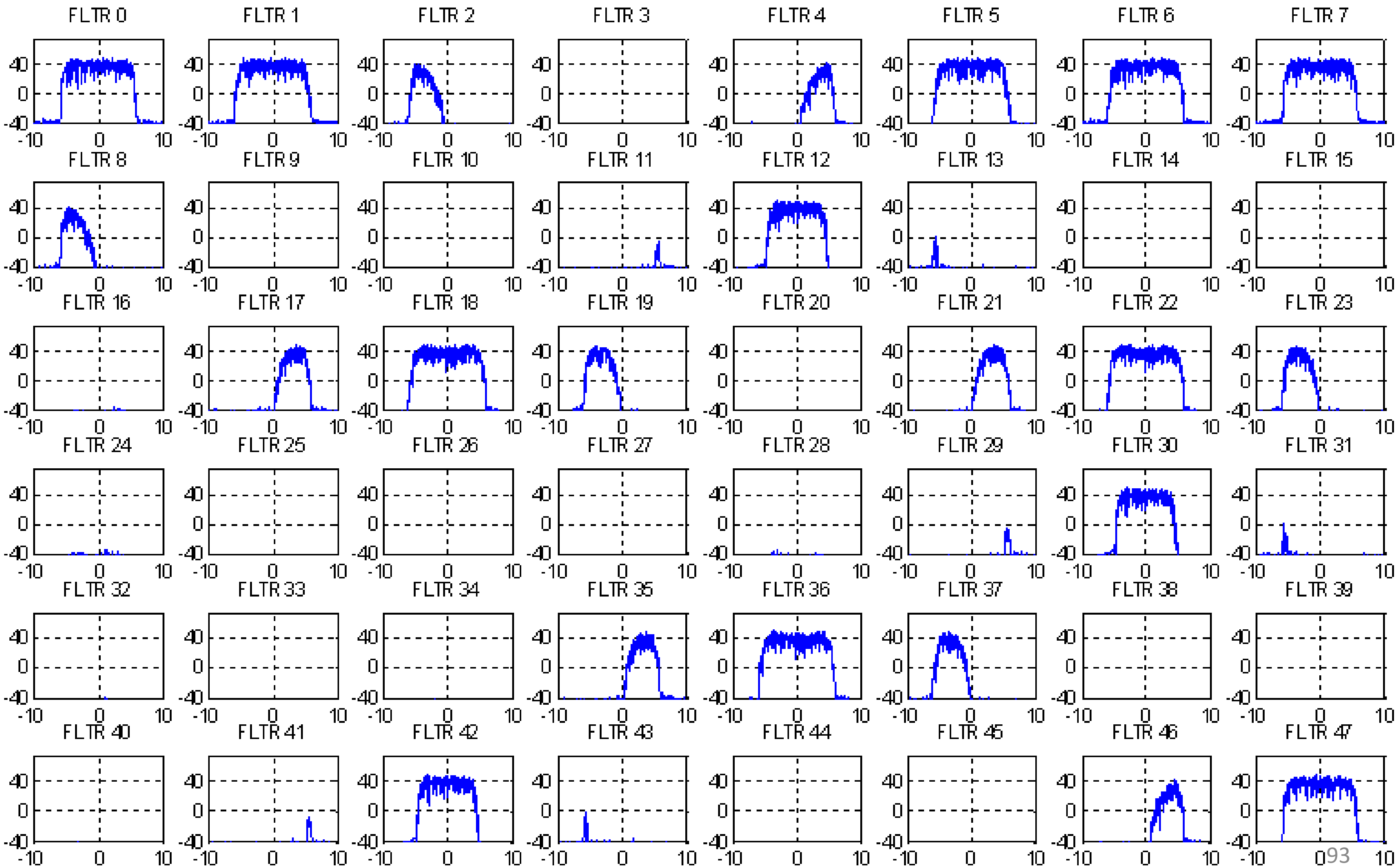
Analyzer

Synthesizer

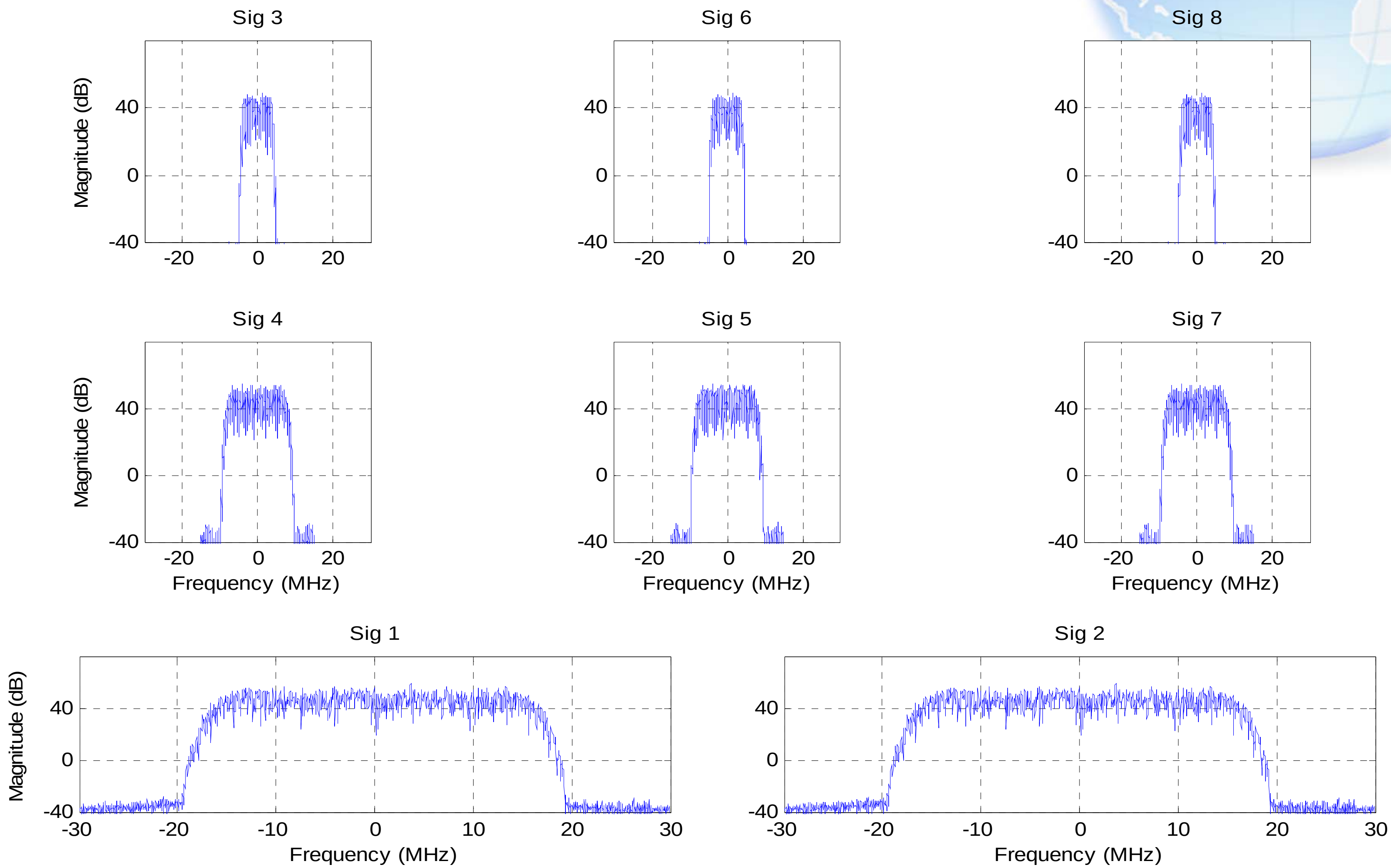
Input Spectrum to Be Dissembled in M-Path Channelizer
Multiple BW Channels from Single Analysis Channelizer



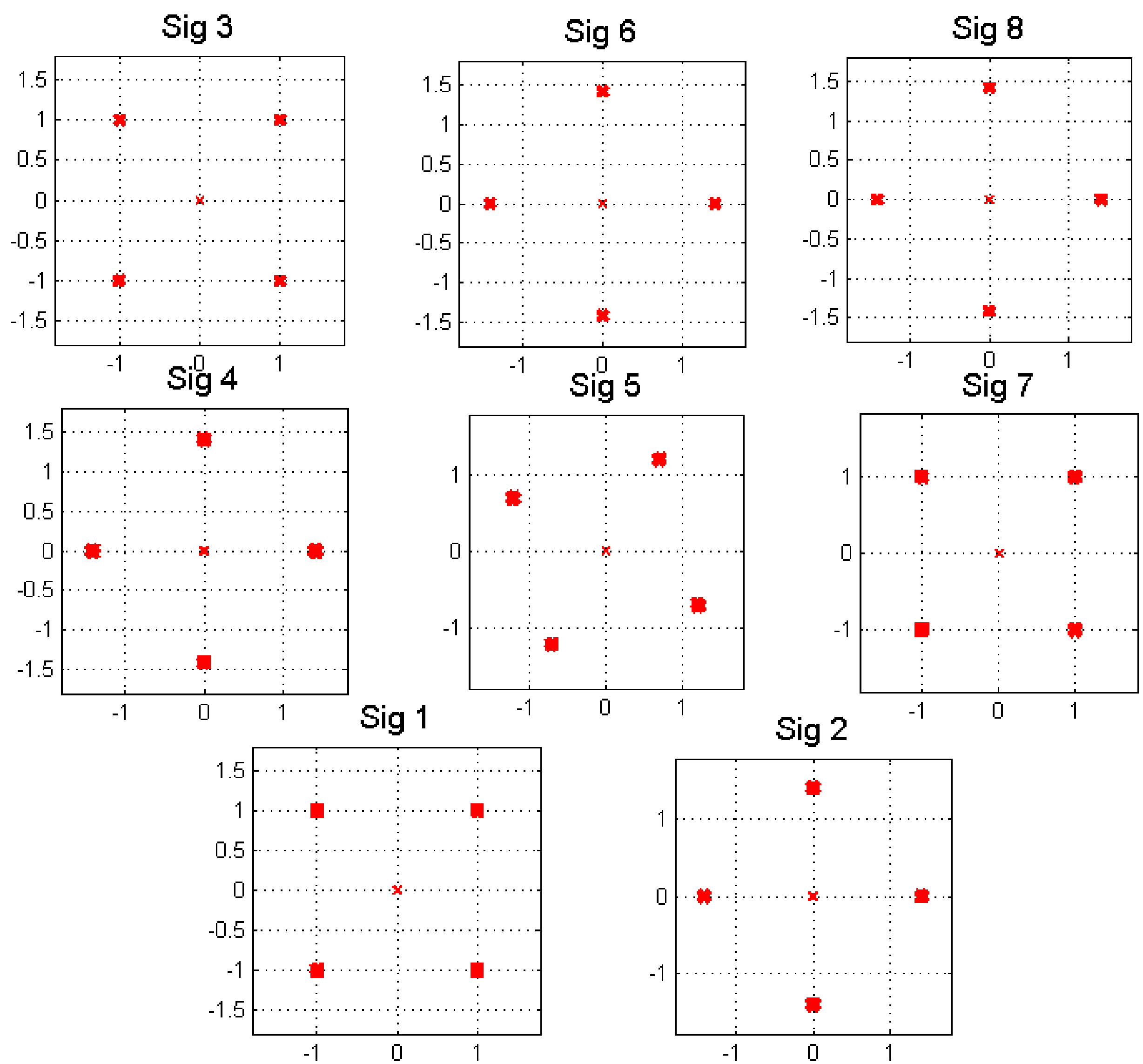
Partitioned Spectral Components from Single Multi-Channel Analyzer



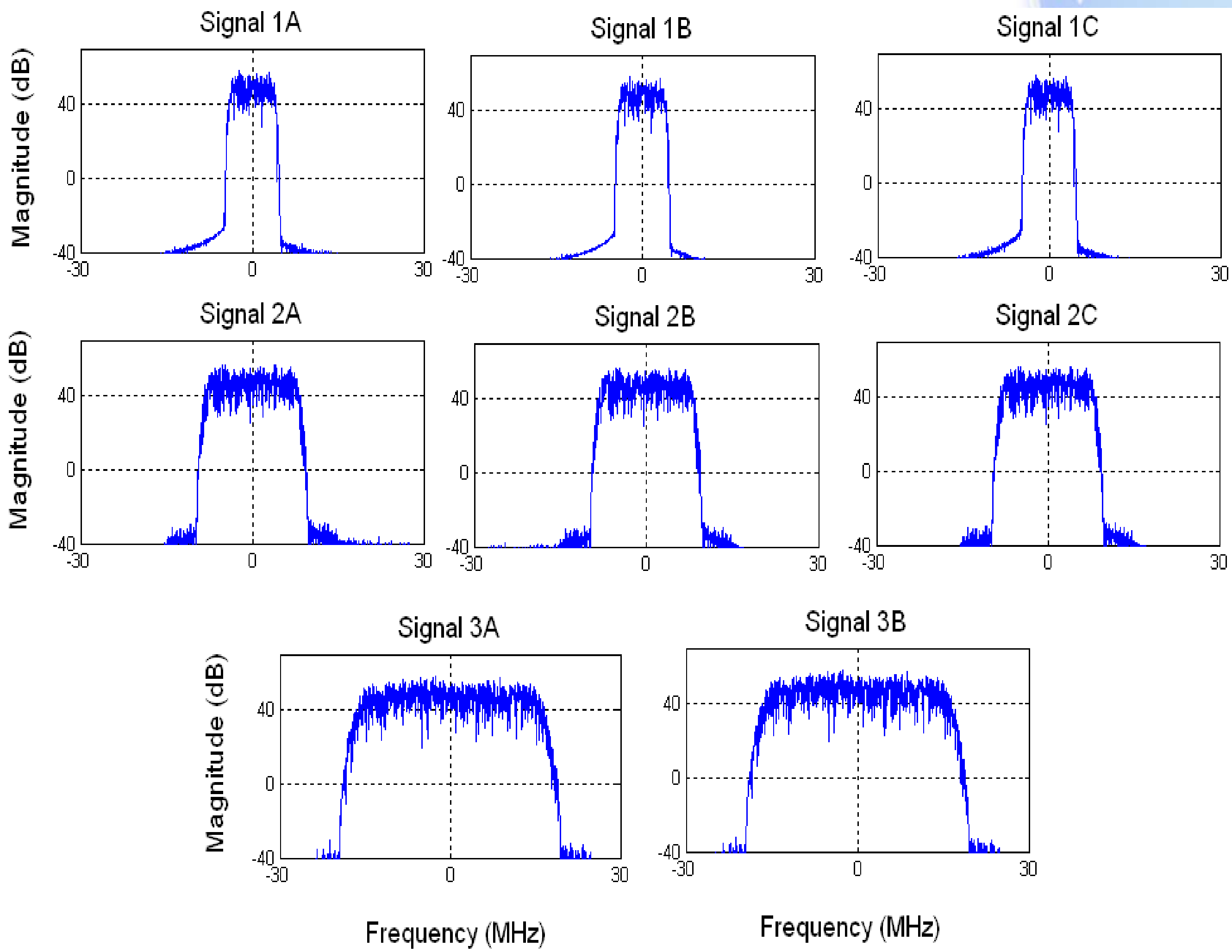
Reassembled Wide Band Channels from Short Synthesis Channelizers



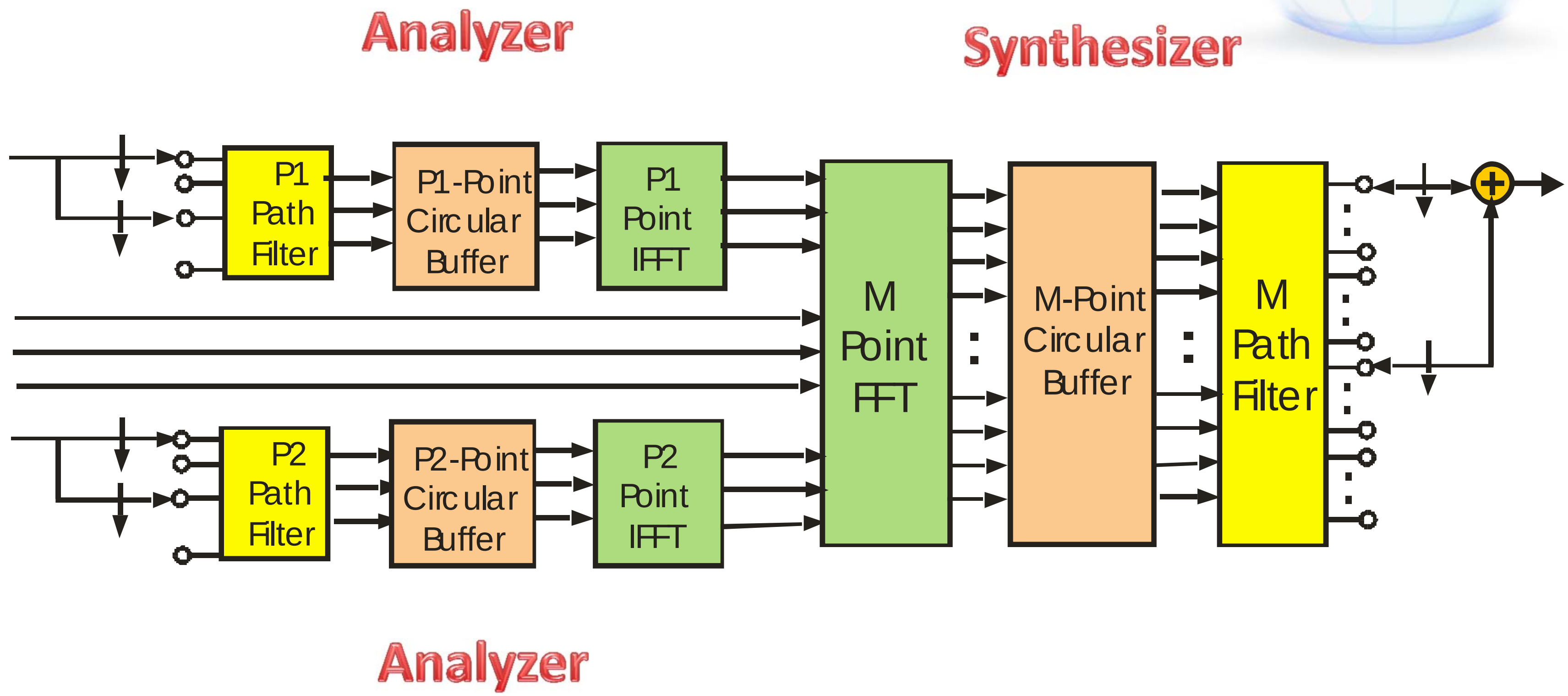
Signal Fidelity Preserved under Multiple Sub-Channel Disassembly and Reassembly



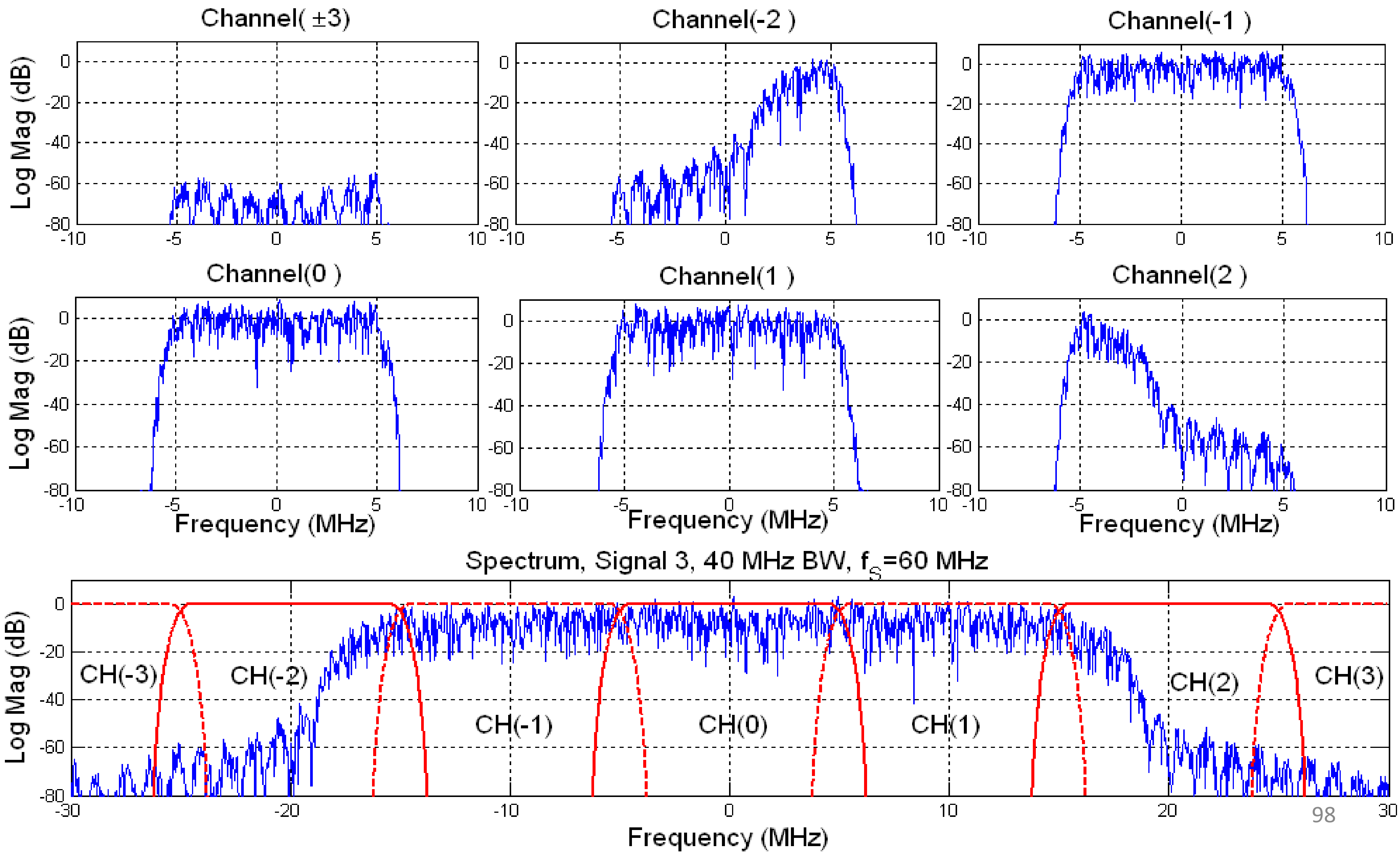
Mixed Bandwidth Signals Presented to Channel Synthesizer



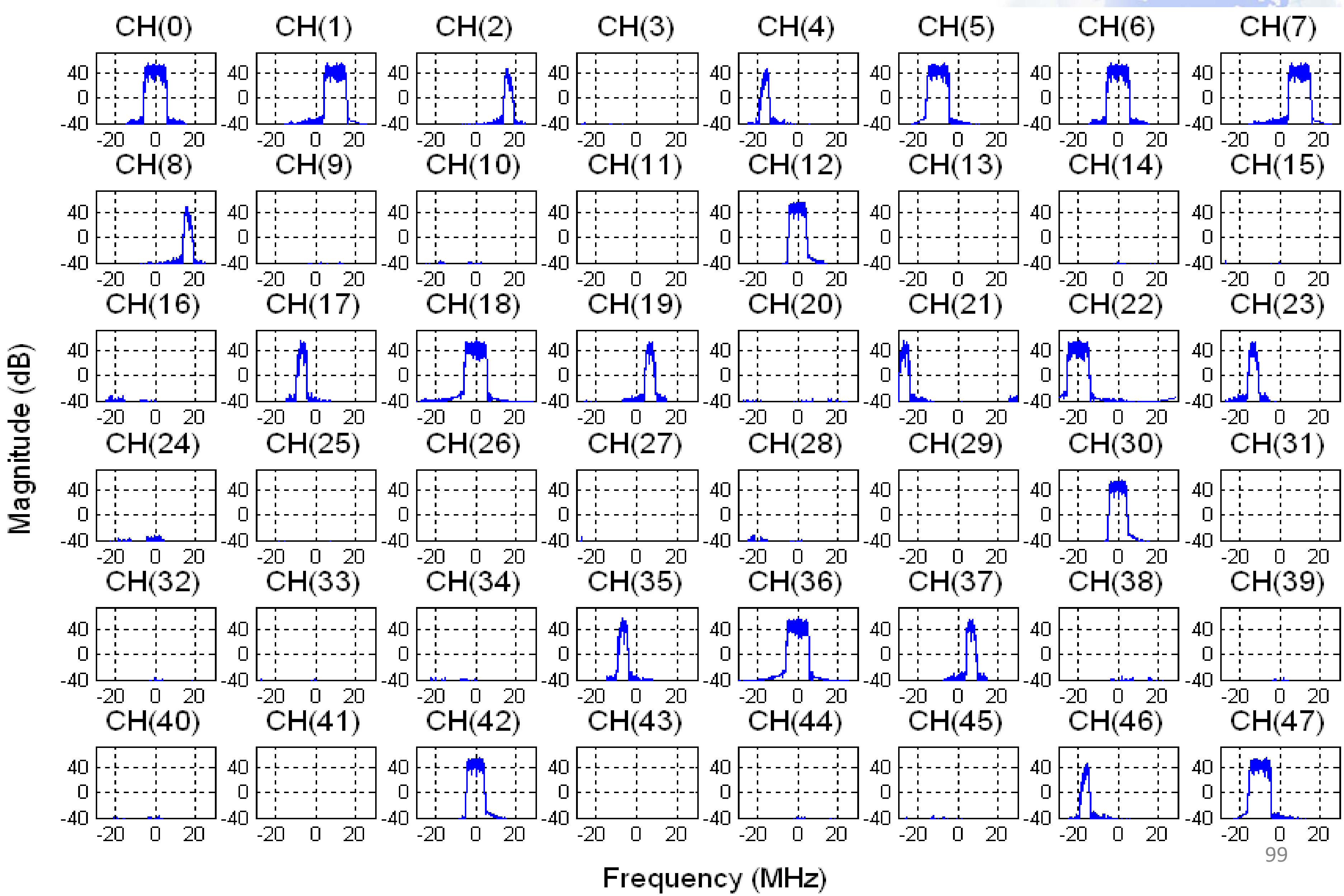
Decompose Broadband Signals Using Short Analysis Filters and Present Components to Synthesizer



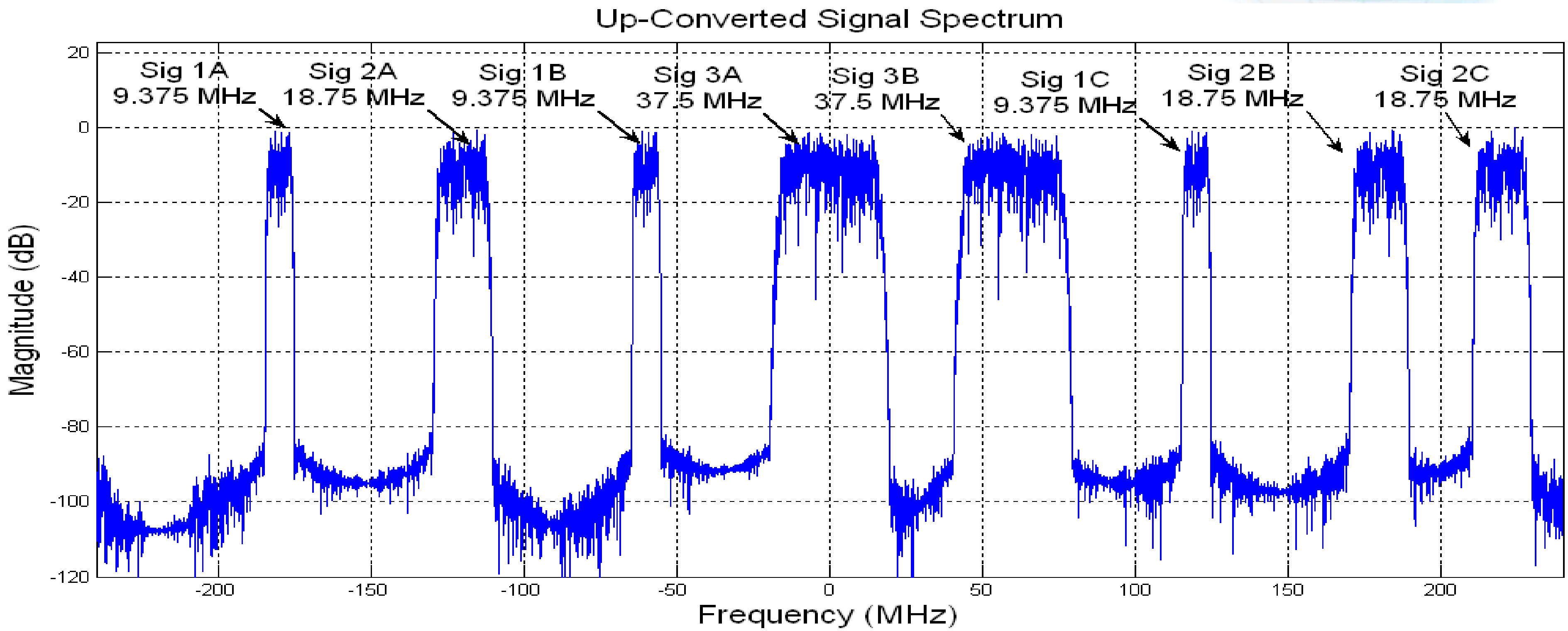
40-MHz Input Signal Partitioned into Five 10-MHz Sub-Channels: f_S=20 MHz



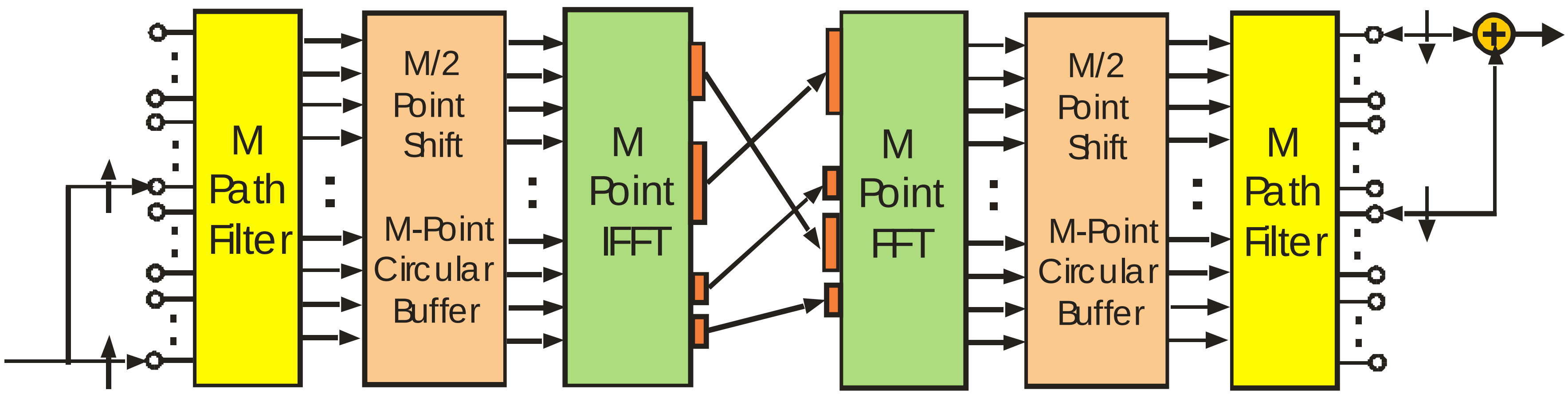
Multiple Partitioned Input Bands Presented to Synthesizer



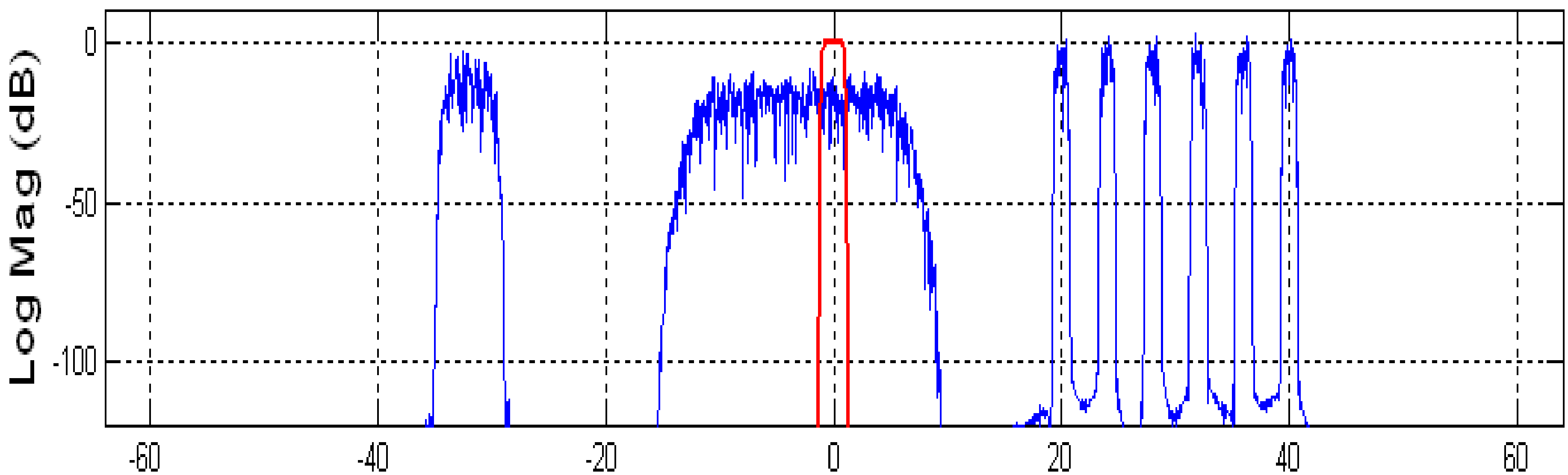
Assembled Multiple BW Channels in Single Synthesis Channelizer



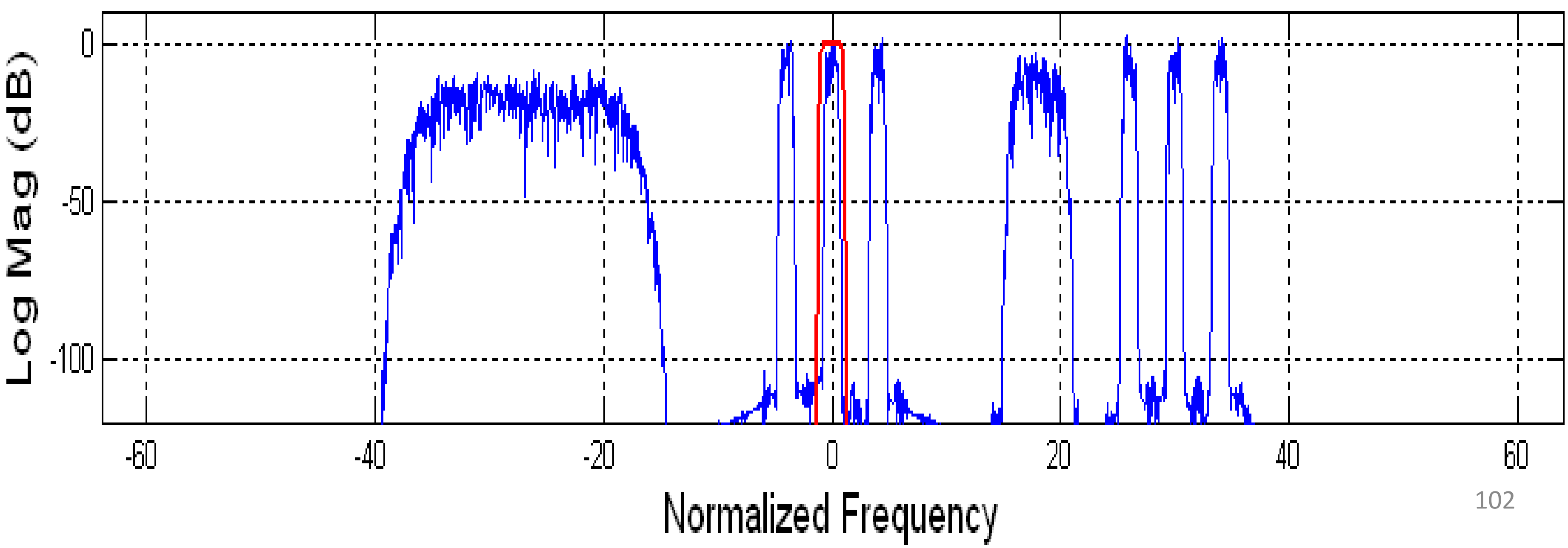
Cascade M/2-to-1 Analysis and 1-to-M/2 Synthesis Channelizers Frequency Domain Filtering and Spectral Shuffle



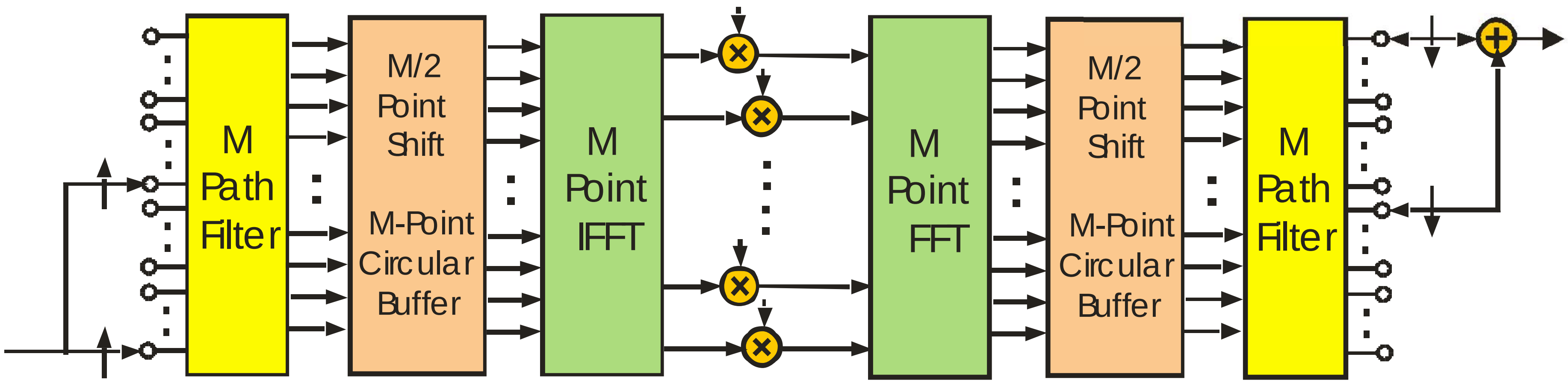
Composite Multi-Channel Input Spectrum



Composite Analysis, Rearranged, and Synthesized Output Spectrum



Spectral Weights:
Arbitrary Filter-Equalizer



SOFTWARE
DEFINED
RADIO
MAN

Is Open For Questions


Going to work on my trusty steed, Trigger

Going to work
on my other
trusty steed
Big Girl

Commuting
from
EC&E office
to my office
on the
Skateboard
Express

We Now Are Really Open For Questions