Digital Modulation Webinar

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Agenda

Brief refresh on analog modulation.
Concepts of digital modulation.
Modulation Formats.
I-Q Modulator and Demodulator.
Filtering.
Signal Generation Solution.
VSA Presentation and demonstrations.
Agenda.

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Modulation of a Carrier $A \sin 2\pi f_c t$

Intentional modification of a carrier signal for transmission of information.

- Unintentional modification of a carrier degrades Intentional Modulation

Types of Modulation:
- Amplitude Modulation (AM) - Modifies $A(t)$
- Frequency Modulation (FM) - Modifies $f_c$
- Phase Modulation (PM) - Modifies $\Phi(t)$
- Digital Modulation - Modifies both $A$ and $\Phi$

Goal of Modulation:
- To transmit information with high fidelity
- Adequate S/N, signal quality and minimize cost and power
- Obtain maximum spectral efficiency
  - (bits/sec/Hz - information density)
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**Concepts of digital modulation.**

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Digital Modulation Review

\[ x(t) = A(t) \cos(2\pi f_c t + \phi(t)) \]

- **Carrier Amplitude Change**
  - \( \Delta A(t) \)

- **Phase Change**
  - \( \phi(t) \)

- **Quadrature**
  - **In-phase**
  - **0 deg**

- **Frequency Change**
  - 0 deg

- **QAM** changes both \( A(t) \) & \( \phi(t) \)

Digital Modulation can change any one of the variables.
Polar Display-Magnitude and Phase represented together.

The polar display shows the time relationships of sinusoids. The polar display of an IQ demodulator can be assumed to be "normalized" to the carrier frequency of the IQ demodulator.
Polar vs « I-Q » Format

Project signal to I and Q axes

Instead of measuring phase, measure baseband DC voltages.
Signal changes or modifications

Magnitude Change

Phase Change

Both Change

Frequency Change
States, Bit Rate & Symbol Rate

**Quadrature Phase Shift Keying**
*Two bits per symbol*

State Diagram
*Bit Rate = 2 x Symbol Rate*

**Bit Rate:** is the number of bits per second in the system.

**Symbol Rate** = Bit Rate / No. of bits per symbol, AKA Baud Rate.

**Symbol Rate** determines the minimum system bandwidth requirement.
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**Modulation Formats.**
I-Q Modulator and Demodulator.
Filtering.
Signal Generation Solution.
VSA Presentation and demonstrations.
Digital I/Q Modulation Formats

- BPSK
- QPSK
- $\pi/4$ DQPSK
- 16QAM
- 32QAM
- MSK
- 8 PSK
Modulation Formats

BPSK encodes one binary bit per symbol by a 180° phase change of the Carrier. The occupied spectrum bandwidth is proportional to the symbol frequency.

- Quadrature modulation formats increases the bit rate by 2X using the same symbol clock frequency and therefore same occupied bandwidth.

Binary Phase Shift Keying

- One bit per symbol

Quadrature Phase Shift Keying

- Two bits per symbol

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Offset QPSK minimizes power variations between symbols by delaying the I to Q timing so the carrier trajectory does not go through zero, the origin.
Binary Phase Shift Keying and 8 Level Phase Shift Keying

BPSK
One Bit per Symbol
Symbol Rate = Bit Rate

8PSK
3 Bits per Symbol
Symbol Rate = 1/3 of Bit Rate
Quadrature Amplitude Modulation

16 QAM

4 Bits per Symbol
Symbol Rate = 1/4 of Bit Rate

32 QAM

5 bits per Symbol
Symbol Rate = 1/5 of Bit Rate
Major Modulation Goal: Spectral Efficiency

Theoretical Bandwidth Efficiency Limits:

- **BPSK** 1 bit/second/Hz
- **QPSK** 2 bits/second/Hz
- **8PSK** 3 bits/second/Hz
- **16QAM** 4 bits/second/Hz
- **32 QAM** 5 bits/second/Hz
- **64 QAM** 6 bits/second/Hz
- **256 QAM** 8 bits/second/Hz
- **512 QAM** 9 bits/second/Hz
- **1024 QAM** 10 bits/second/Hz
- **2048 QAM** 11 bits/second/Hz
- **4096 QAM** 12 bits/second/Hz
- **8192 QAM** 13 bits/second/Hz

*Note: The figures are theoretical limits and CAN NOT be achieved in practical radios*
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**I and Q Modulator**

Quadrature (90°) mixing, I and Q are "Orthogonal" to each other and do not interact.
I - Q Modulation

\[ \frac{1.5}{V} \div \frac{0.3}{\text{div}} F_1 + (K_4 \times F_2) \]

\[ \frac{1.5}{V} \div \frac{D_1}{\text{div}} + (K_4 \times D_3) \]

\[ Q(t) \sin 2\pi f_c(t) \]

\[ I(t) \cos 2\pi f_c(t) \]

\[ \Sigma \]

\[ Q(t) \sin 2\pi f_c(t) \]

\[ I(t) \cos 2\pi f_c(t) \]
Demodulating I and Q in a Receiver

Composite Input Signal

\[ M(t) \cos (\omega_c t + \phi(t)) \]

Power splitter

\[ 2 \sin \omega_{LO} t \]

\[ x \cdot M(t) \cos (\omega_c t + \phi(t)) = ? \]

\[ 2 \cos \omega_{LO} t \]

\[ \text{Let } \omega_c = \omega_{LO} \]

\[ x \cdot M(t) \cos (\omega_c t + \phi(t)) = ? \]

\[ \text{In-Phase Component} \]

\[ \text{Quadrature Component} \]

\[ I(t) = \text{In-Phase}, \quad Q(t) = \text{Quadrature} \]

Can be extracted from the carrier with simple circuits

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Detecting I(t) and Q(t)

Down converted composite input signal MQAM(t)

\[ MQAM(t) \cos \omega c t + \phi(t) \]

Power splitter

\[ x_1(t) = (MQAM(t) \cos \omega c t + \phi(t))^2 \cos \omega_c t \]

90° Phase Shift

\[ x_2(t) = \frac{1}{2} \sin 2\pi (f_c - f_{LO})t + \frac{1}{2} \sin 2\pi (f_c + f_{LO})t \]

Local Osc.

\[ I(t) = \frac{1}{2} \cos 2\pi (f_c - f_{LO})t - \frac{1}{2} \cos 2\pi (f_c + f_{LO})t \]

\[ Q(t) = \frac{1}{2} \sin 2\pi (f_c - f_{LO})t - \frac{1}{2} \sin 2\pi (f_c + f_{LO})t \]

The Trigonometric identities \( \cos \phi \times \cos \theta \) & \( \cos \phi \times \sin \theta \) applied to QAM demodulation of carrier \( \omega_c = \omega_{LO} \).

\[ x_1(t) = (MQAM(t) \cos \omega c t + \phi(t))^2 \cos \omega_{LO} t = [I(t) \cos \omega c t + Q(t) \sin \omega c t]^2 \cos \omega_{LO} t \]

\[ x_1(t) = I(t) \cos 2\pi (f_c - f_{LO})t + I(t) \cos 2\pi (f_c + f_{LO})t + Q(t) \sin 2\pi (f_c + f_{LO})t + Q(t) \sin 2\pi (f_c - f_{LO})t \]

Low pass filter selects \( I(t) \) & rejects the \( 2\omega_c \)

\[ x_2(t) = (MQAM(t) \cos \omega c t + \phi(t))^2 \sin \omega_{LO} t = [I(t) \cos \omega c t + Q(t) \sin \omega c t]^2 \sin \omega_{LO} t \]

\[ x_2(t) = I(t) \sin 2\pi (f_c - f_{LO})t - I(t) \sin 2\pi (f_c + f_{LO})t + Q(t) \cos 2\pi (f_c - f_{LO})t - Q(t) \cos 2\pi (f_c + f_{LO})t \]
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Filters-Modulation Shaping

Filtering Benefits
- Reduces transmitted bandwidth
- Improved Bandwidth efficiency
- Reduced noise interference
- Reduced Inter Symbol Interference
- Improved receiver sensitivity

Filtering Costs
- Complexity
- Possible inter-symbol interference
- Increased power amplifier Linearity
- Higher Peak Power

Filter Types
- Nyquist, square-root Nyquist
- Gaussian
- IS-95 (CDMA Filter)
- User-defined
I-Q Modulation Occupied Band Width

No Filtering of the Modulating Signal

I(t) Modulating Signal

I(f ) Spectrum
Nyquist or Raised-Cosine Filter
Zero Inter-Symbol Interference

Impulse Response crosses 0 for all adjacent symbol clock transitions.
Raised Cosine Digital Filter

Log Mag RAISED COSINE FREQUENCY RESPONSE

IMPULSE RESPONSE
Time Response I(t)
Filter Bandwidth Parameter "\( \alpha \)"

Alpha describes the "sharpness" of the filter.

Occupied bandwidth is approximately: Symbol rate \( \times (1 + \alpha) \).
Raised Root Cosine $\alpha = 1/2$
Raised Cosine Filter Band Width

$I(t)$ No Filtering

$\alpha = 1$

$\alpha = 1/2$
Raised Cosine

\[ \alpha = 1 \]

\[ \alpha = 0.5 \]
Effect of Different Filter Bandwidths

QPSK Vector Diagrams

- No Filtering
- $\alpha = 0.75$
- $\alpha = 0.375$

No Overshoot
More Overshoot
Symbol Rate, Filter Shape and Occupied Bandwidth

Bit Stream = 20 kHz
Symbol Rate = Bit Rate / 2 = 10 kHz

Occupied Bandwidth
OCBW (Hz) = Symbol Rate x (1 + α) = 10kHz x 1.5 = 15 kHz
The Error Vector vs Time Measurements

I-Q Magnitude Error

\[
\text{I-Q Mag Error} = \frac{\sqrt{I_{\text{mea}}^2(t) + Q_{\text{mea}}^2(t)} - \sqrt{I_{\text{ref}}^2(t) + Q_{\text{ref}}^2(t)}}{\sqrt{I_{\text{ref}}^2(t) + Q_{\text{ref}}^2(t)}} \times 100\%
\]

I-Q Phase Error

\[
\text{I-Q Phase Error} = \theta(t) = \theta_{\text{meas}}(t) - \theta_{\text{ref}}(t)
\]

Error Vector Time

\[
\text{EVT} = \frac{\sqrt{[I_{\text{ref}}(t) - I_{\text{mea}}(t)]^2 + [Q_{\text{ref}}(t) - Q_{\text{mea}}(t)]^2}}{\sqrt{I_{\text{ref}}^2(t) + Q_{\text{ref}}^2(t)}}
\]

\[
\phi(t) = Tan^{-1} \left( \frac{Q_{\text{meas}} - Q_{\text{ref}}}{I_{\text{meas}} - I_{\text{ref}}} \right)
\]

Reference to Decision Point
Modulator

Impairments & Measurements

- Gain Imbalance
- I-Q Offsets
- Phase Imbalance

Modulation Impairments

- Interference
- Phase Noise
- Added Noise
Digital Communication System Characterization

**Transmitter**

- Voice Input
- A/D
- Processing/Compression/Error Correction
- Encode Symbols
- Mod
- AD

**Receiver**

- IF RF
- AGC
- IF Demod
- Decode Bits
- Adaption/Process/Decompress
- D/A
- Voice Output
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**Signal Generation Solution**

VSA Presentation and demonstrations.
Signal Generation Solution

Complex signal generation made easy

First-to-market track record
- Standards-based & custom signal creation
- Recognized benchmark reference signal

Broasted application coverage
- Fully & partially coded signals
- MIMO applications

Easy-to-use
- Flexible signal creation
- Ready for automation

Validated and performance-optimized
Agilent Signal Studio & Embedded Software

Mobile Communications
- W-CDMA/HSPA (ARB)
- HSPA+ (ARB)
- W-CDMA/HSPA (ARB)
- W-CDMA (ARB)
- HSPA (RT)
- LTE FDD (ARB) + MIMO
- TD-LTE (ARB)
- IS-95-A & CDMA2000 (ARB)
- 1xEV-DO (ARB)
- TD-SCDMA (ARB)
- IS-95-A & CDMA2000 (ARB)
- IS-95-A & CDMA2000 (RT)
- GSM/EDGE (ARB)
- EGPRS (ARB)
- TDMA (RT): GSM/EDGE/GPRS/EGPRS
  NADC/PDC/PHS
  DECT/TETRA
- TDMA (ARB): GSM/EDGE
  NADC/PDC/PHS
  DECT/TETRA
  APCO/PWT/CDPD

Wireless Connectivity
- Mobile WiMAX (ARB)
  802.16e + MIMO
- Fixed WiMAX (ARB)
  802.16d
- WLAN (ARB)
  802.11 a/b/g/n/p/j
  802.11n + MIMO
- Bluetooth (ARB)
  V1.1
  V2.1+EDR
  Ultra Low Energy (Wibree)
- MB-OFDM UWB (ARB)
  802.15

Audio/Video Broadcasting
- Digital Video (ARB):
  DVB-T/H/C/S/S2
  J.83 Annex A/B/C
  ISDB-T
  DTMB
  ATSC
  CMMB/StiMi
  Digital Video (RT)
- Broadcast Radio (ARB):
  FM Stereo/RDS/RDBS
  mono & stereo
  DAB/DAB+

Detection, Positioning, Tracking & Navigation
- Pulse Building (ARB)
- GPS (RT)
  1 to 8 satellites
- GPS (RT)
  multi-satellite

General RF/MW
- Toolkit (ARB)
- Jitter Injection (ARB)
- Multitone Distortion (ARB)
  (Enhanced Multitone & NPR)
- Multitone (ARB)
- Calibrated AWGN (ARB & RT)
- Phase Noise Impairments (RT)
- Custom Modulation (ARB & RT)

www.agilent.com/find/signalstudio
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- Filtering.
- Signal Generation Solution

**VSA Presentation and demonstrations.**
VSA Software – 89601A.
Synthesis of the Reference I-Q Signal
"Measurement and Reference Filters"

Reference Signal Generation

- I-Q Data
- DAC
- Modulator
- PA
- Root Raised Cosine Filter
- Measurement Filter
- (Receiver 89600A)
- Demodulator
- Detected Bits
- Ideal/Reference Signal Generated
- Raised Cosine Filter
- Reference Filter

- Root Raised Cosine Filter
- Measured Waveform
- 1001 0001 0110
- \( \sqrt{\cos \times \sqrt{\cos}} \)
- Reference Waveform

- I-Q Error Waveform

Agilent Technologies
VSA Software – Hardware support.

High End Spectrum Analysers

Dig RF v3 / v4 solutions

Middle-range Signal Analyzers

Data Acquisition cards

Logic Analysers

Middle-range Scopes

High End Scopes
Formats supported by VSA Software.

89601A Vector Signal Analysis Software
- Advanced signal analysis capabilities
- Runs **INSIDE** the MXA or EXA
- All optional formats available

**50+ Demodulation Types:**
AM/FM/ΦM, WiMAX 802.16 OFDM/OFDMA, WLAN IEEE 802.11a/b/g/j/p, Digital Video, Private Mobile Radio, CDMA (base), CDMA (mobile), CDPD, GSM, EDGE, NADC, PDC, PHP (PHS), W-CDMA, TD-SCDMA, HSDPA, 1xEV-DO, 1xEV-DV, Bluetooth™, ZigBee™, APCO 25, DECT, TETRA 1, TETRA 2 (TEDS), VDL mode 3, FSK: 2, 4, 8, 16 level (including GFSK), MSK (including GMSK), BPSK, QPSK, OQPSK, DQPSK, D8PSK, π/4-DQPSK, 8PSK, 3π/8-8PSK, 16/32/64/128/256/512/1024 QAM, 16APSK, 32APSK, 8VSB, 16VSB, RFID
Let’s take example of a Device.

Common Signal Analysis Platform

- common measurements
- common interface
- single learning curve

Multiple Signal Interfaces

DSP

Digital (SSI) BB (I-Q) IF/RF

Logic Analyzer MXA BBIQ Signal Analyzer

DSO 90000A Series Oscilloscope

Superior Signal Integrity
Deep Application Analysis
Better Insight

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Vector Diagram

NADC, $\pi/4$ DQPSK, 157 symbols, 10 points/symbol

157 symbols
1 point/symbol
Constellation Diagram

$\pi/4$ DQPSK signal shown with added white Gaussian noise contamination
The EVM display shows the Magnitude of the error between the measured and ideal I(t) - Q(t) trajectories referenced to the Symbol State.

The points per Symbol sets the number of points between symbols up to 20.

The green bars show the error at the symbol times. Errors can be seen at the symbol points and in between.

X axis scale expanded

Error Vector Magnitude (EVM)
I/Q Eye Diagram Under Data Format Key

NADC Signal
Symbol Table and Error Summary

**NADC \( \pi/4 \) DQPSK Signal**

I - Q Modulator Quality:

- **Gain Imb:**
  - What is the gain match between I & Q?

Quad Skew Err:
- How close to 90° are I & Q?

I - Q Offset
- DC Offset

See Product Note 89400-8 for definition of each term.
Digital Demodulation Default Quad Display Four Main Analysis Tools

- **Trace A**: Constellation Display
- **Trace B**: Spectrum
- **Trace C**: Error Vector Magnitude
- **Trace D**: Symbol Table & Error Summary

**Gain Compression?**

**Coupled Markers**
Hardware used for demonstrations

MXA Signal Analyser N9020A

MXG Vector Signal Generator N5182

www.agilent.com/find/MXA
www.agilent.com/find/MXG
Demo 1

Demodulation of simple QPSK Signal with VSA software. Filtering effects.
Demodulation of OQPSK Signal
Demo 2

Demodulation of perturbated signal.
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89600A VSA’s Adaptive Equalization

Compensates for Linear Gain/Phase
- Multi-path Reception
- Group Delay Error
- Frequency Response
  - Ripple/Tilt

Does NOT Remove
- Noise
- Nonlinear Distortion
  - Spectral Regrowth or IMD
  - Harmonic Distortion
  - Spurious Responses

$G_{\text{comp}}(f)$
Why Use Adaptive Equalization?

Most Receivers have internal Adaptive Equalizers
- Important to measure a signal the way a real receiver would. Adaptive Equalizer may be required for Symbol Lock.
- Some signals cannot be measured without equalization.

Valuable Design and Troubleshooting Insights:
- Distinguish between linear gain/phase errors and non-linear distortion.
- Measure real systems while in service.
- Quantify amount of stress put on receiver's equalizer.
- Provides feedback to hardware and software designers.
Using the VSA’s Equalizer

1. VIEW CONSTELLATION, SYMBOL TABLE, EVM

2. TURN THE EQUALIZER ON
   MeasSetup, Demod Properties
   Check [✓✓✓✓] Equalization Filter

3. WATCH FOR:
   EVM TO DROP
   CONSTELLATION CLOUDS TO CONVERGE

4. IF CLOUDS DIVERGE OR LOSS OF LOCK
   REDUCE [CONVERGENCE] (Small changes only!)
   RESET EQUALIZER [EQ RESET]
Equalizer Measurement Results

A Math function computed the FFT of the EQ filters Impulse Response.
Demo 3

Demonstration of Equalization benefits.
Demo 4

Demodulation of a Wireless standard.
Summary