An Introduction to Orthogonal Frequency Division Multiplex Technology

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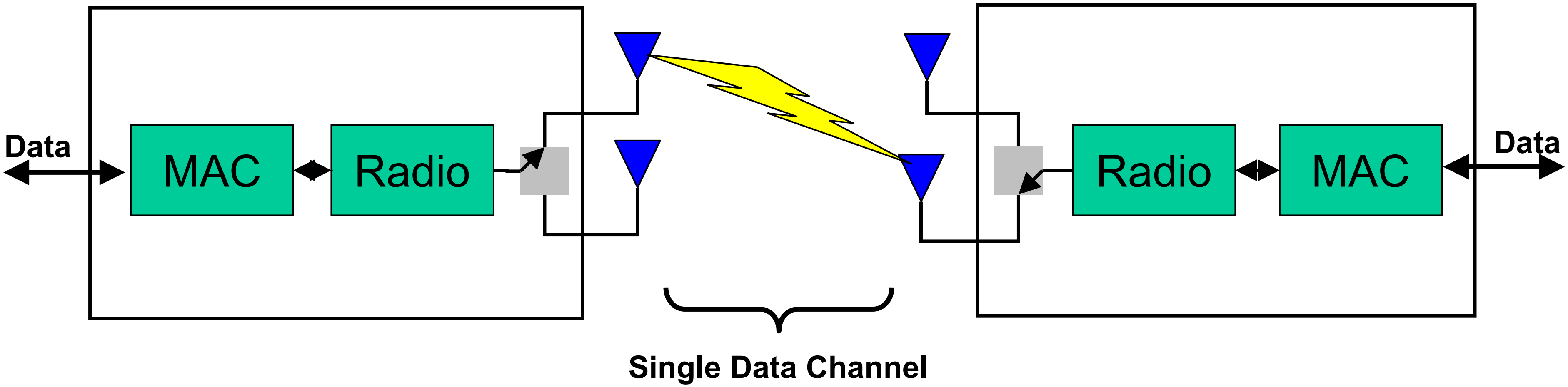
Agenda

- **Part One – OFDM and SISO radio configurations**
  - SISO – Single Input Single Output Radio Topology
  - Why use OFDM?
  - Digital Modulation Overview
  - Multi-path Issues
  - OFDM and WLAN
  - OFDMA and WiMAX
  - Test Equipment Requirements
- **Part Two – OFDM and MIMO radio configurations**
  - MIMO – Multiple Input Multiple Output Radio Topology
  - MIMO and WLAN
  - MIMO and WiMAX
  - Beam Forming
  - Test Equipment Requirements
- **Conclusion**
  - Technology Overview and Test Equipment Summary

What is SISO?
Single-Input Single-Output

Traditional – SISO Architecture



- One radio, only one antenna used at a time (e.g., 1 x 1)
- Antennas constantly switched for best signal path
- Only one data “stream” and a single data channel

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System Standards using OFDM

Wireless

- IEEE 802.11a, g, j, n (WiFi) Wireless LANs
- IEEE 802.15.3a Ultra Wideband (UWB) Wireless PAN
- IEEE 802.16d, e (WiMAX), WiBro, and HiperMAN Wireless MANs
- IEEE 802.20 Mobile Broadband Wireless Access (MBWA)
- DVB (Digital Video Broadcast) terrestrial TV systems: DVB-T, DVB-H, T-DMB and ISDB-T
- DAB (Digital Audio Broadcast) systems: EUREKA 147, Digital Radio Mondiale, HD Radio, T-DMB and ISDB-TSB
- Flash-OFDM cellular systems
- 3GPP UMTS & 3GPP@ LTE (Long-Term Evolution), and 4G

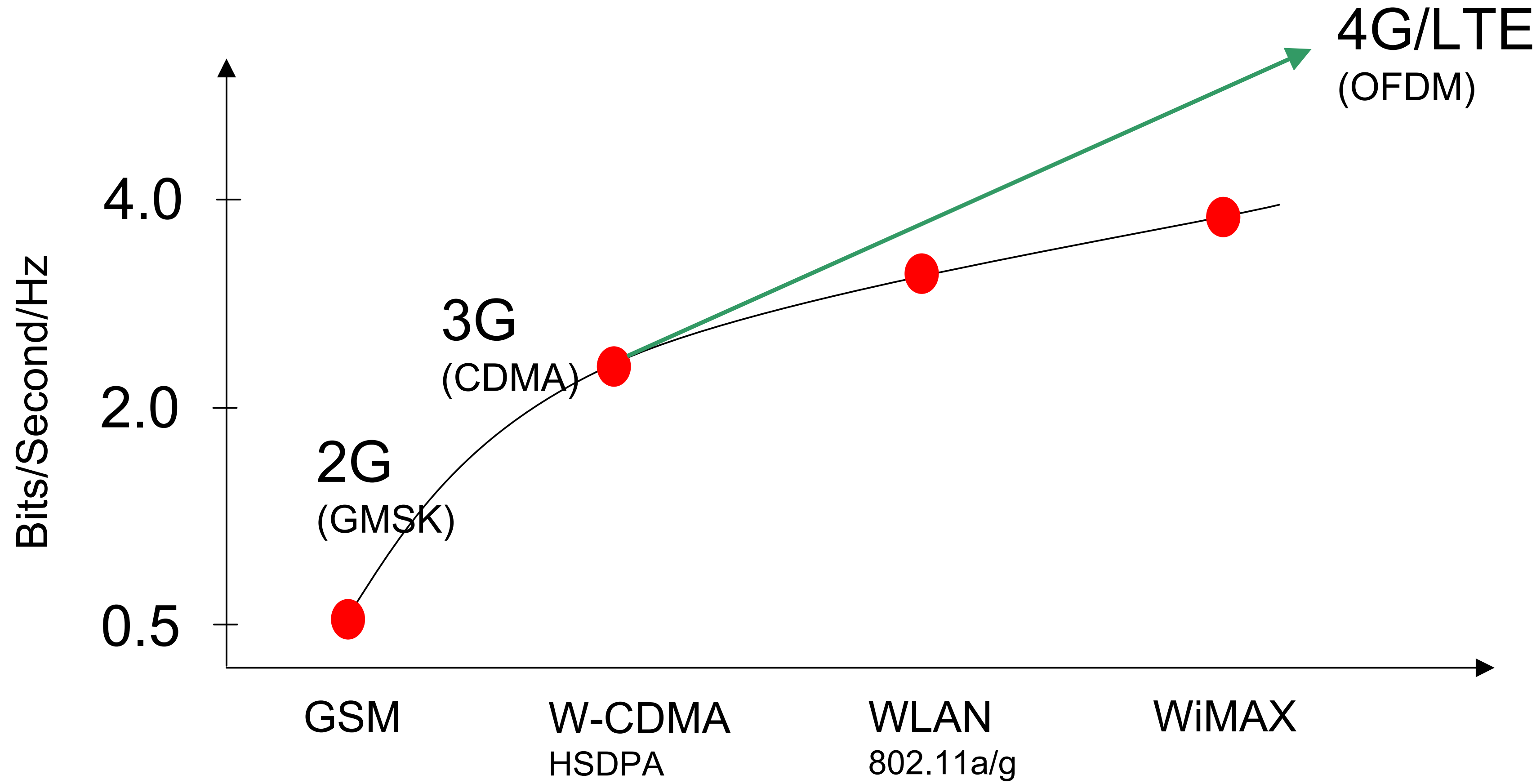
Wireline

- ADSL and VDSL broadband access via POTS copper wiring
- MoCA (Multi-media over Coax Alliance) home networking
- PLC (Power Line Communication)

Why Orthogonal Frequency Division Multiplex?

- **High spectral efficiency –** provides more data services.
- **Resiliency to RF interference –** good performance in unregulated and regulated frequency bands
- **Lower multi-path distortion –** works in complex indoor environments as well as at speed in vehicles.

Spectrally Efficiency – OFDM



Why OFDM?

…Resiliency to RF interference.

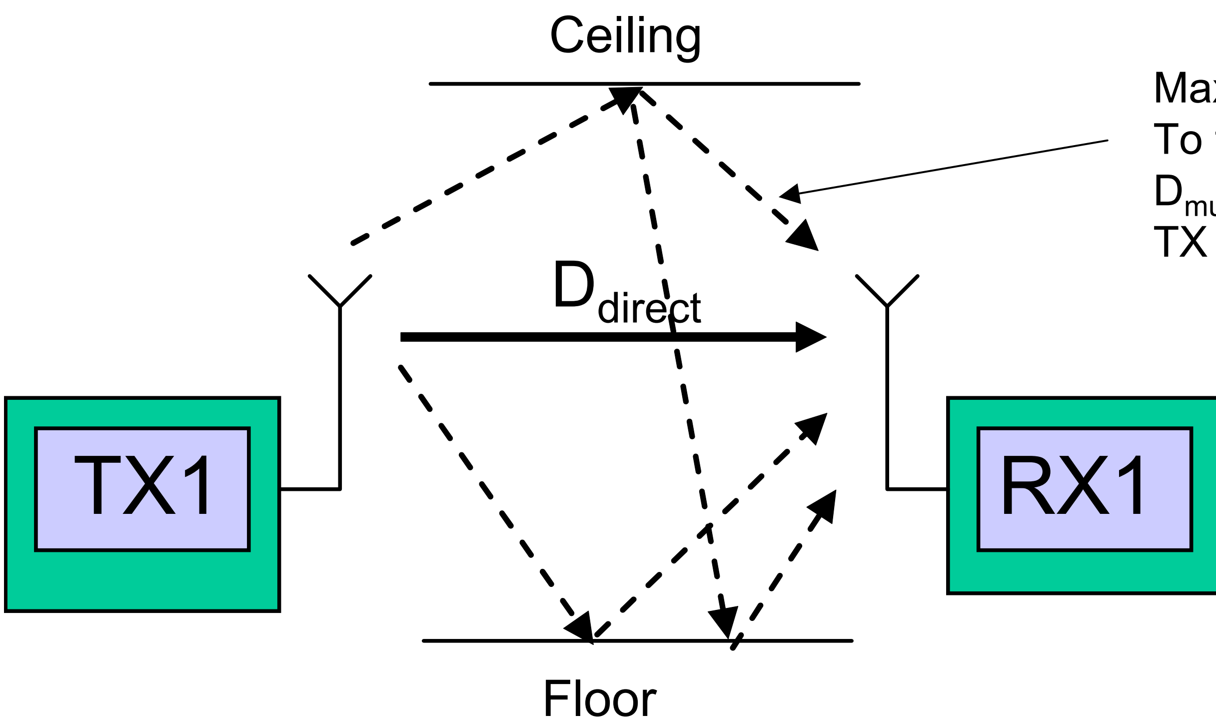
- **The ISM Band (Industrial Scientific and Medical) is a set of frequency ranges that are unregulated.**
- **Most popular consumer bands**
  - 915MHz Band (BW 26MHz)
  - 2.45GHz Band (BW 100MHz)
  - 5.8GHz Band (BW 100MHz)
- **Typical RF transmitters in the ISM band include…**
  - Analog Cordless Phones (900MHz)
  - Microwave Ovens (2.45 GHz)
  - Bluetooth Devices (2.45GHz)
  - Digital Cordless Phones (2.45GHz or 5.8GHz)
  - Wireless LAN (2.45GHz or 5.8GHz).

The Multi-Path Problem

Example: Bluetooth Transmitter & Receiver

Symbol Rate = 1MSymbols/s
Symbol Duration = 1/1E6 = 1us

Maximum Symbol Delay < 1us



Maximum time for signal
To travel D (Distance)
$D_{multipath} > D_{direct}$
TX to RX < 1us

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Single Carrier – Single Symbol

- **Bluetooth, GSM, CDMA and other communications standards use a single carrier to transmit a single symbol at a time.**
- **Data throughput is achieved by using a very fast symbol rate.**

W-CDMA - 3.14 Msymbols/sec

Bluetooth – 1 Msymbols/sec

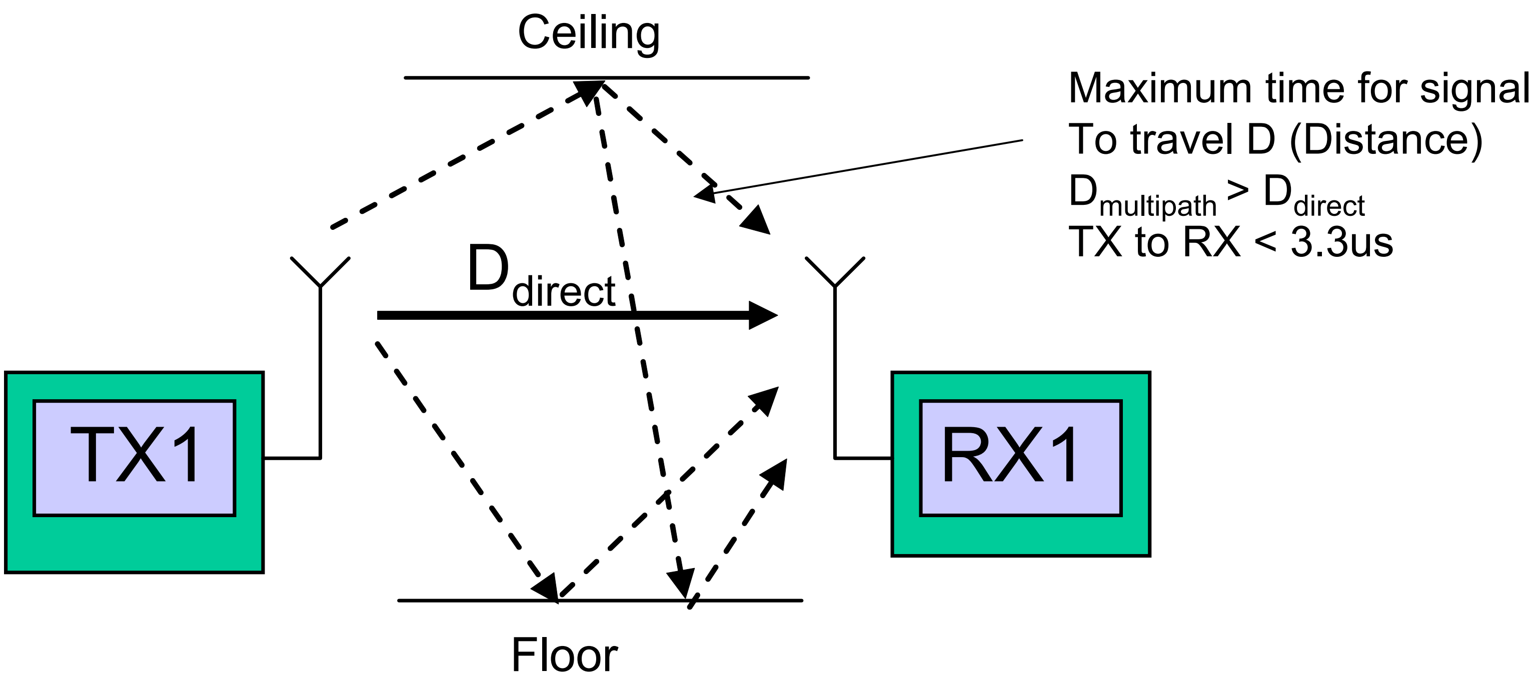
- **A primary disadvantage is that fast symbol rates are more susceptible to Multi-path distortion.**

Slow the symbol rate

Reduce the previous examples symbol rate by a third

Symbol Rate = 300kSymbols/s
Symbol Duration = 1/300 = 3.3us

Maximum Symbol Delay < 3.3us



But the data throughput is reduced!

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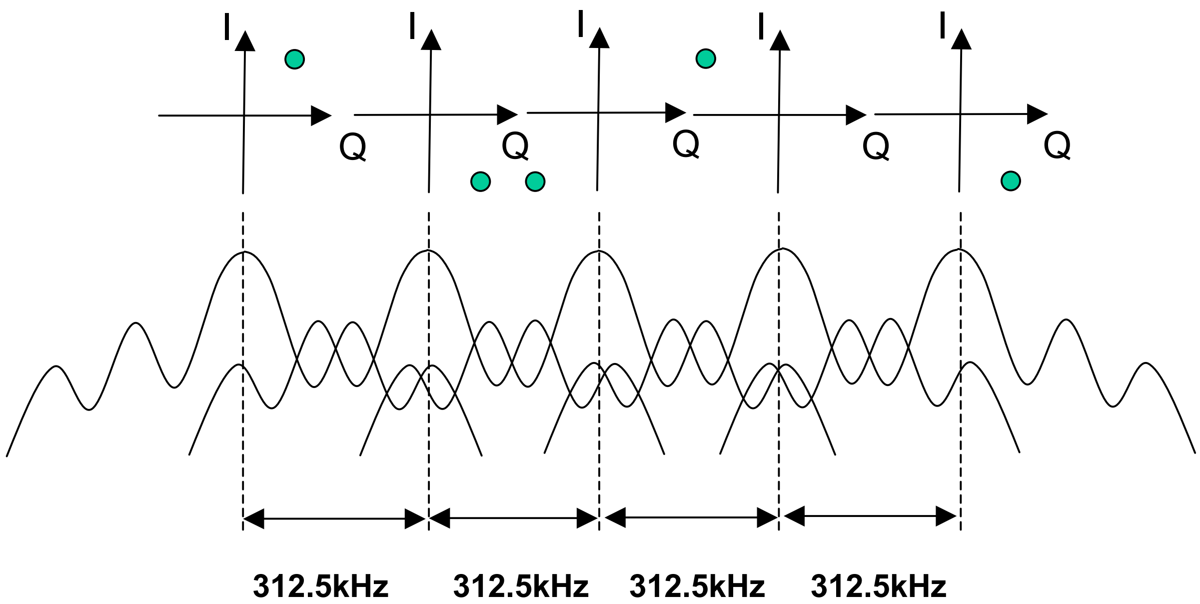
Improve the throughput - use more than one carrier!

802.11a-g WLAN example



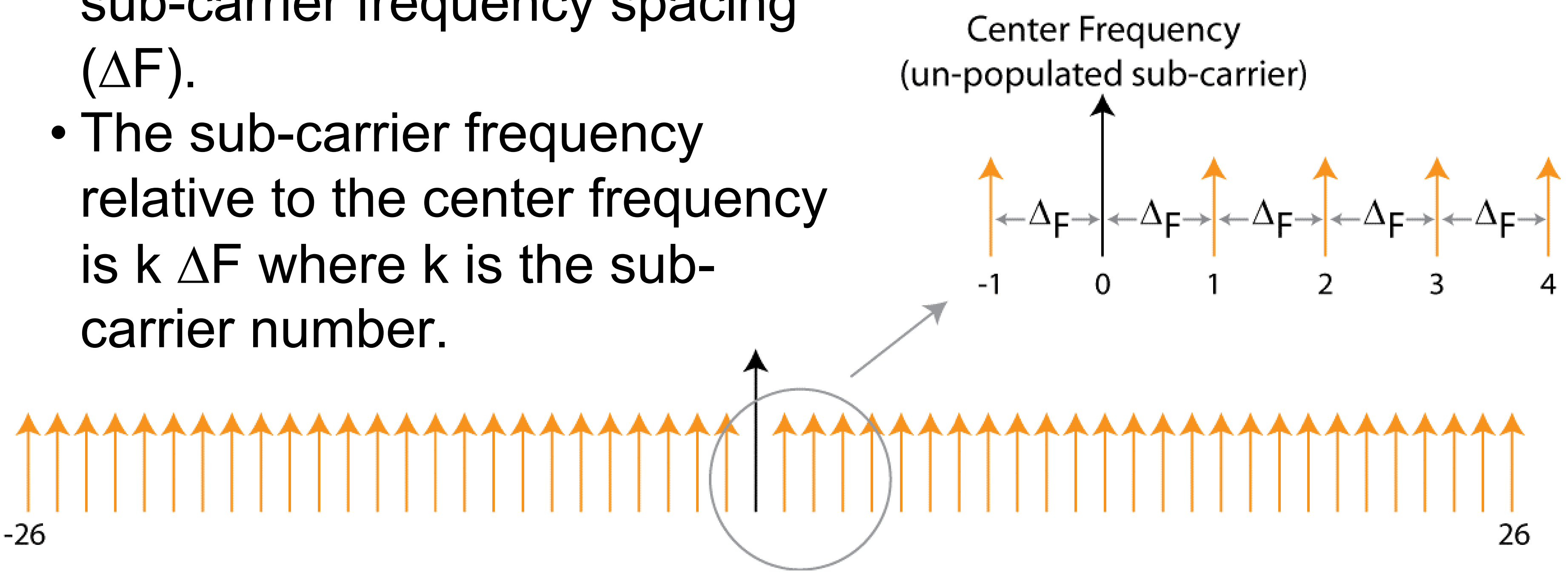
Low symbol rate per carrier * multiple carriers = high data rate

250 kbps symbol rate * 48 sub-carriers * 6 coded bits /sub-carrier * ¾ coding rate = 54 Mbps

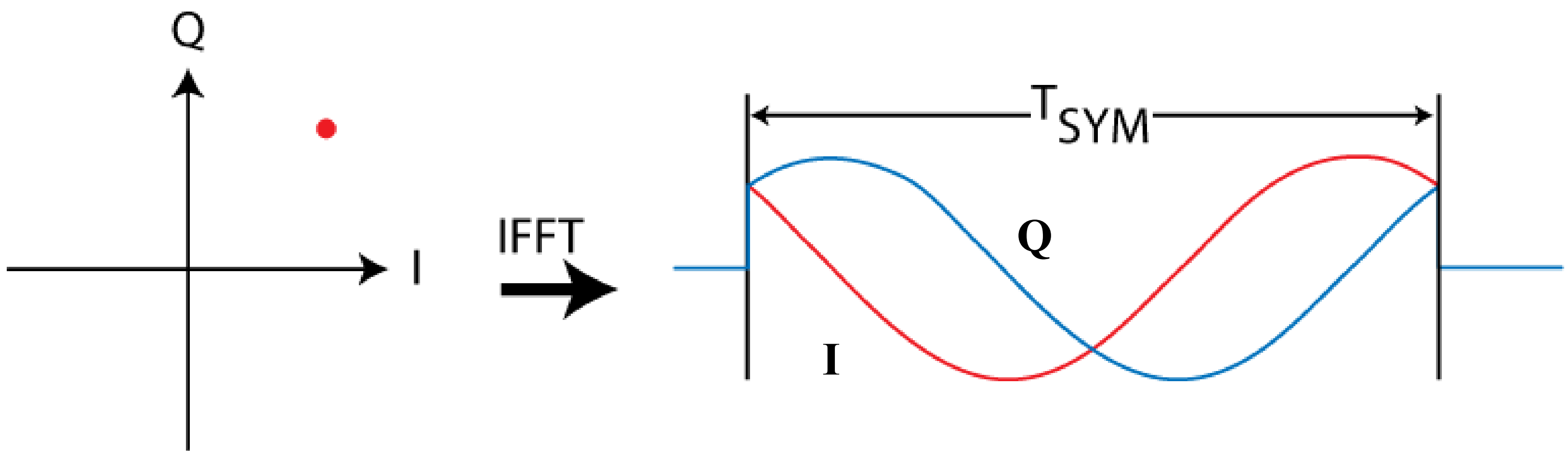
(for 64QAM)

Sub Carrier Spacing

- The sub-carriers are spaced at regular intervals called the sub-carrier frequency spacing (ΔF).
- The sub-carrier frequency relative to the center frequency is k ΔF where k is the sub-carrier number.



Symbol to Waveform
Traditional – Serial Symbol Transmissions



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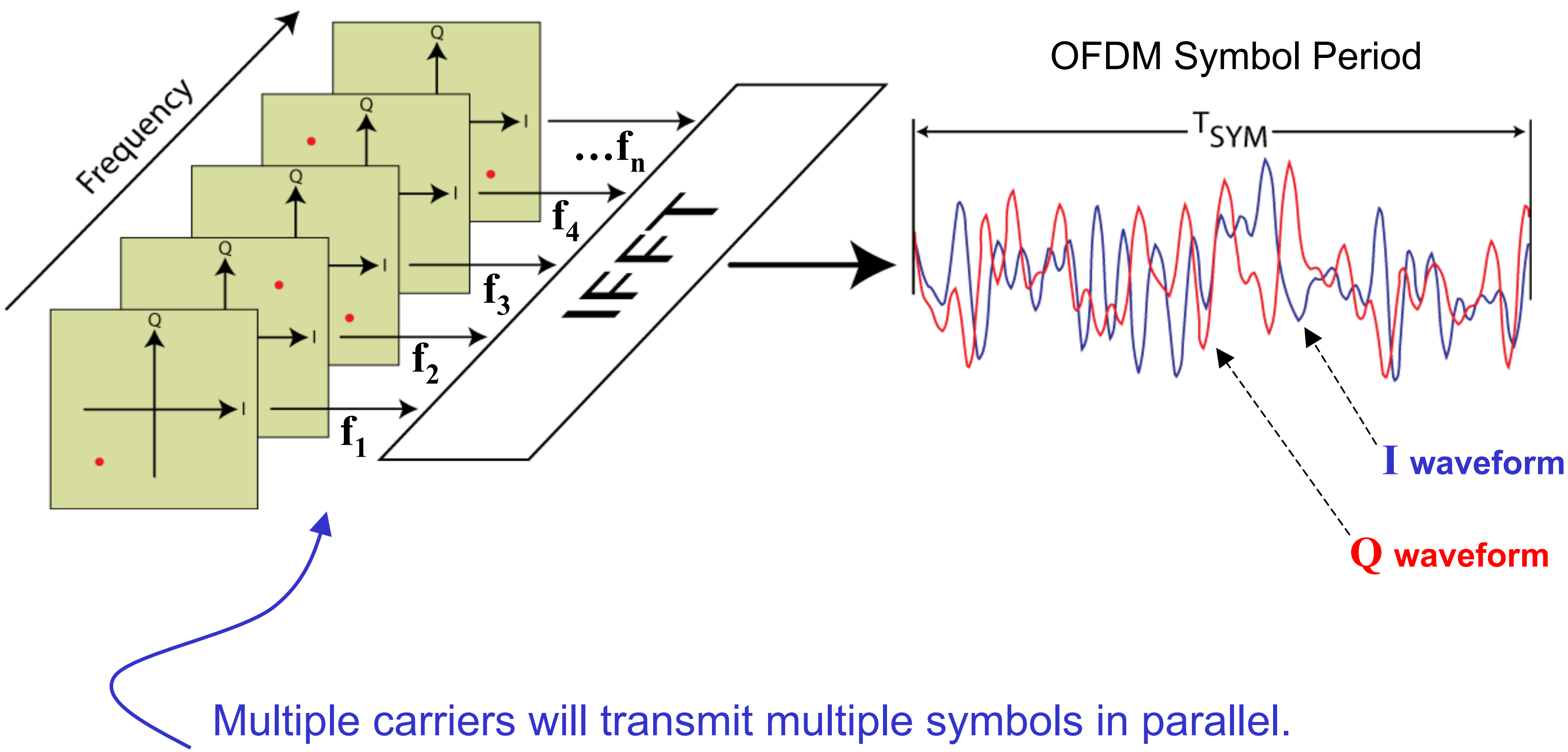
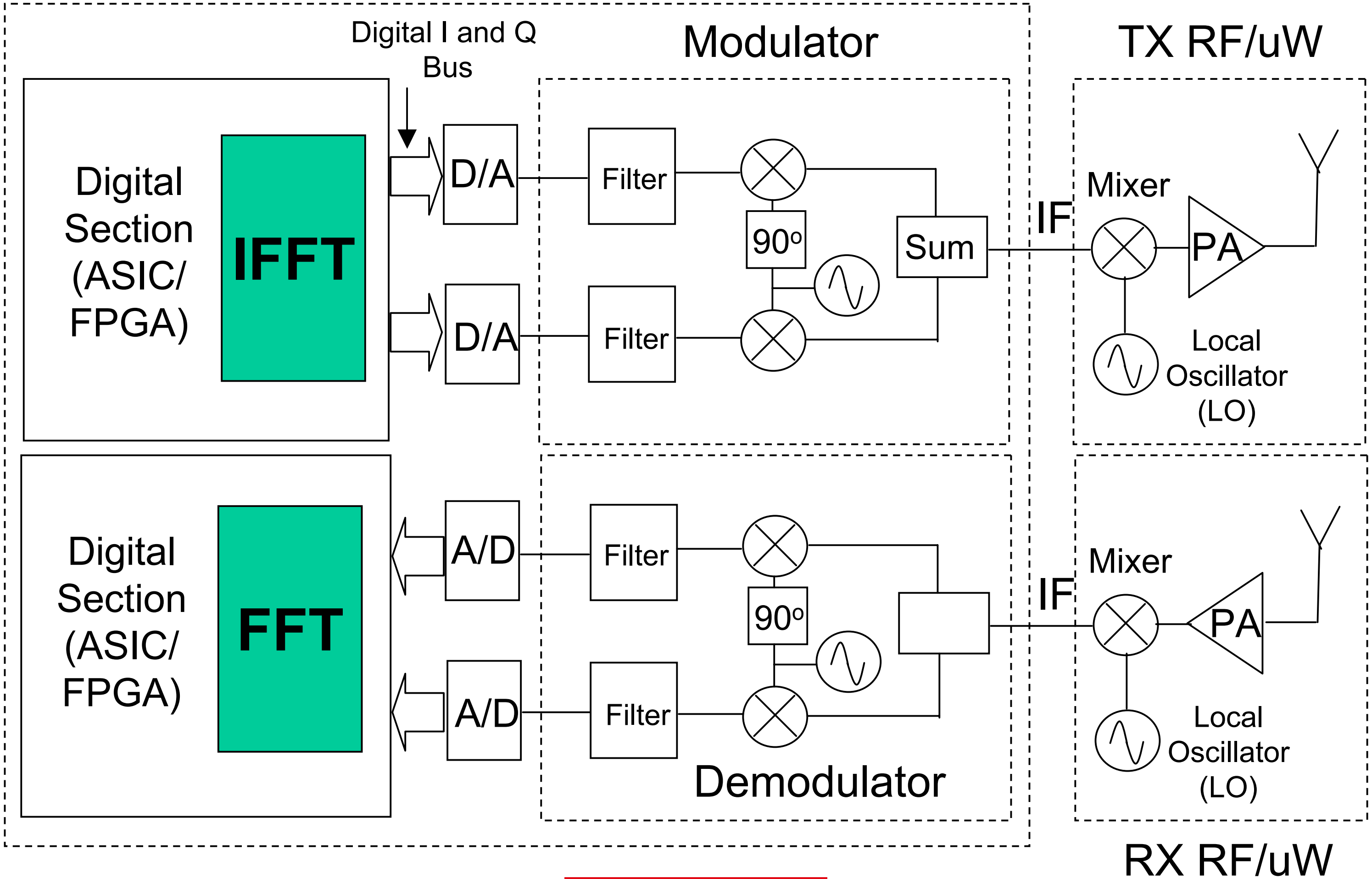
Symbol to Waveform
OFDM – Parallel Symbol Transmissions



Multiple carriers will transmit multiple symbols in parallel.
Carriers may have different modulations – BPSK, QPSK… 64QAM.

The OFDM Radio



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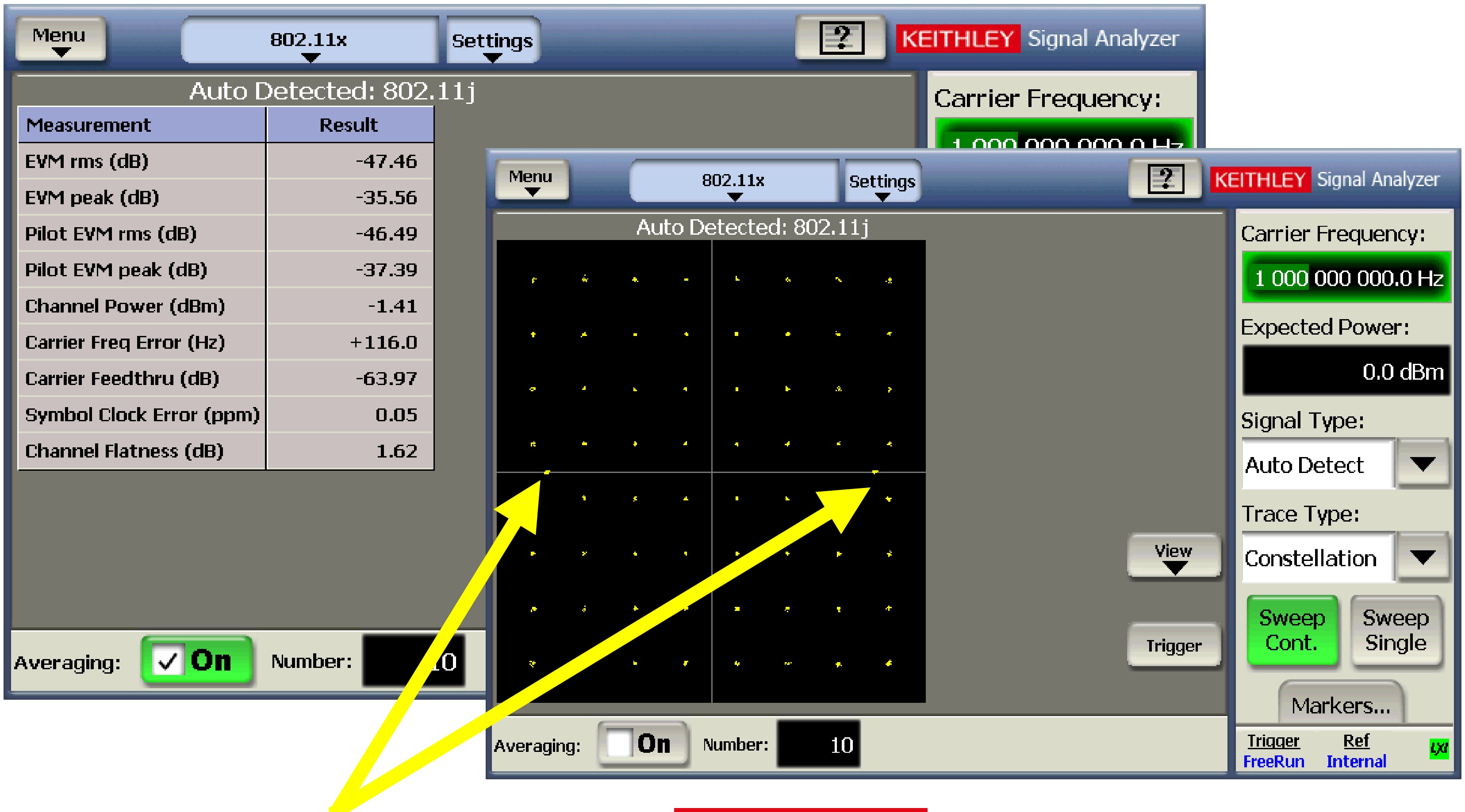
Key Measurements: Constellation and EVM



Pilot Symbols

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Vector Signal Analyzer Measurements
Modulation Quality Analysis

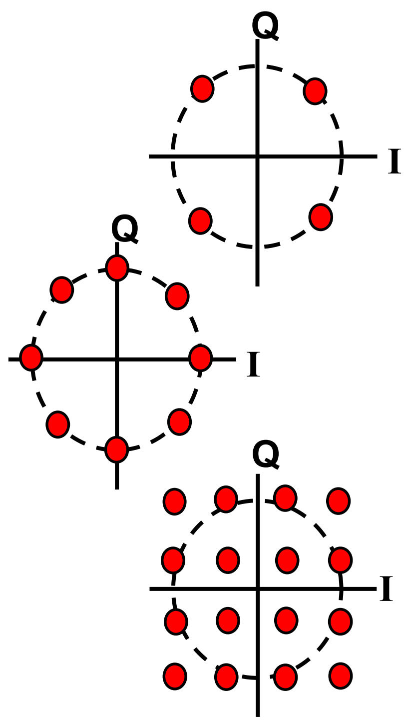
Input Signal | **Analyzer Display** | **Measurement Analysis**

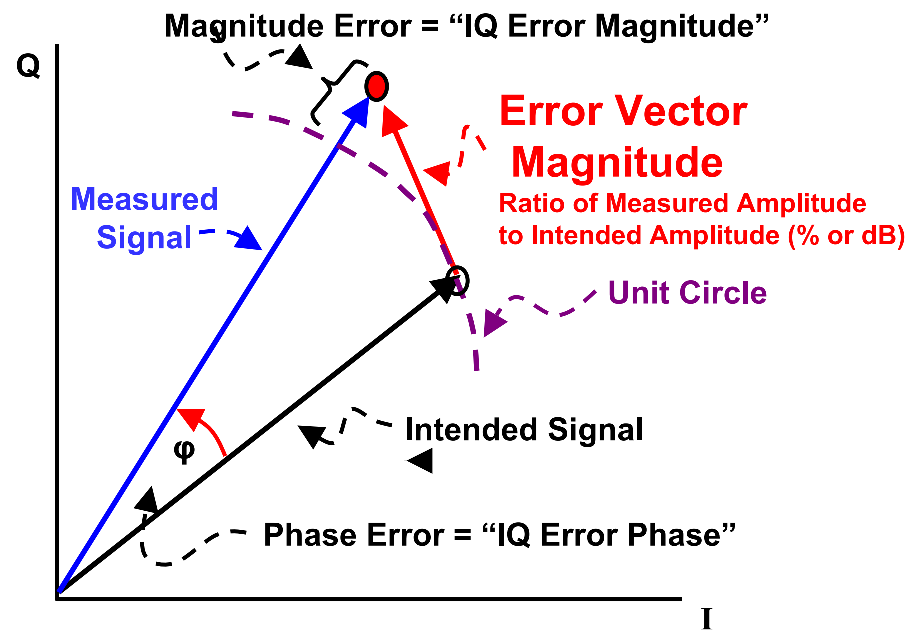
QPSK

8PSK

16QAM

etc…





RCE (dB) = 20 log(EVM in %/100)

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EVM Metrics

$$\mathrm{EVM}(\%) = \sqrt{\frac{P_{\mathrm{error}}}{P_{\mathrm{reference}}}} * 100\%$$

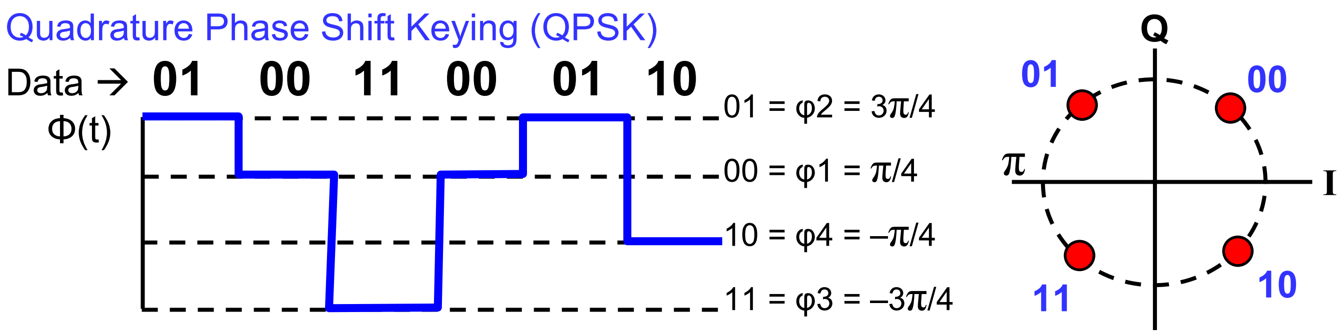
$$\mathrm{EVM}(\mathrm{dB}) = 10\log_{10}\left(\frac{P_{\mathrm{error}}}{P_{\mathrm{reference}}}\right)$$

P = RMS Power

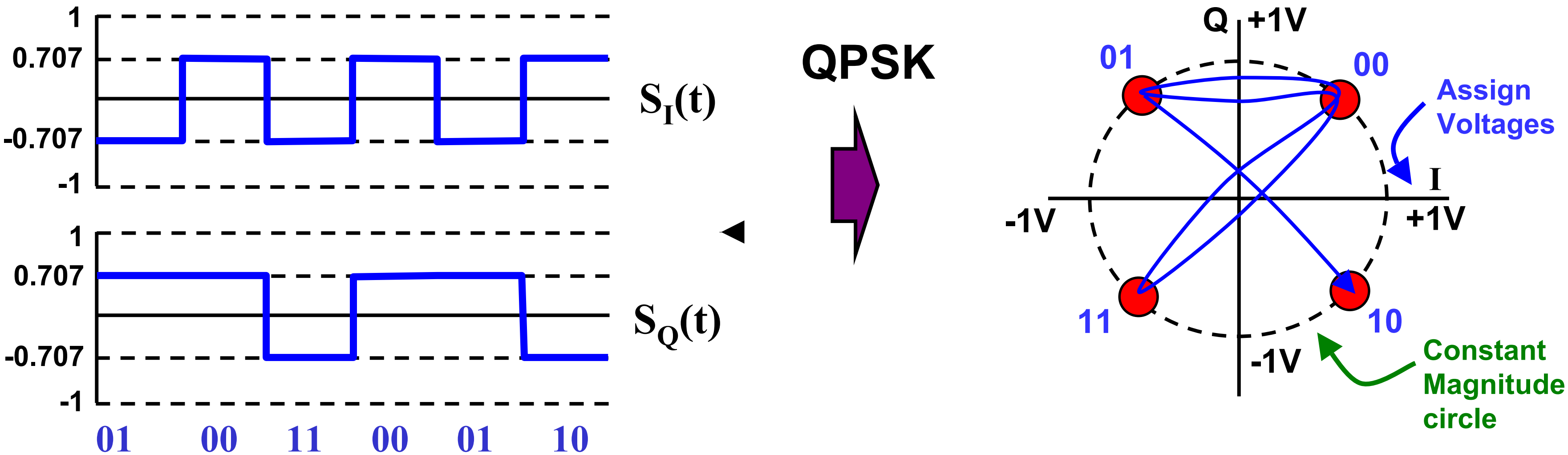
Source: Wikipedia

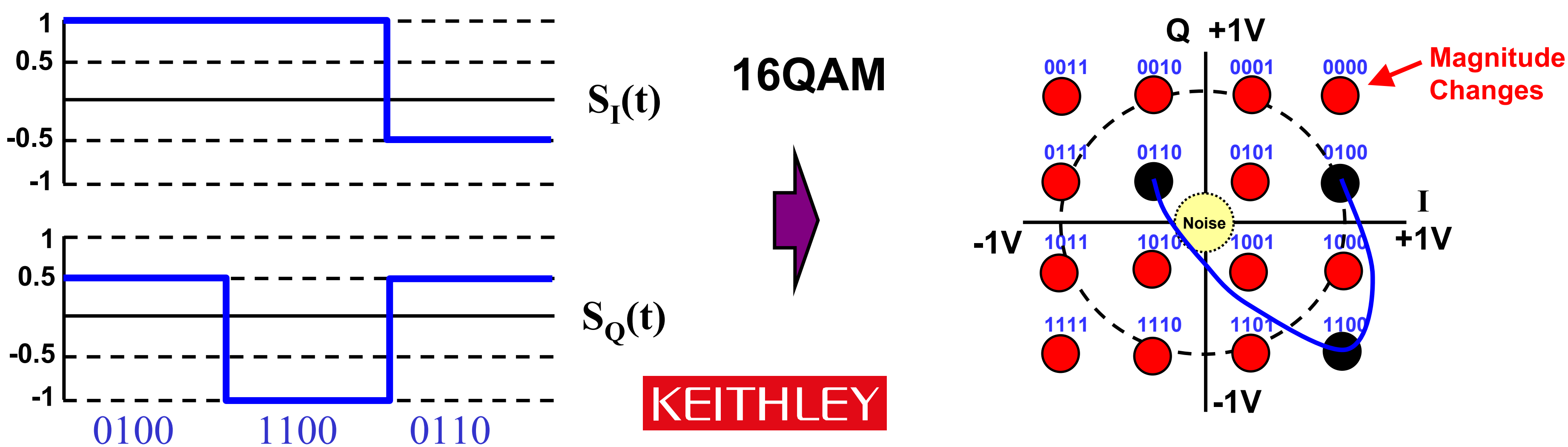
Introduction to Constellation Diagrams

- **A constellation diagram is a representation of a digital modulation scheme in the complex plane.**
  - The real and imaginary axes are often called the in phase, or I-axis and the quadrature, or Q-axis.
- **Example: four-symbol Quadrature Phase Shift Keying (QPSK) modulator**



Recovering the Data
QPSK and 16QAM Signals





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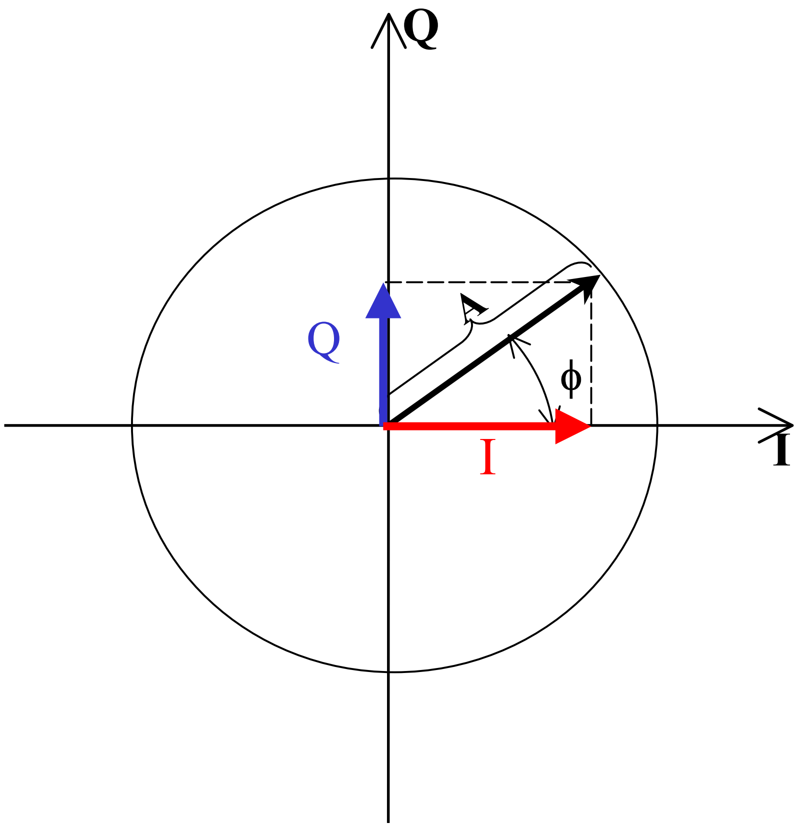
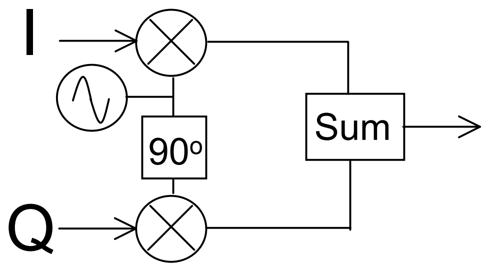
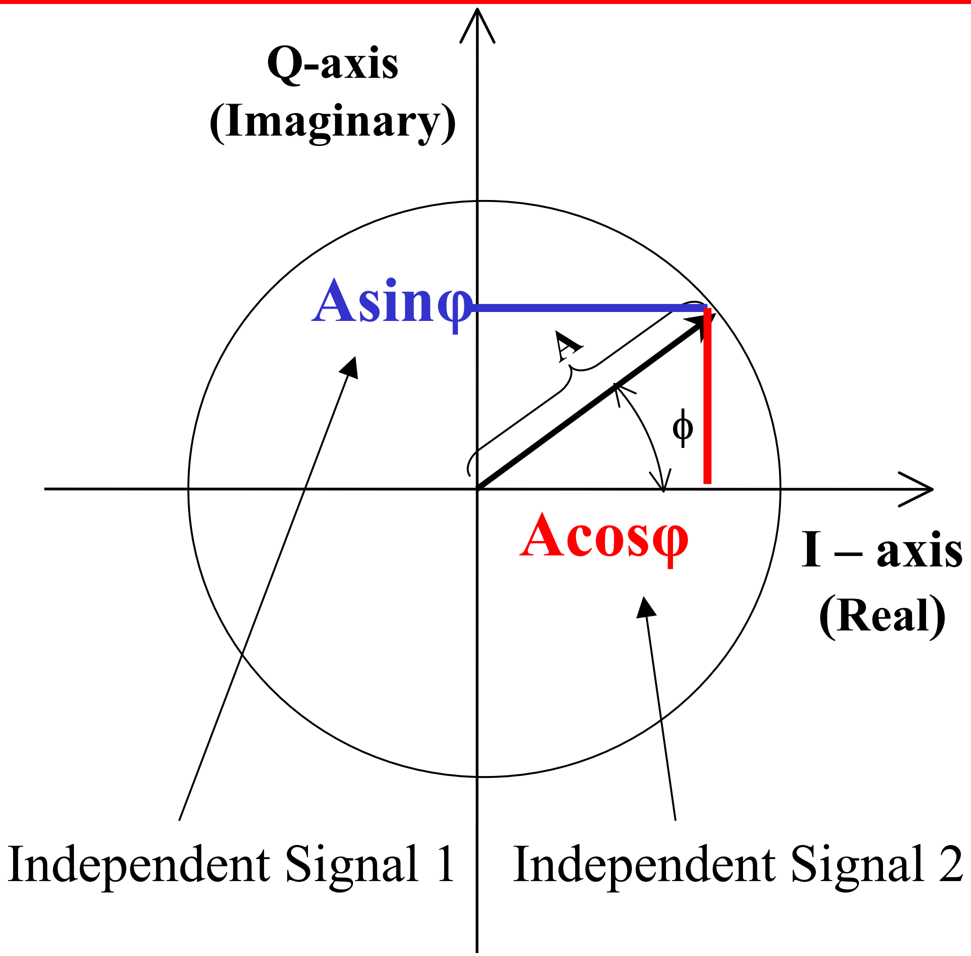
Digital Modulation Overview
I and Q Components of a Signal





Simple Pythagoras
Amplitude (Length of A) = SQRT $(I^2 + Q^2)$
Phase (Angle ϕ) = $\tan^{-1}$ (Q/I)

Representation of Signal in Complex Plane

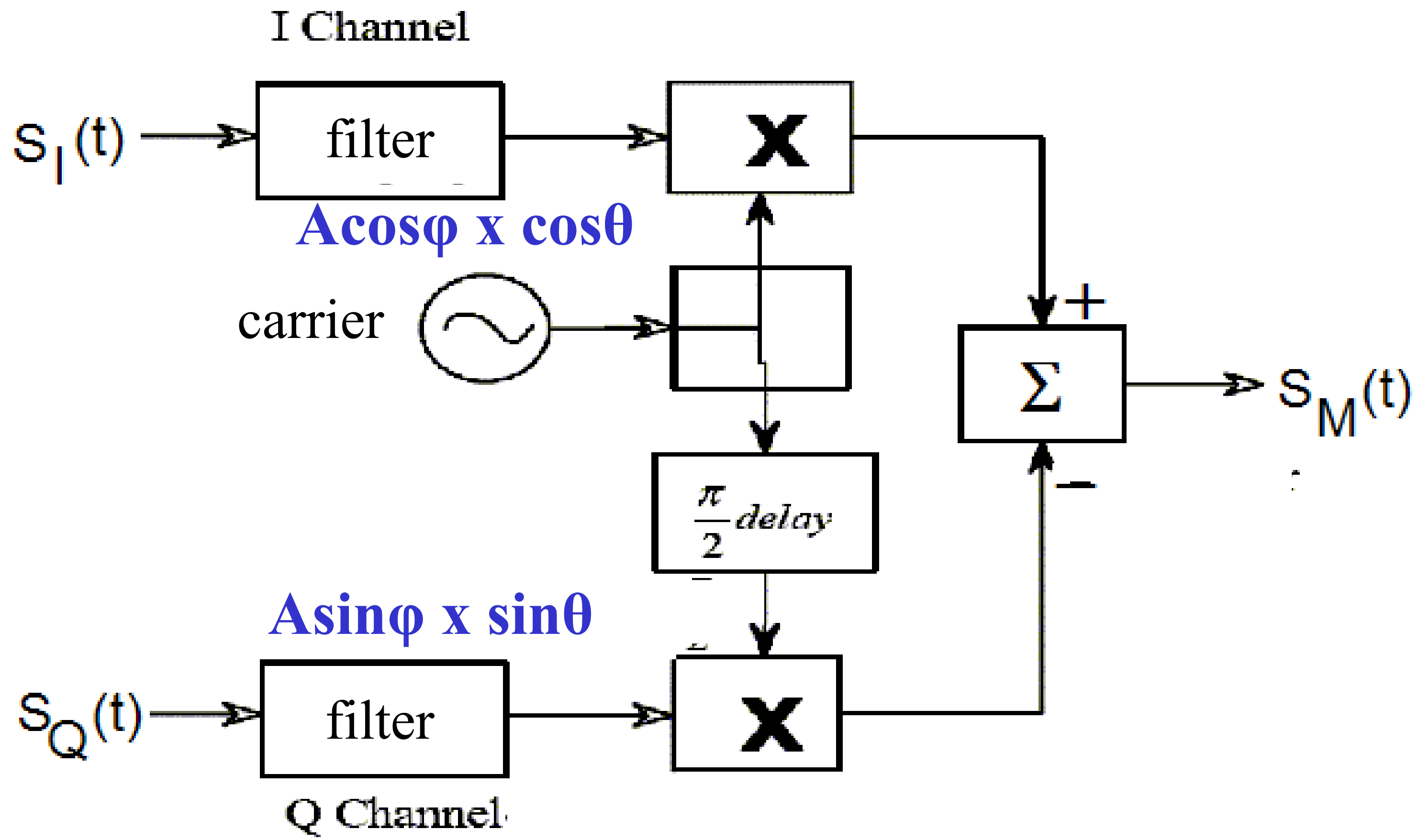


$$S(t) = A\cos(2\pi f_c t + \varphi)$$

$$f_c = signal\ frequency$$

Quadrature Modulator Hardware

$$A\cos\varphi \times \cos\theta - A\sin\varphi \times \sin\theta = A\cos(\varphi+\theta)$$



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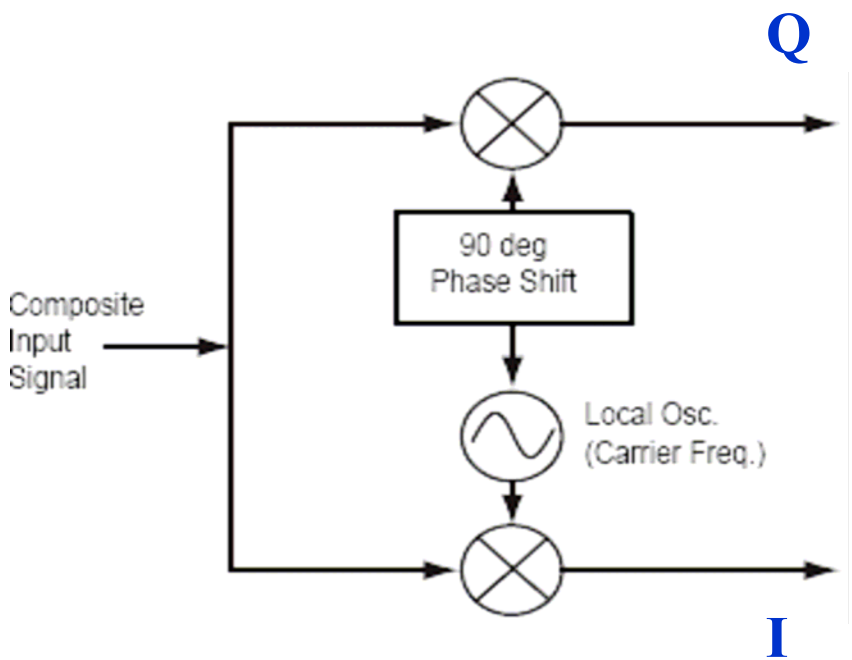
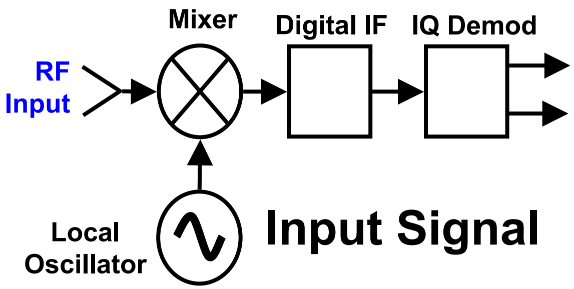
Quadrature Demodulation

- **The receiver can recover the two independently modulated signals, even though they share the same carrier frequency.**



Vector Signal Analyzer Measurements

Modulation Quality Analysis



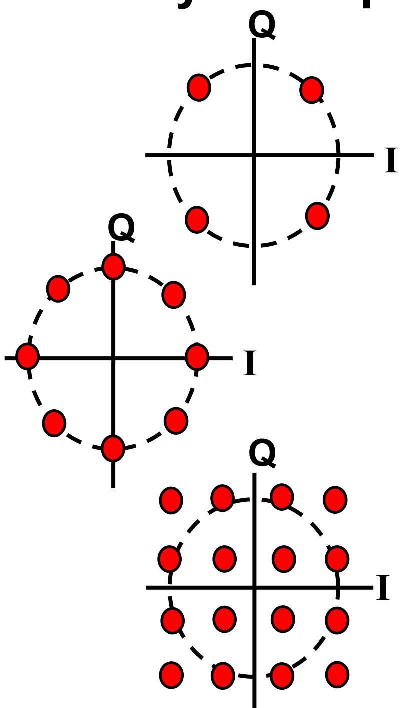
Input Signal **Analyzer Display** **Measurement Analysis**

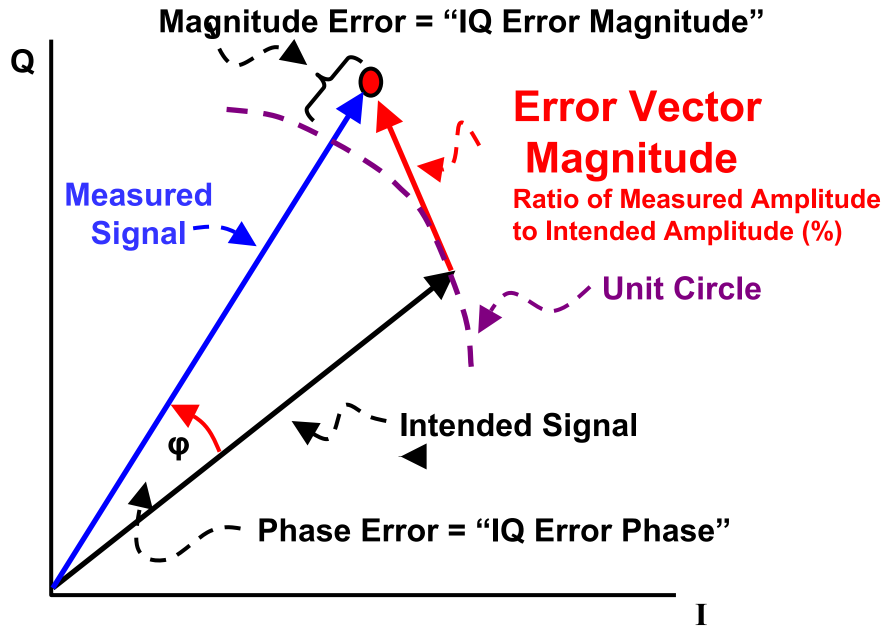
QPSK

8PSK

16QAM

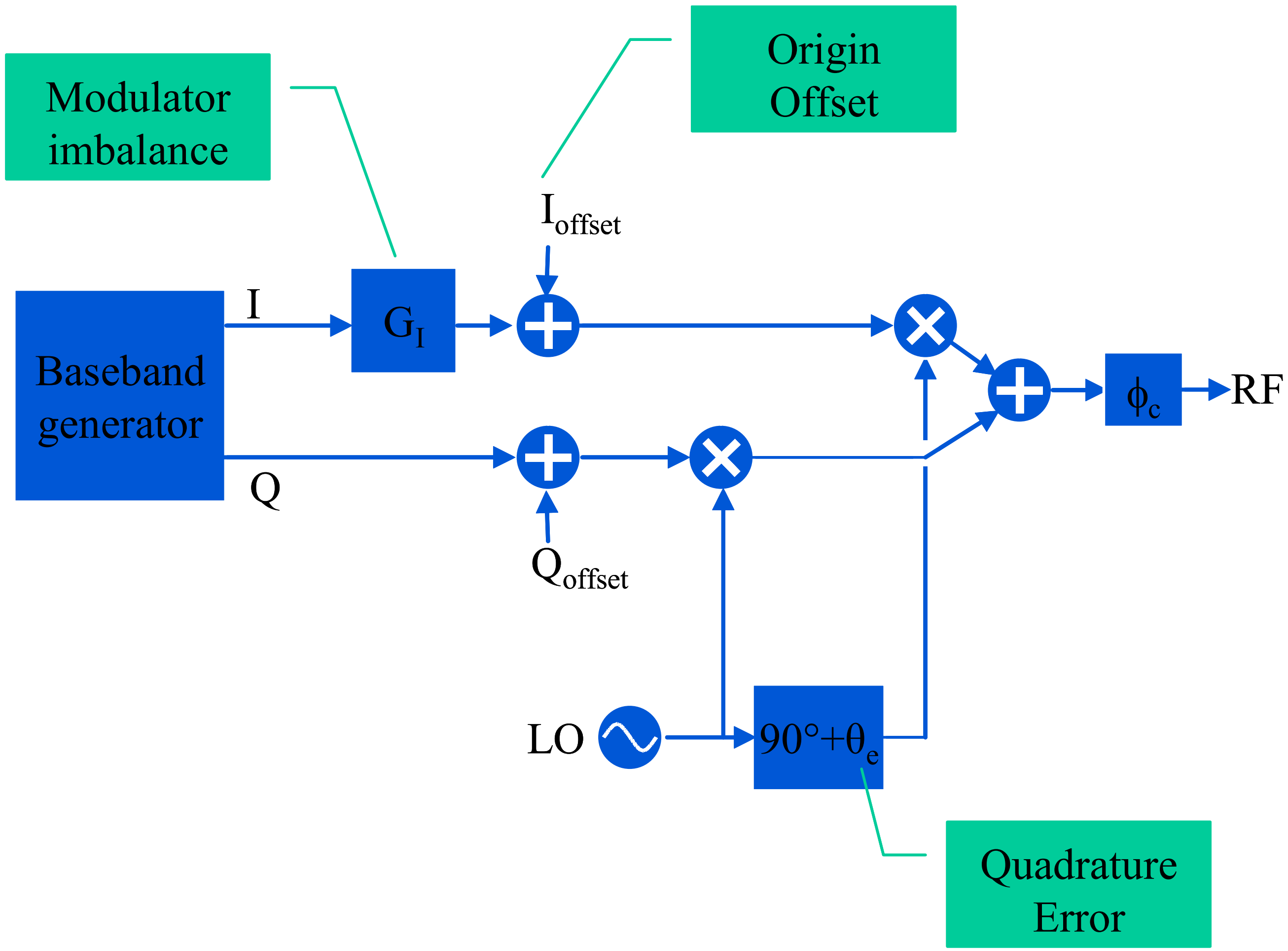
etc…





RCE (dB) = 20 log(EVM in %/100)

I/Q Modulator Impairments Contributions to EVM



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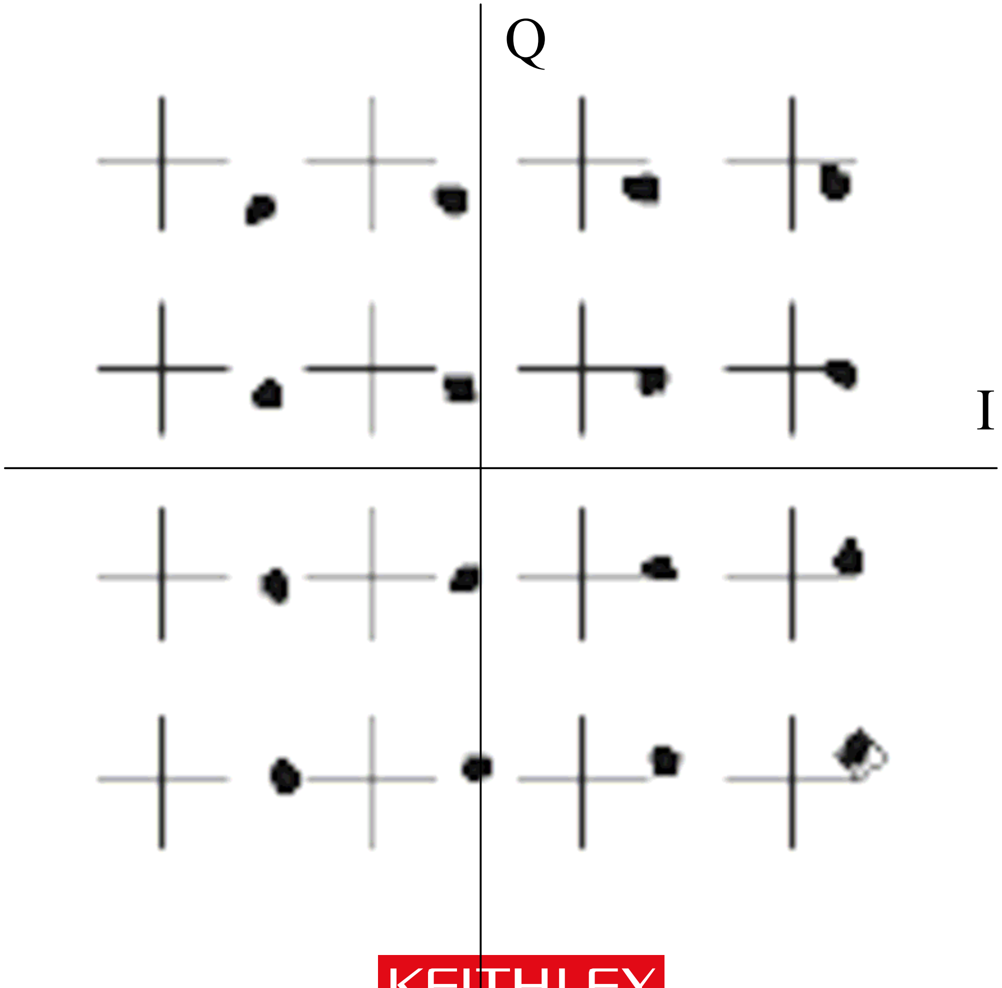
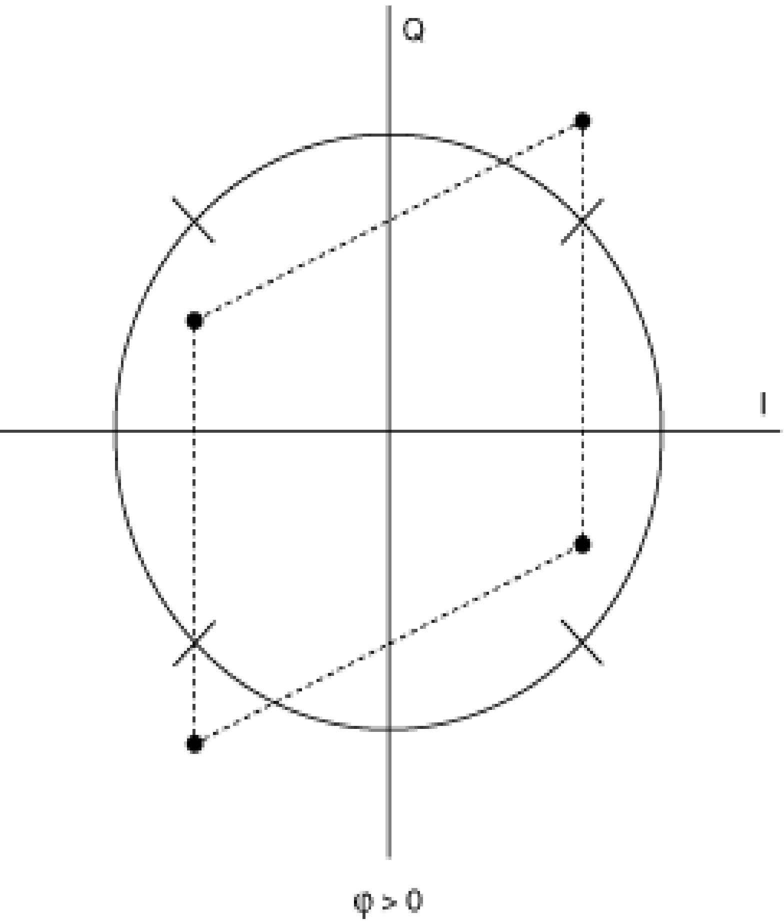
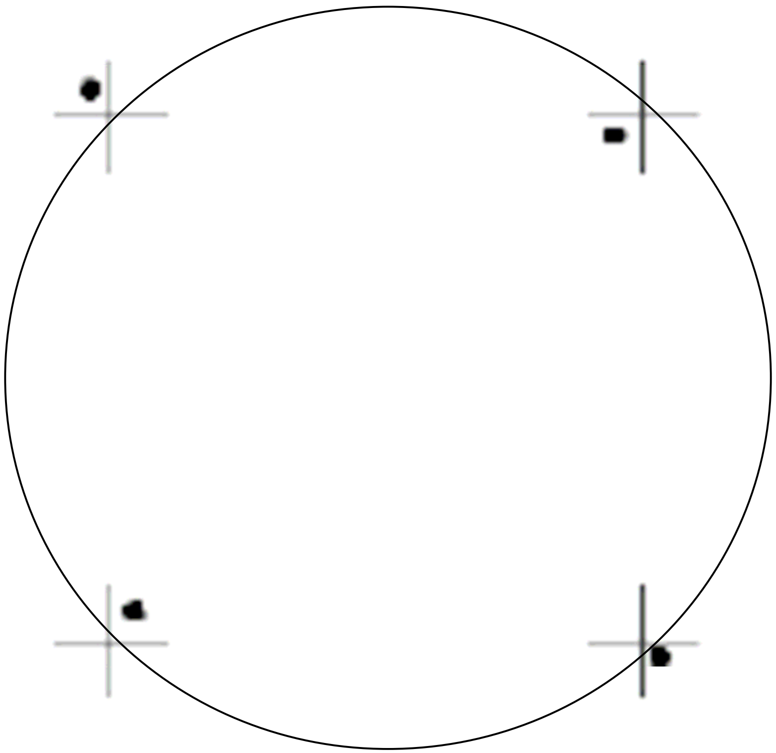
Origin Offset Example
16-QAM Constellation

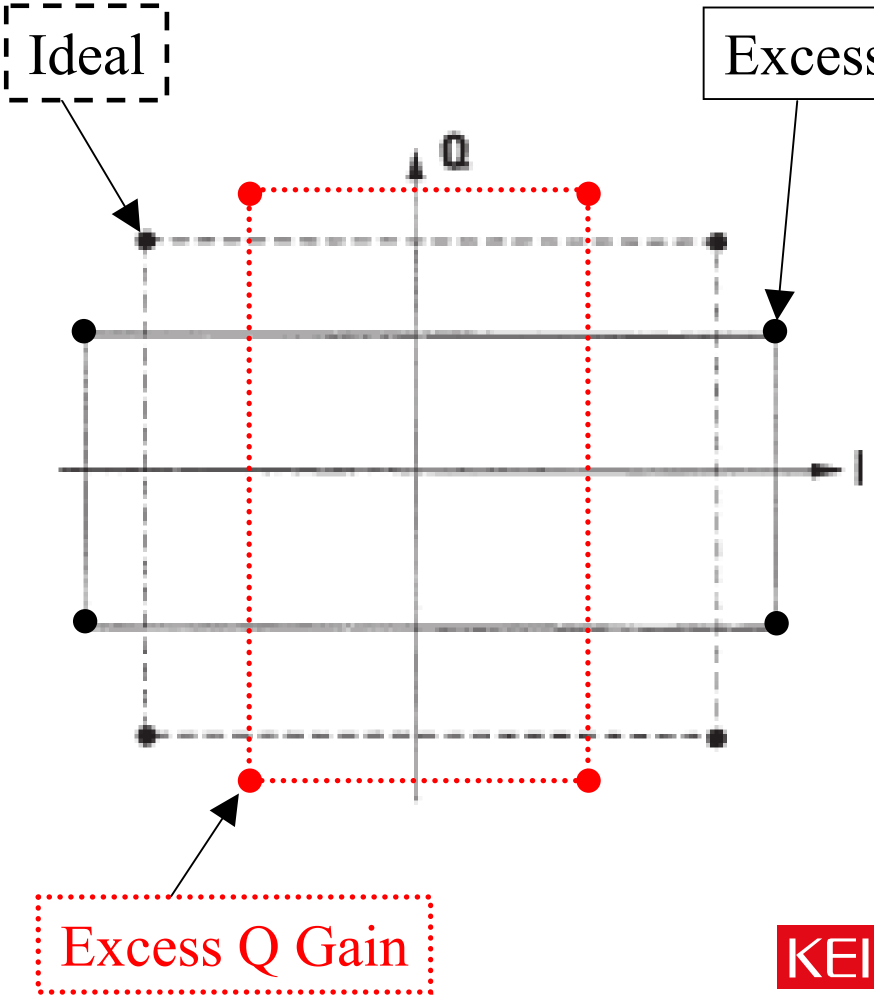


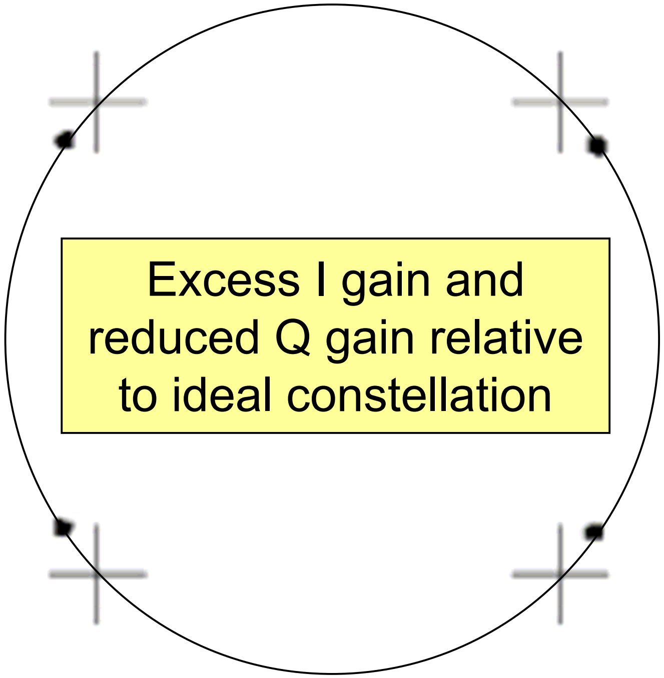
Quadrature Error Examples
QPSK Constellations



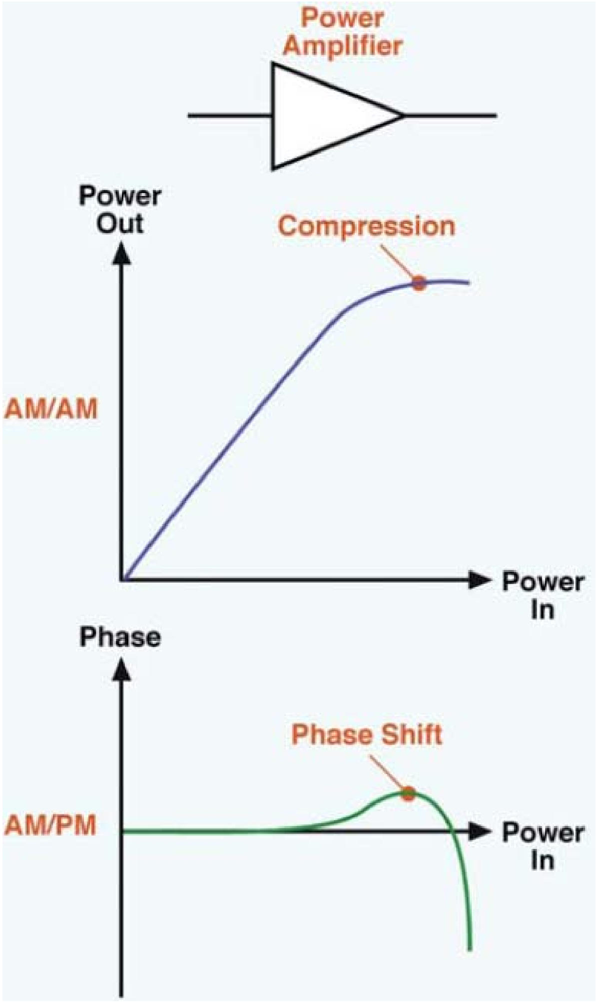


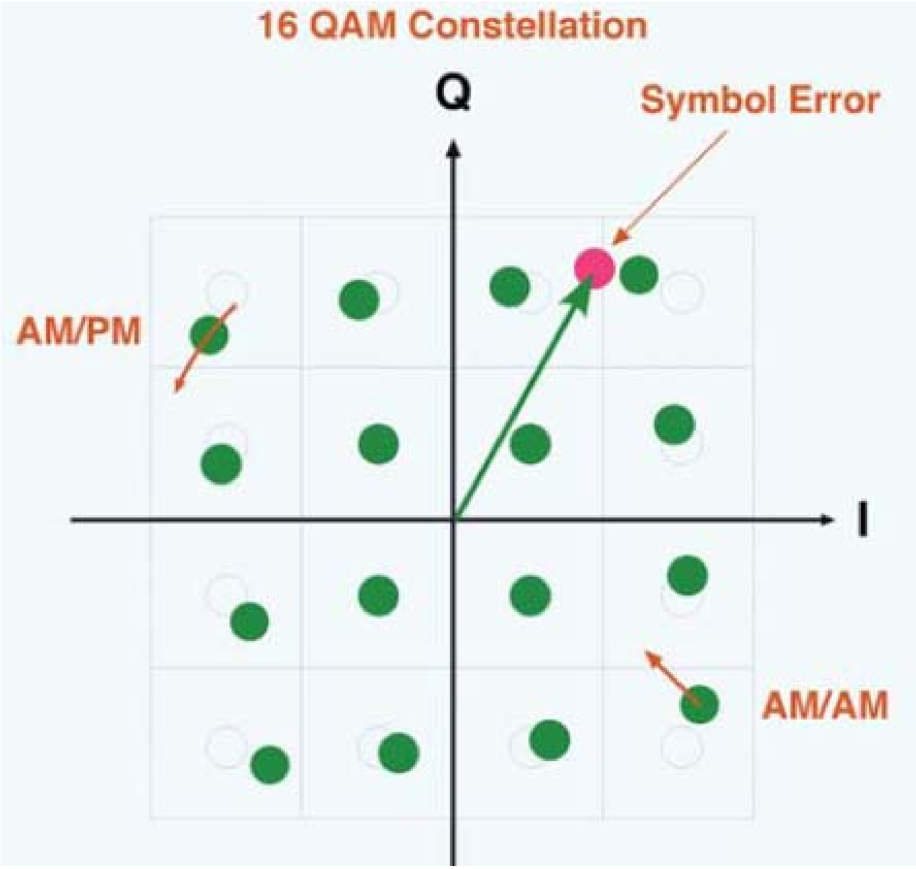
Modulator Imbalance Examples
QPSK Constellations





Power Amplifier Nonlinearity
Another Contributor to EVM





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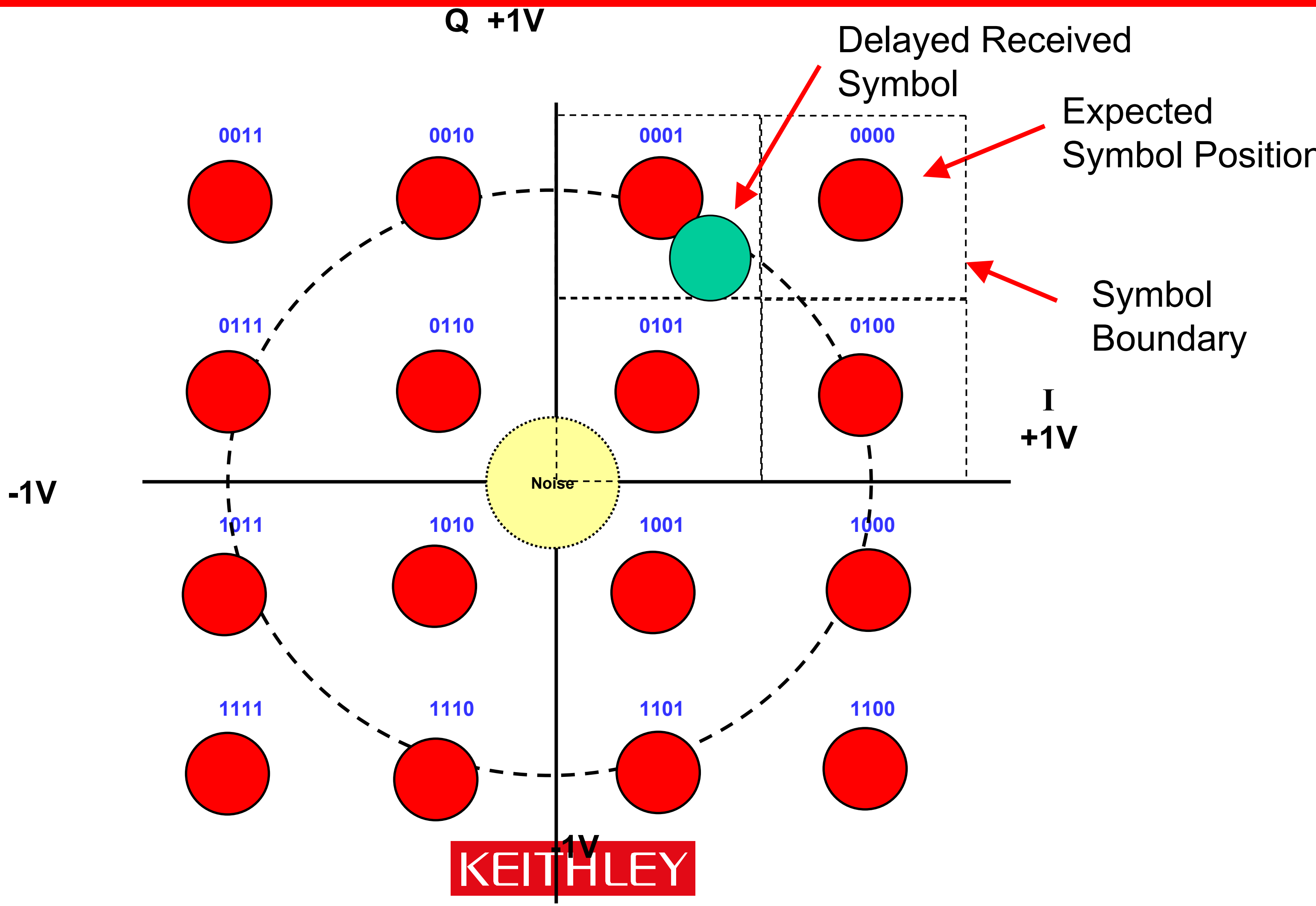
ISI – Inter Symbol Interference



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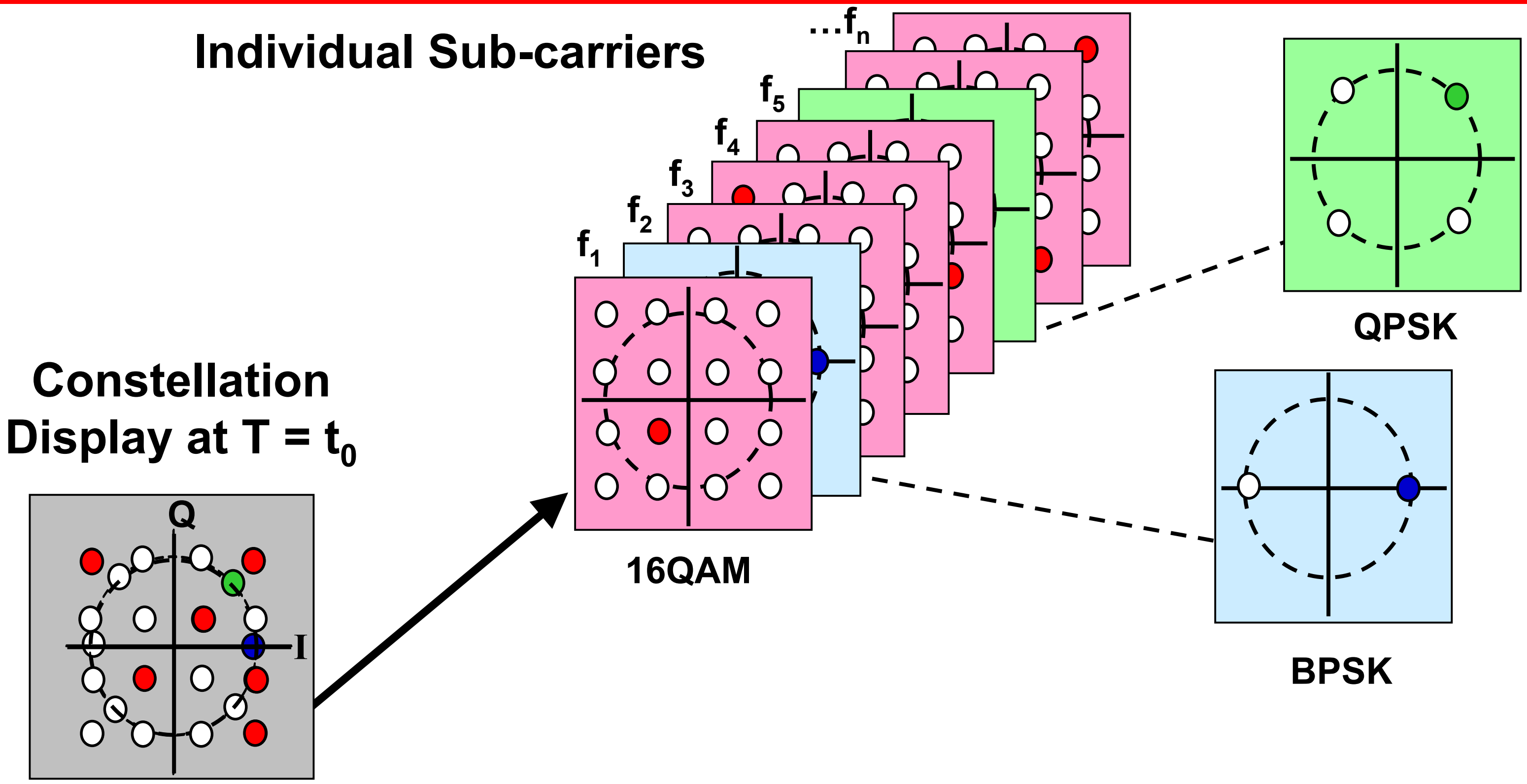
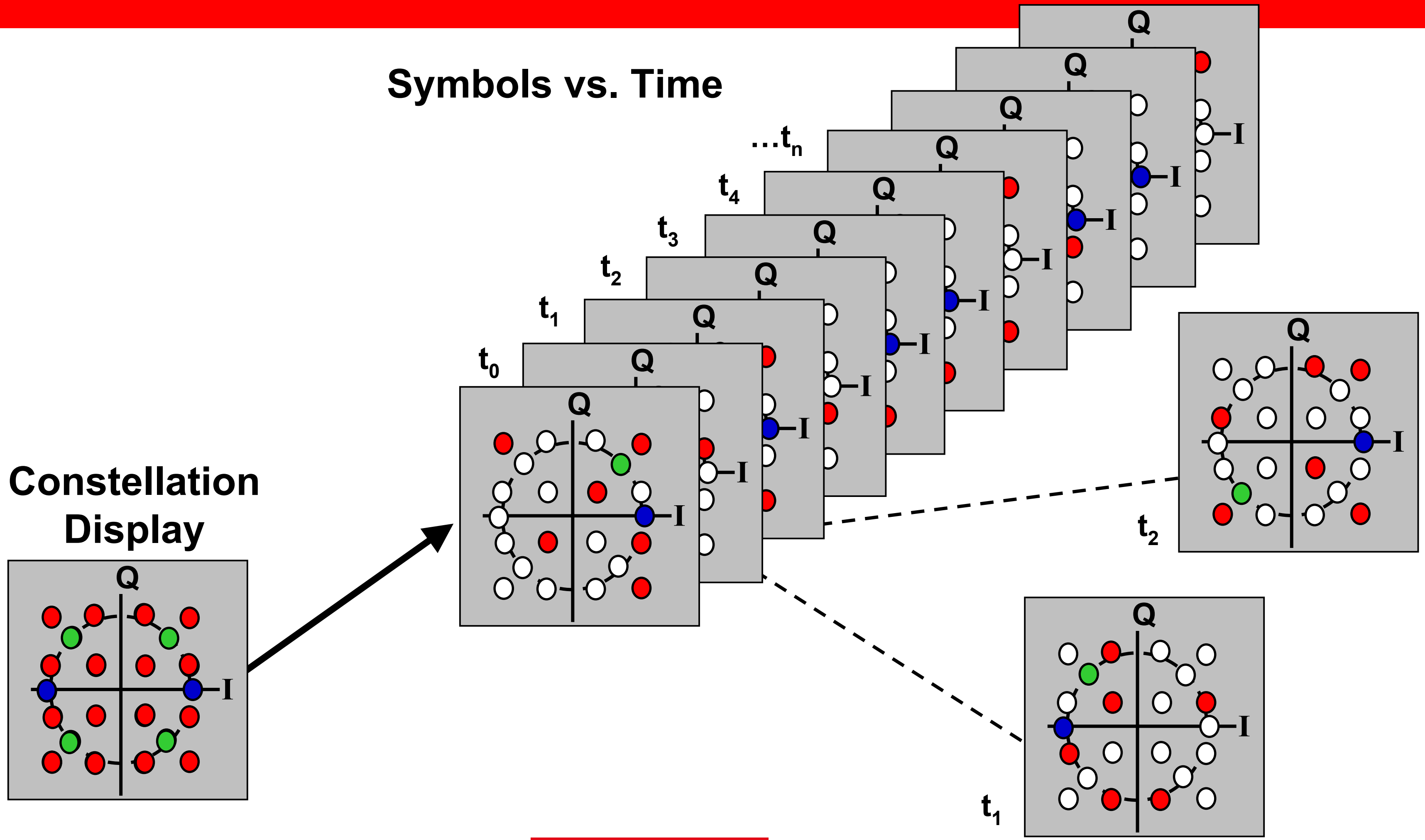
Constellation Display Is a Composite of all OFDM Sub-carrier Symbols

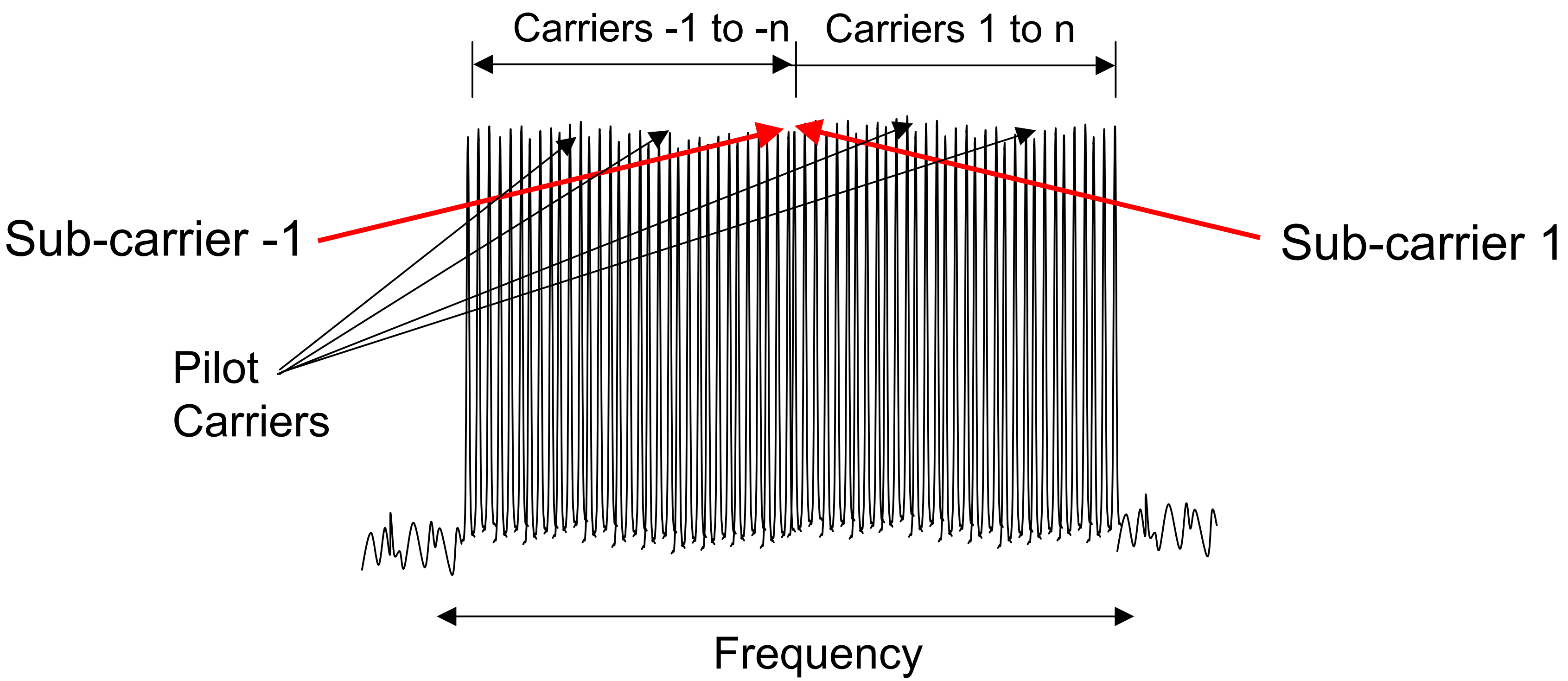


Constellation Display Is a Composite of all OFDM Sub-carrier Symbols… and time



Data and Pilot Carriers

- **Used as reference for phase and amplitude to demodulate the data in the other sub-carriers.**



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Example: WLAN (802.11a/g)

- Modulation Technique OFDM
- Bandwidth 16.25MHz
- Number of sub-carriers 52
- Sub-carrier numbering -26 to + 26
- Sub-carrier spacing 312.5kHz
- Maximum sub-carrier symbol rate 250 kHz (64QAM)
- Pilot sub-carriers -21, -7, +7 and +21 (BPSK)
- Packet Structure – Preamble – Header – Data Block
- SUB Carrier Modulation Types - BPSK, QPSK, 16-QAM or 64-QAM

WLAN Summary

- **WLAN implies Wireless LAN compatible with one the IEEE 802.11 sub standards. It is what you have in your laptop.**
- **WiFi is an industry consortium that defines a required subset of 802.11 to ensure better operation between different vendor's equipment.**
- **EWC is an industry consortium that took the unfinished N standard, agreed upon a version, and is attempting to field solutions prior to 802.11n ratification.**

802.11	Means
a	54 Mbps OFDM, 5.9 GHz Band, 20 MHz channels
b	11 Mbps CCK, 2.4 GHz (Legacy, not OFDM)
g	What you can easily buy now – same as a, but at 2.4 GHz
j	Japanese version of g that uses half the sample rate.
n	• Not a finished standard yet. • Like g, but up to 600Mbps • OFDM • MIMO • 20 & 40 MHz channels

demo

WLAN OFDM - Test Equipment Requirements

- **Frequency Coverage up to 5.8GHz**
- **Modulation Bandwidth up to 16.25MHz**
- **802.11a/g Signal Creation and Analysis Capability**

Keithley instruments 2820 and 2920 VSA and VSG have a frequency range of 6 GHz and 40 MHz bandwidth as standard.

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OFDM to OFDMA

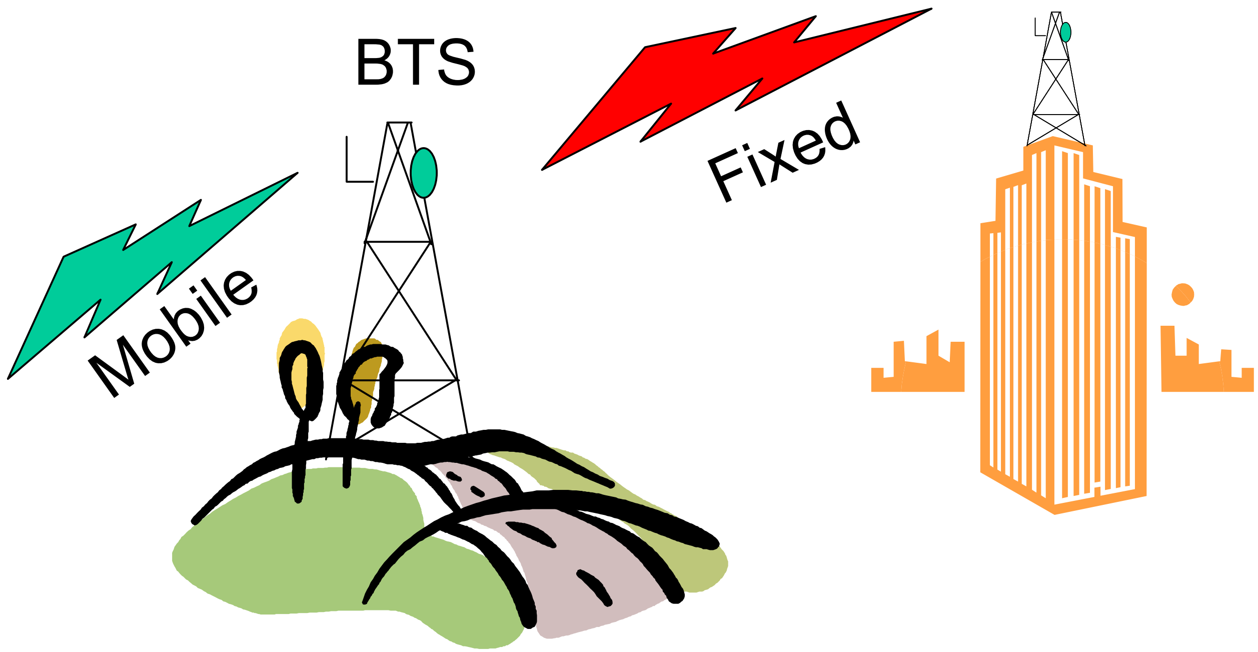
- **OFDM as a modulation technique is not multi user* – all sub-carriers in a channel are used to facilitate a single link.**
- **OFDMA assigning different number of sub-carriers to different users in a similar fashion as in CDMA.**

* 802.11 WLAN supports multiple users with FDMA (frequency-division multiple access)

WiMAX 802.16d/e
OFDMA

- **W**orldwide **I**nteroperability for **M**icrowave **Access**
- **Fixed – 802.16d, point-to-point backhaul applications**
- **Mobile – 801.16e, enhanced data services mobile applications.**

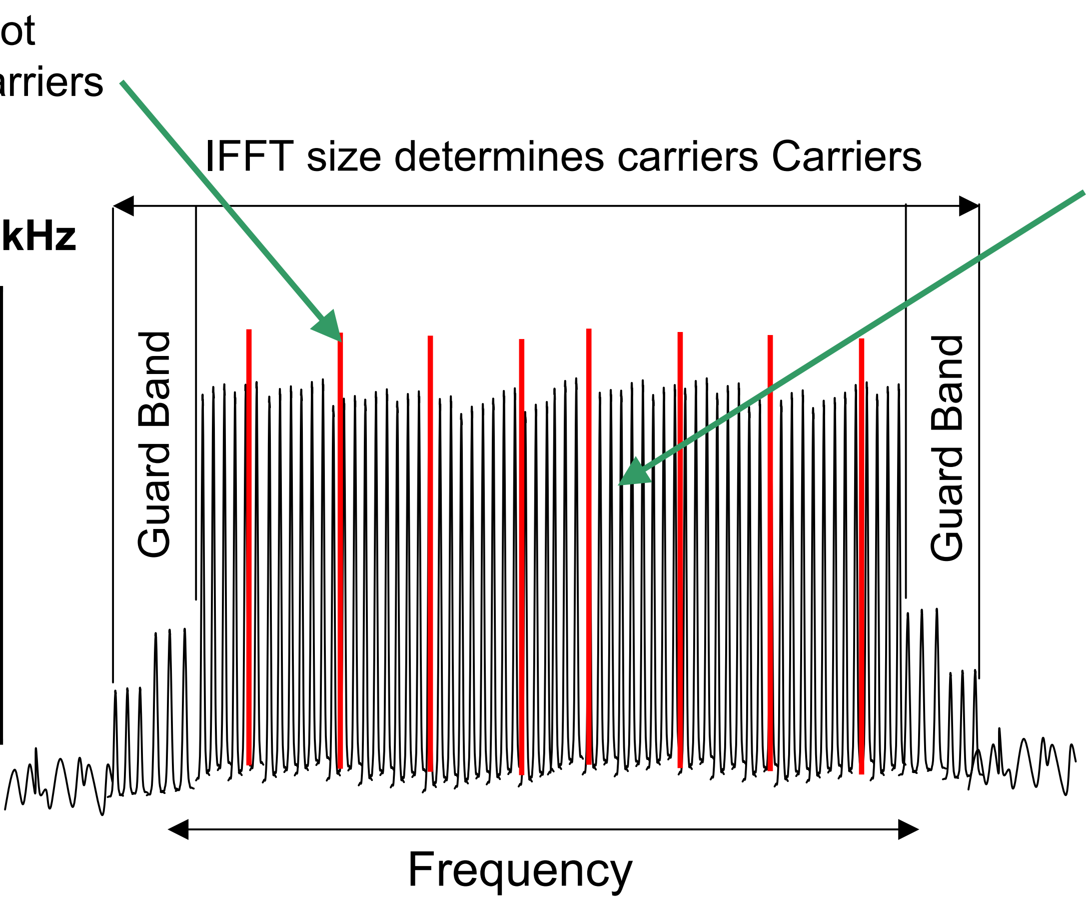
WiMAX enhanced
Mobile Devices



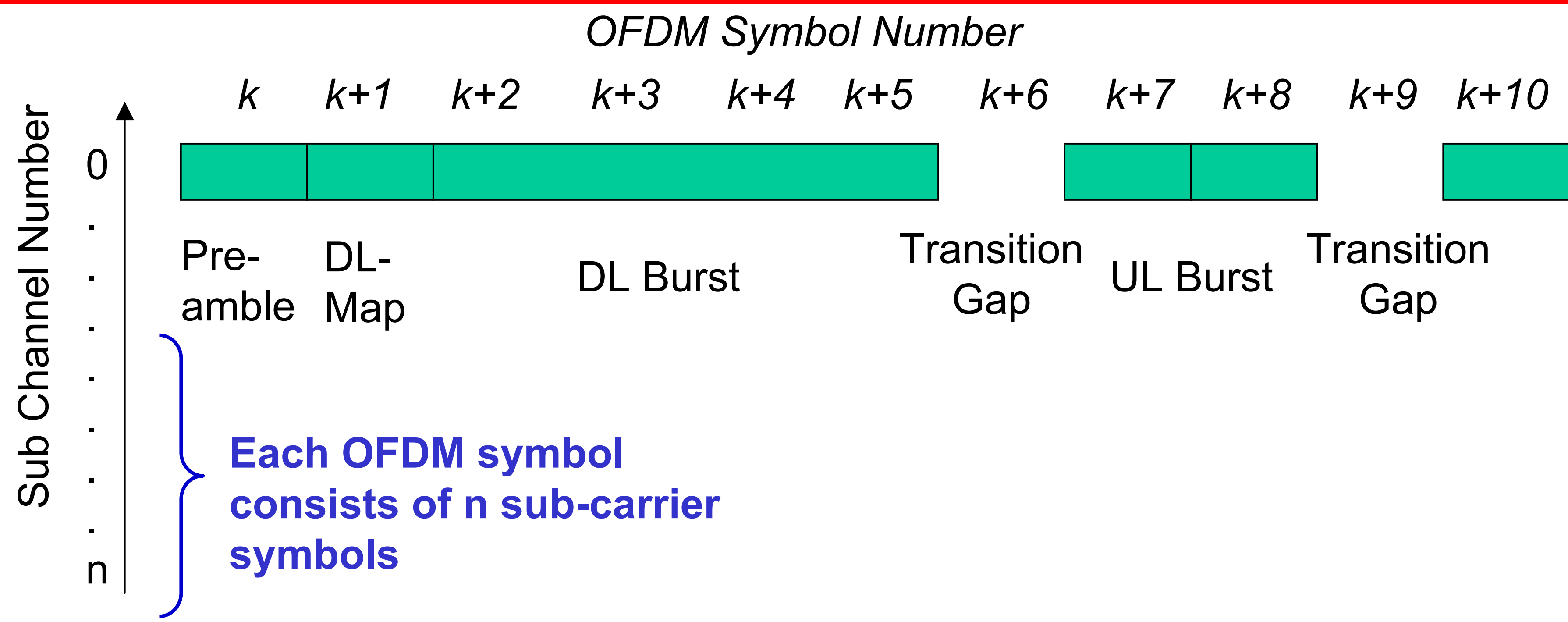
RF Characteristics 802.16e Mobile WiMAX

Subcarrier Spacing: 10.94 kHz

FFT Size	Channel Bandwidth
128	1.25 MHz
512	5 MHz
1024	10 MHz
2048	20 MHz



Symbol Transmission verses Time



802.16e can use time-division or frequency-division multiplexing between the up and down-link bursts.

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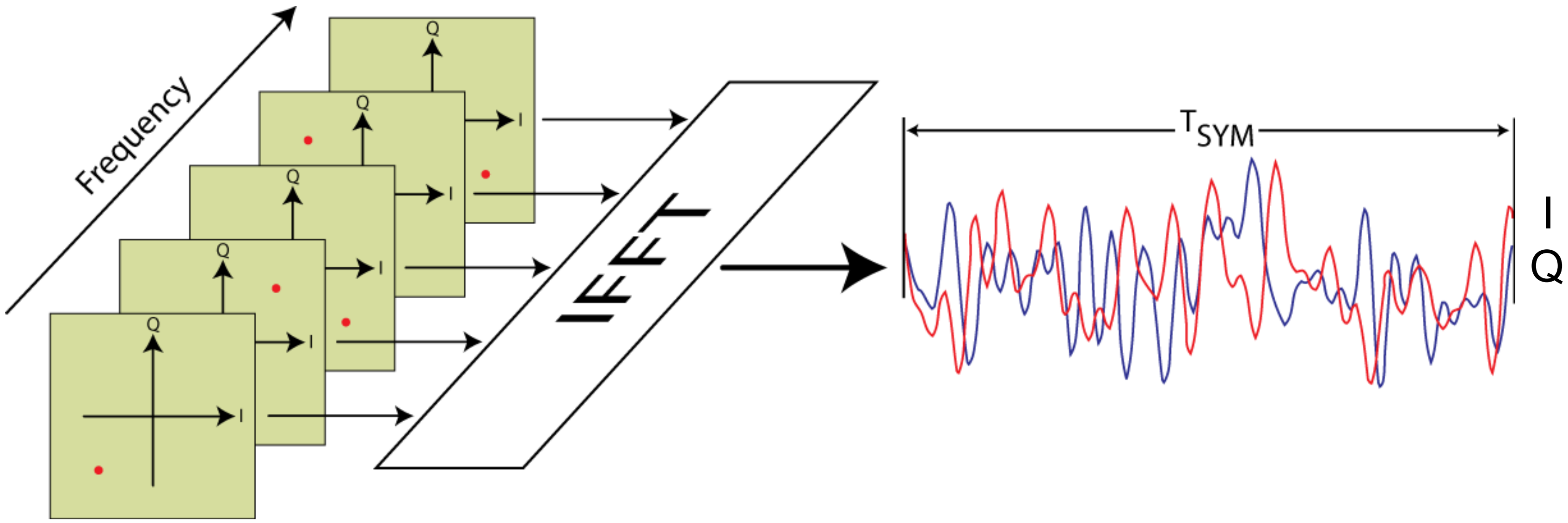
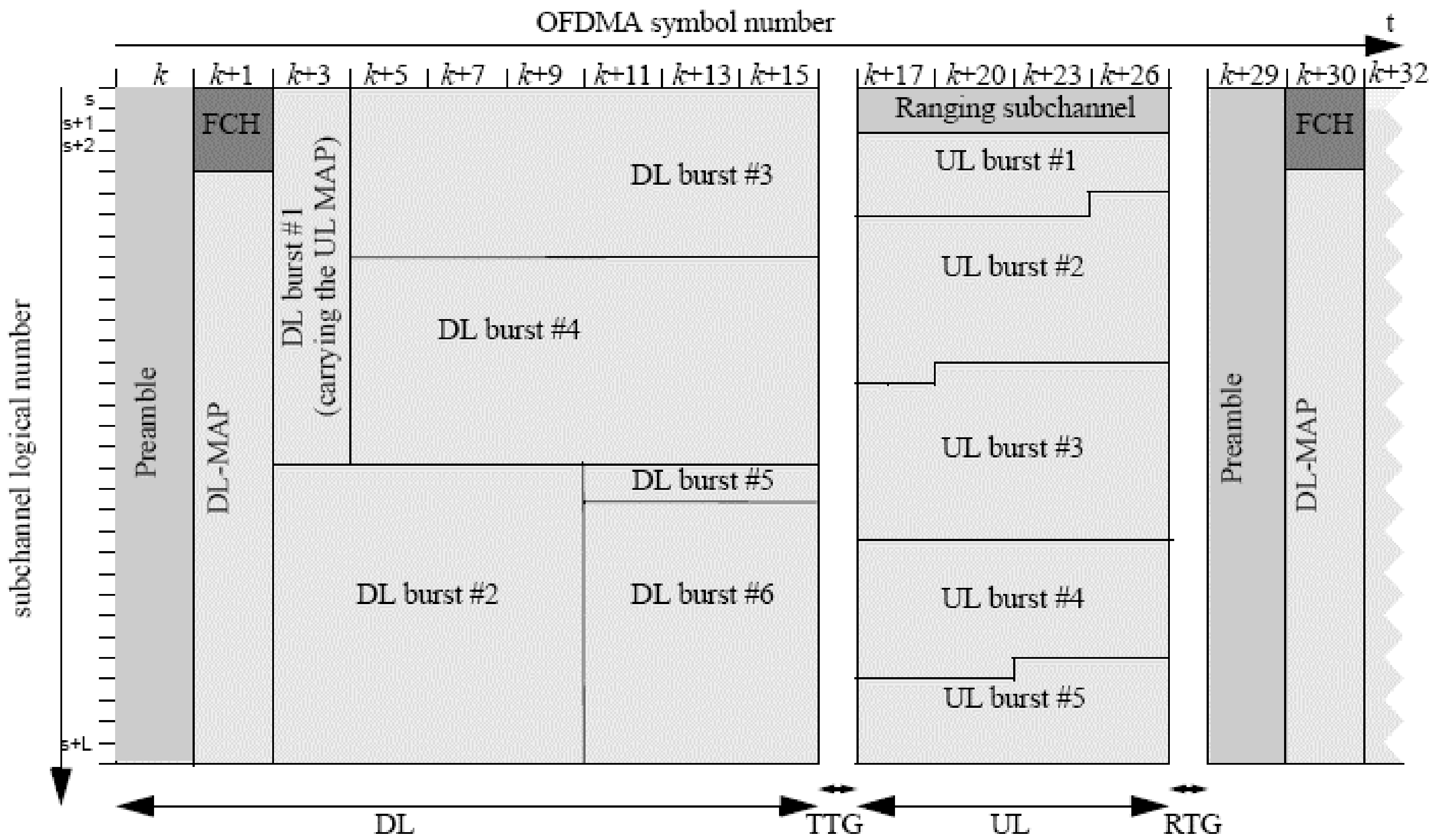
Transmitting Multiple Symbols Simultaneously



Dynamic Symbol Map



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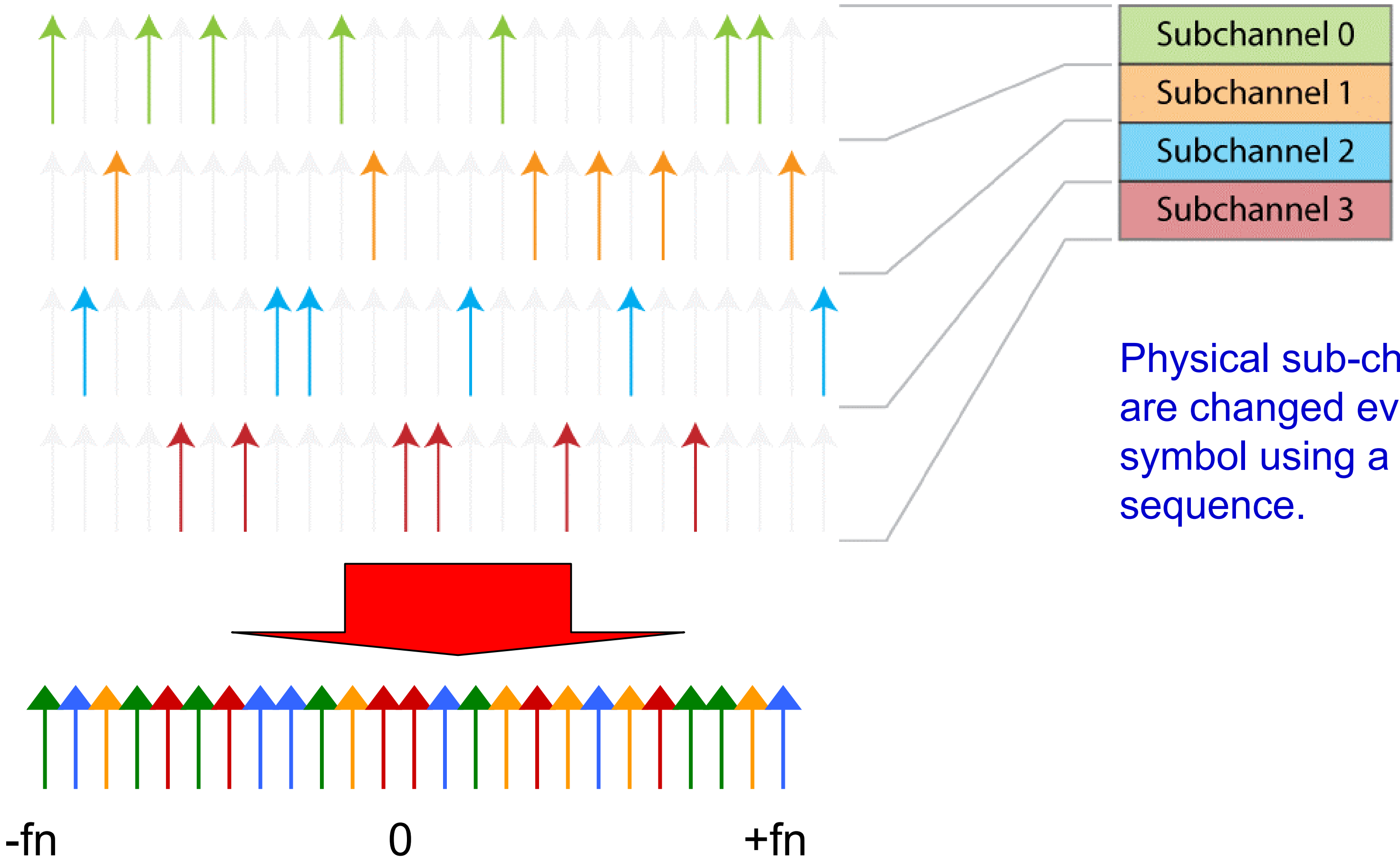
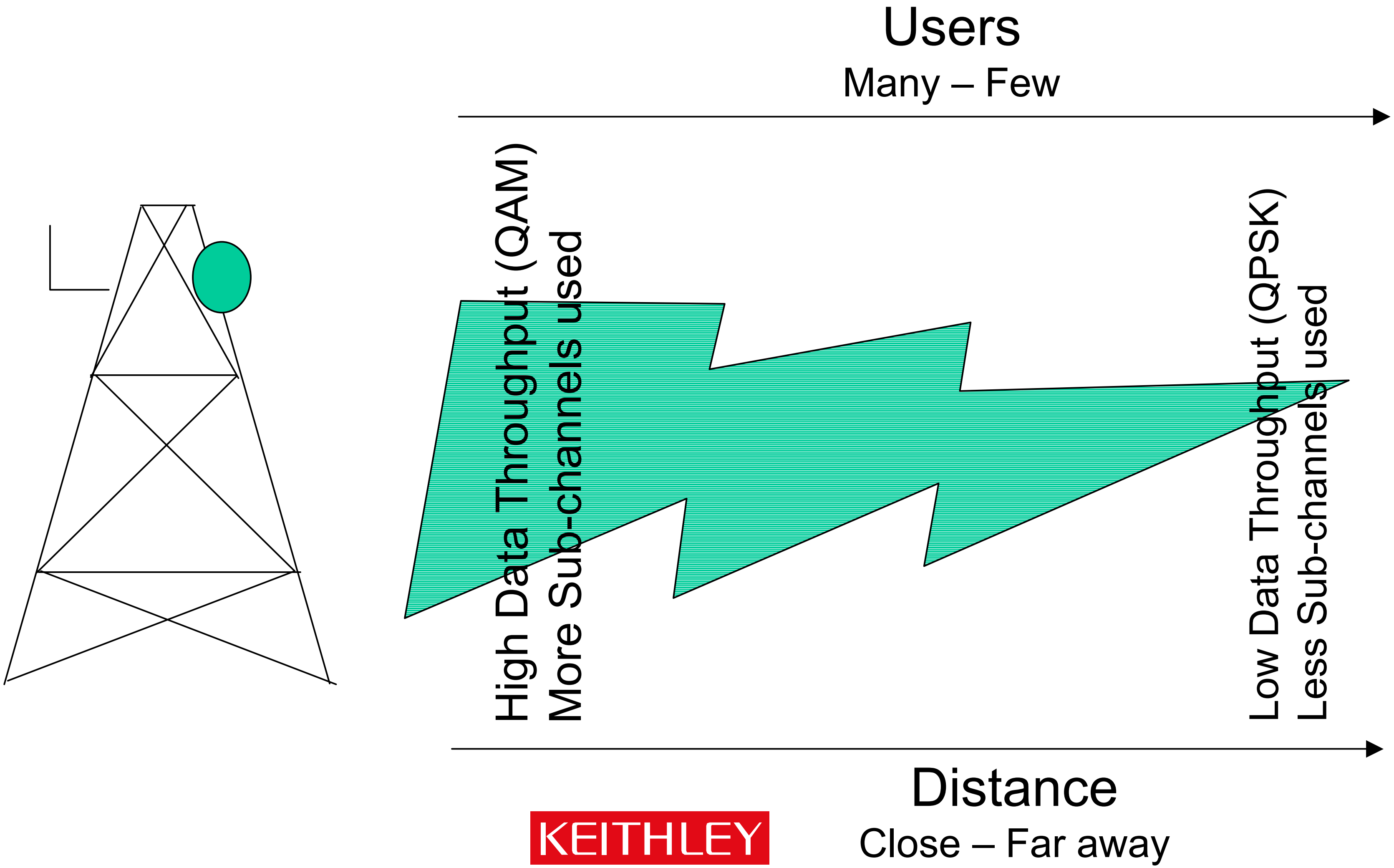
The Physical Channels are Different from the Logical Channels



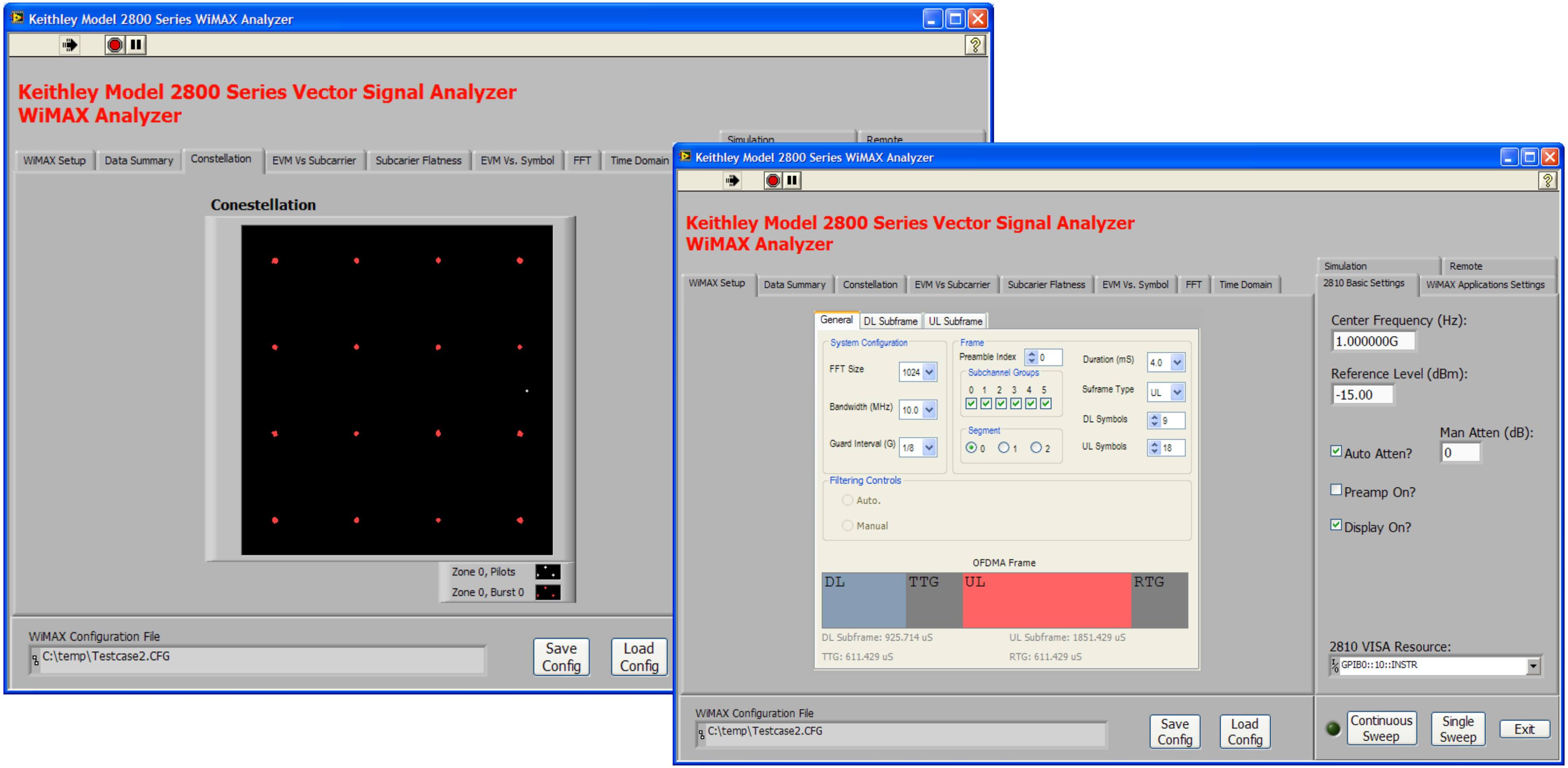
Physical sub-channels are changed every symbol using a PN sequence.

Link Characteristics – Summary



WiMAX Measurements

demo



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WiMAX Summary

- **This is metropolitan area networking – internet to your home, office or car.**
- **Implies one of the 802.16 Standards**
- **Very similar in concept to 802.11, but the demands of multiple simultaneous users (possibly mobile) make the implementation much more complex.**
- **Uses scheduled transactions to ensure all paying users get access. You can get frozen out with WiFi.**
- **Stands for: Worldwide Interoperability for Microwave Access**

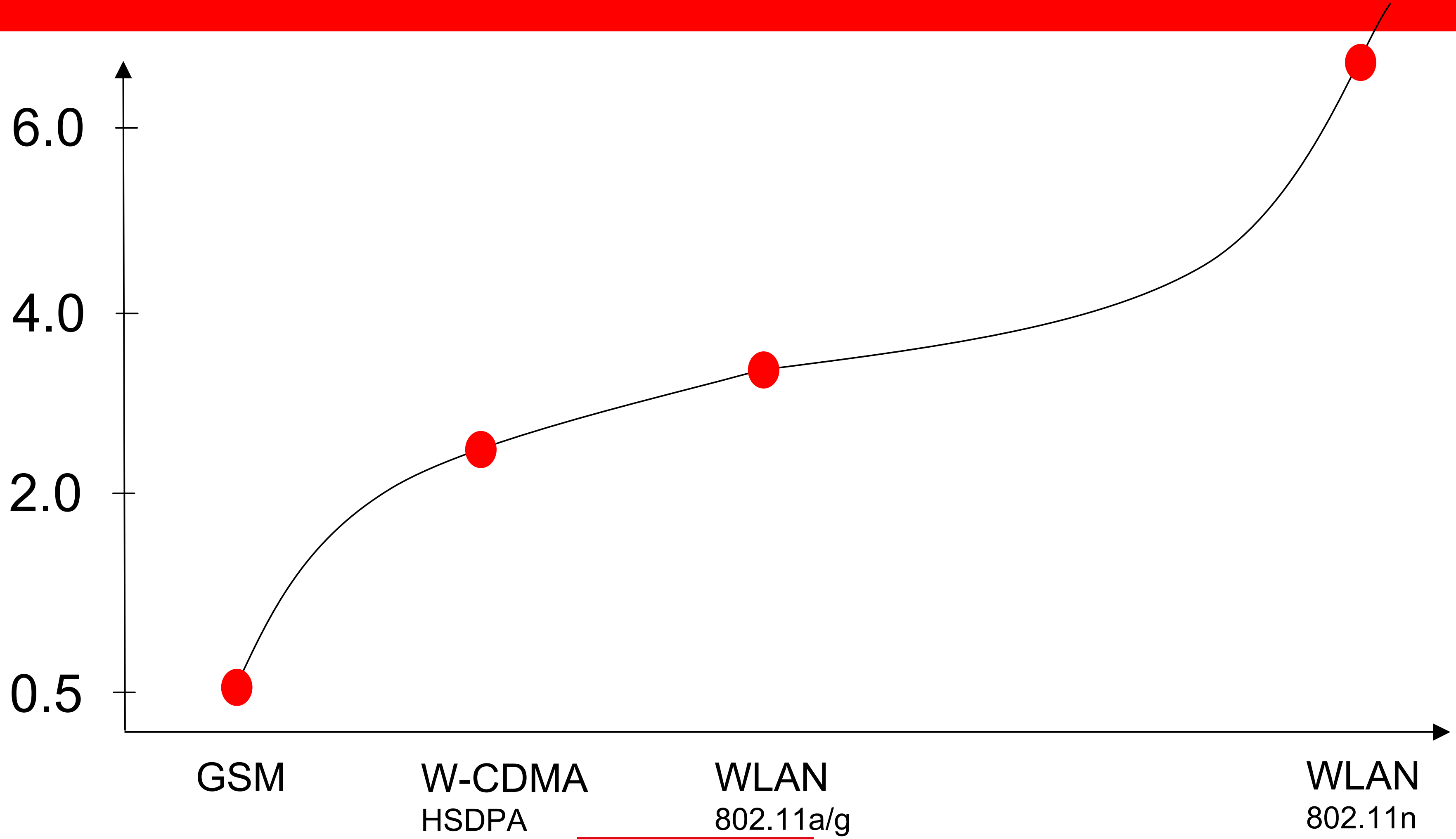
802.16	Means
802.16-2004 (aka 802.16d)	Fielded system for fixed-point access (to the home or office)
	• OFDMA (OFDM multiple access) • 2-11 GHz (no regulatory approval above 5.9 GHz) • Practical rate: 10 Mbps over 2 km
802.16e-2005	The current version of the standard, upgraded to include mobile wireless.
	• SOFDMA (Scalable OFDM Multiple Access) • SOFDMA interoperates with OFDMA, but requires new equipment. • Adds MIMO

OFDM/A to MIMO

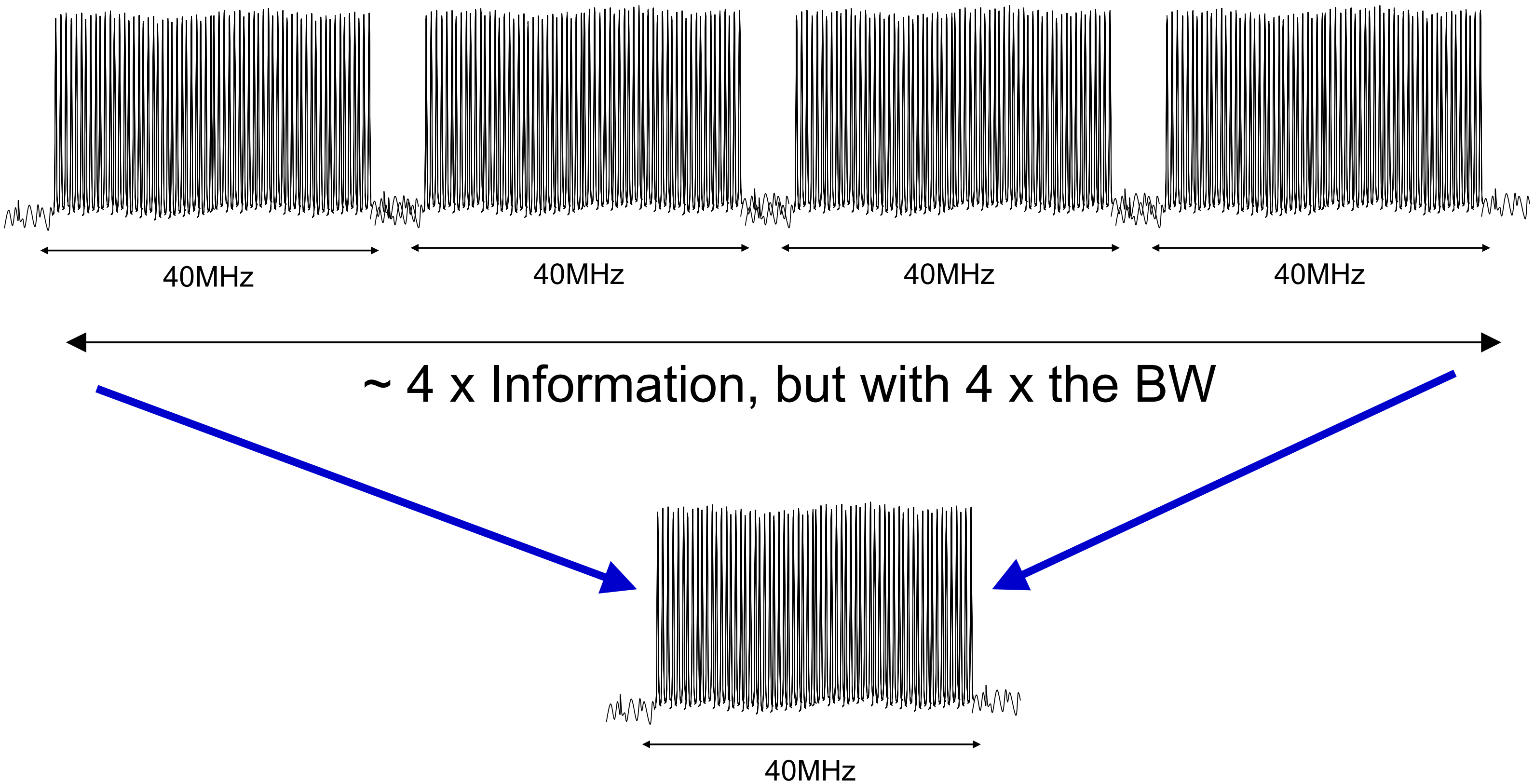
- MIMO uses multiple transmitters and receivers that are modulated with OFDM/A.
- Both WLAN (802.11n) and WiMAX (802.16e) have MIMO configurations

Spectrally Efficiency – SISO → MIMO

Bits/Second/Hz



Why is MIMO different from standard OFDM



~ 3.5 x Information, but with 1 x the BW

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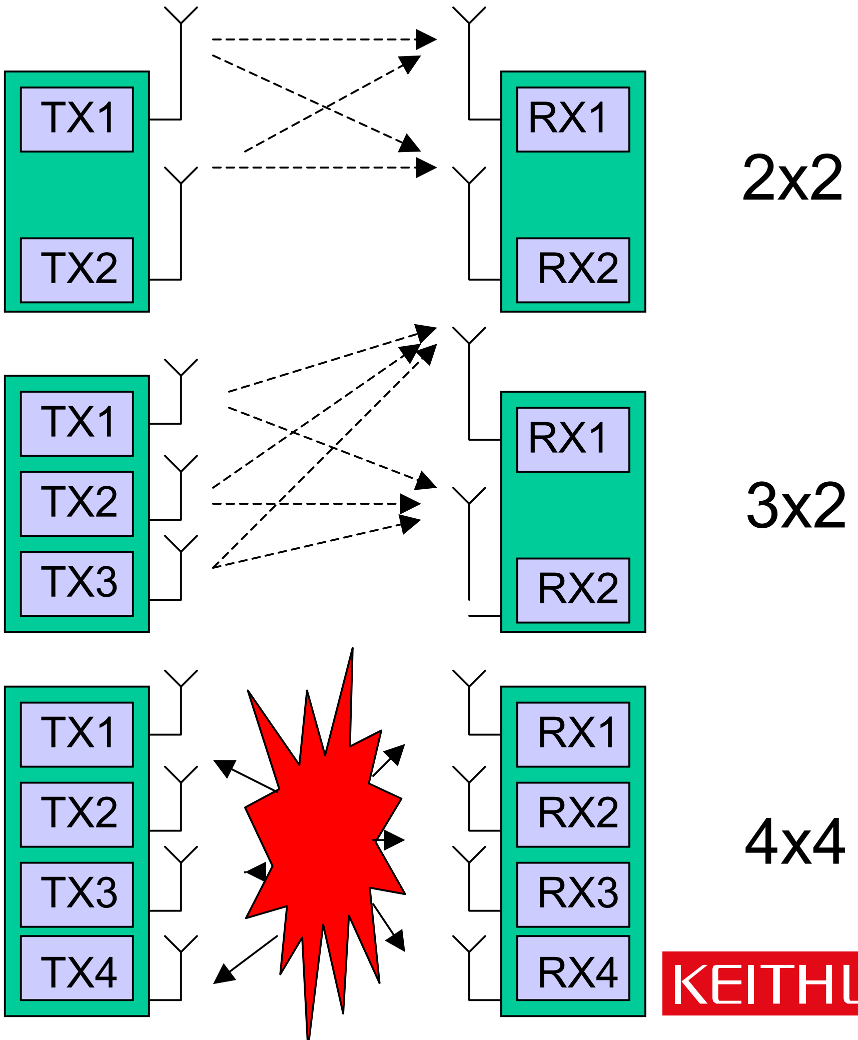
MIMO Radio Configuration



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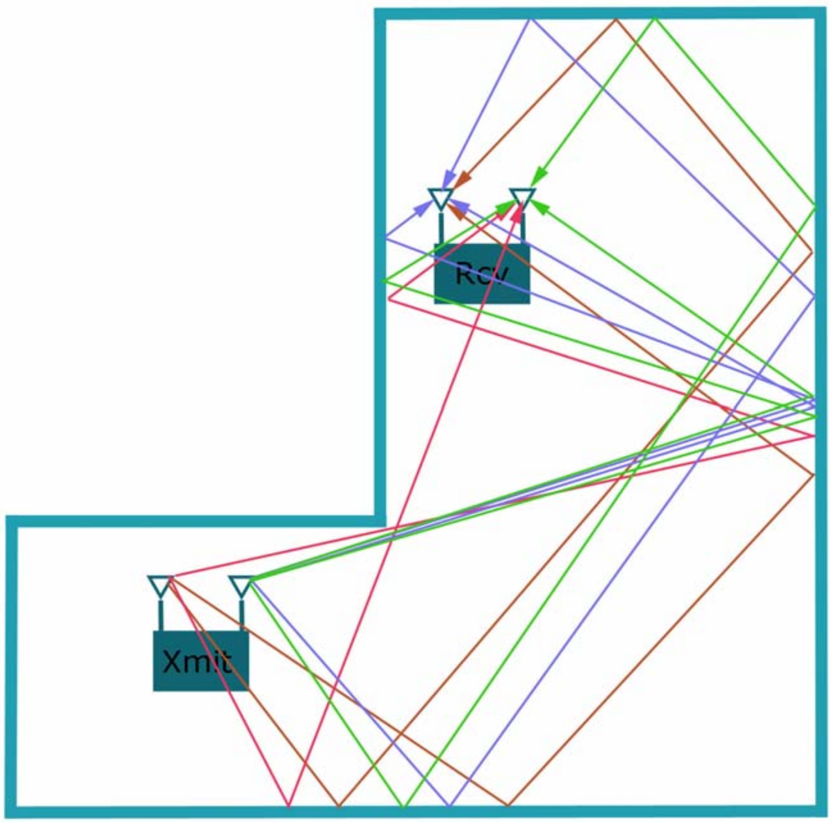
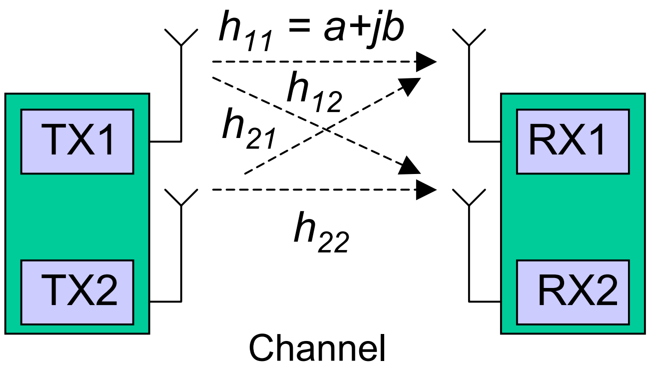
MIMO requires lots of paths!



If you have two unknown transmitted signals and two measurements at the receivers. If the two measurements are sufficiently independent, you can solve for the transmitted symbols!

Mathematically
Model the Channel

$$y = Hx + n$$



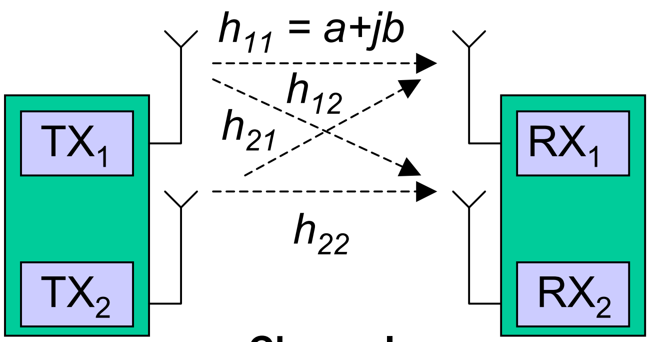
y = Receive Vector
x = Transmit Vector
H = Channel Matrix
n = Noise Vector

$$H = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix}$$

Header

Correct for channel effects

$$RX = H * TX + n$$

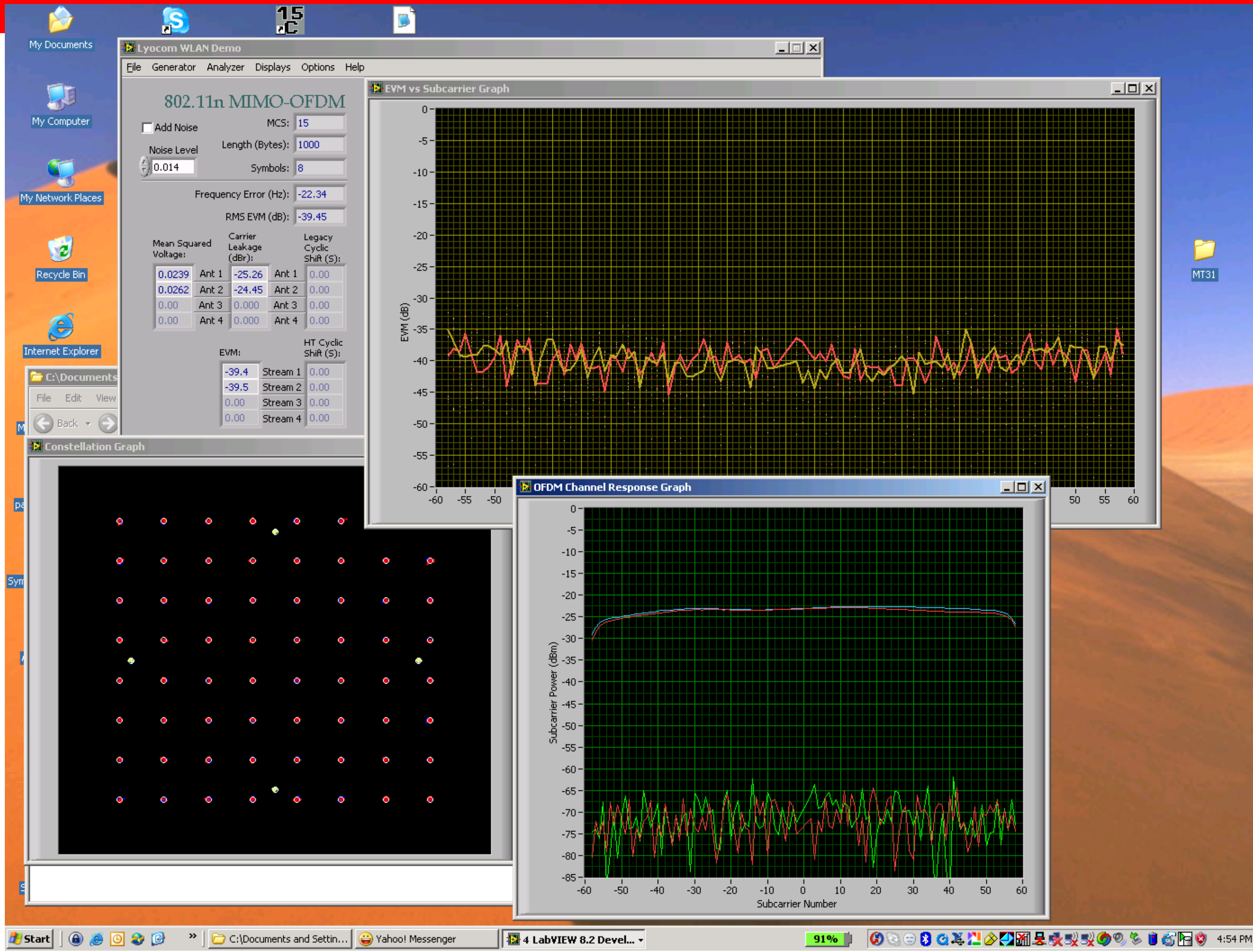


Channel

$$\begin{bmatrix} TX_1 \\ TX_2 \end{bmatrix}_{\text{Data}} = \frac{\begin{bmatrix} RX_1 \\ RX_2 \end{bmatrix}_{\text{Data}} - n}{\begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix}_{\text{Header}}}$$

2x2 Measurement Example

demo



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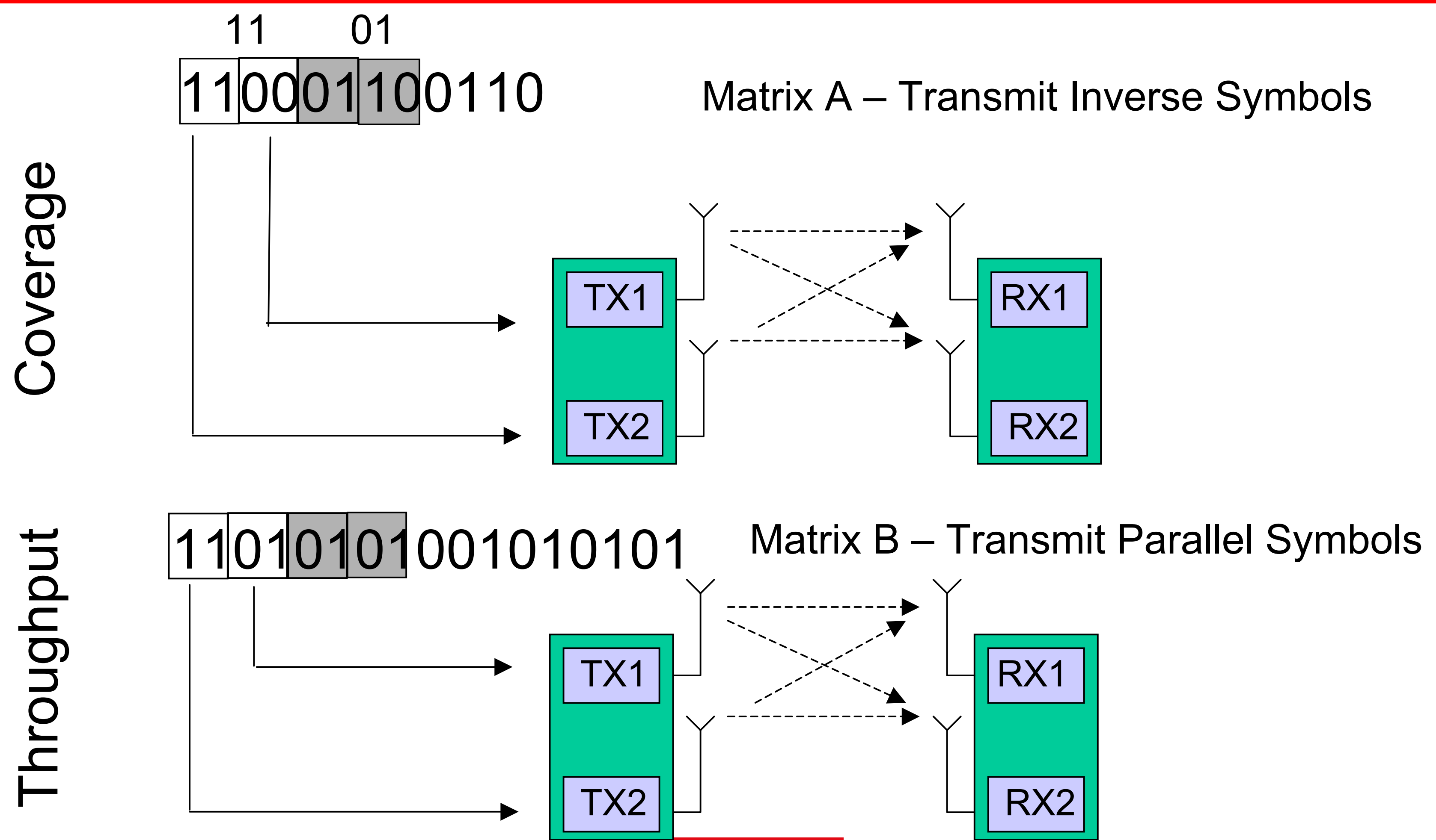
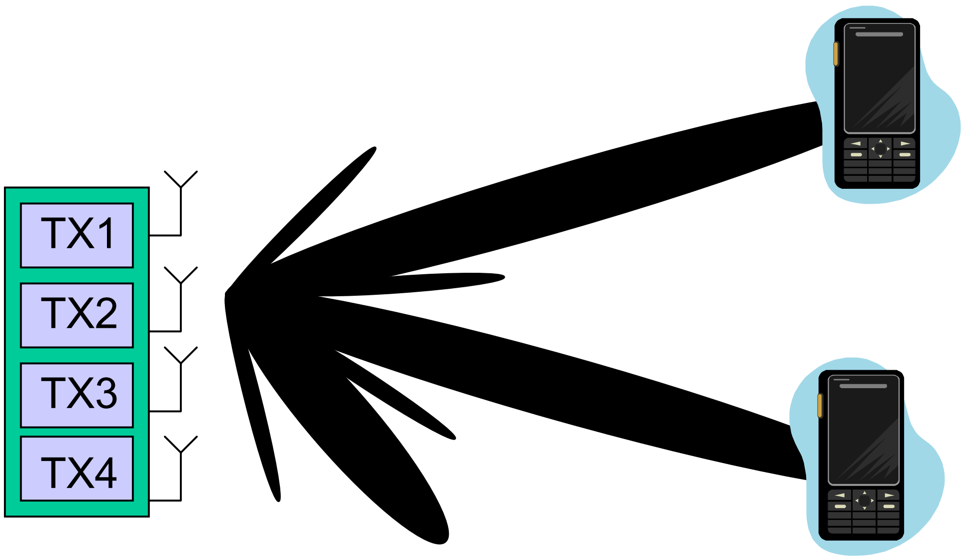
802.16e Matrix A and B
Robust Symbols vs. More Symbols



Beam Forming



- Control the directionality and shape of the radiated pattern

Increase range, capacity and throughput

The Beam Forming Process
WiMAX Example - Closed Loop

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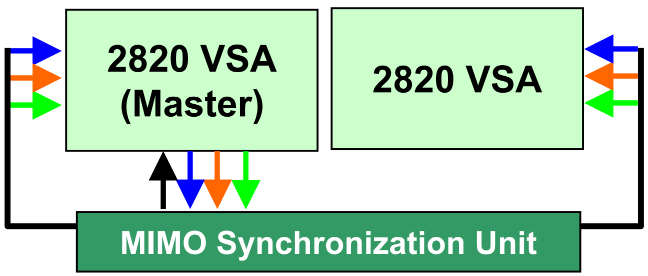
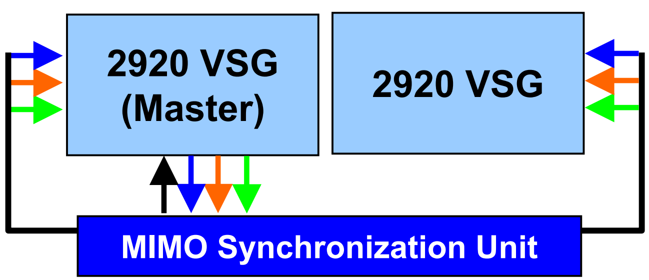
Typical Types of Beam Forming

- Statistical Eigen Beam Forming (EBF)
  - Advantage – Quickly builds a channel model to form a beam, making it ideal for mobile applications.
  - Disadvantage – Not as efficient as Maximum Ratio Transmission.

- Maximum Ratio Transmission (MRT)
  - Advantage – builds a very accurate channel model, thus improving throughput and coverage.
  - Disadvantage – Slow processing times limit to static transmissions

MIMO Instrument Requirements





<u>Hardware</u>

- All 28/2920 VSAs are identical standard units
- Flexibility to use 2820 VSAs as stand-alone generators
- User-definable instrument configuration setting
    - Stand-alone
    - MIMO Master
    - MIMO Slave

<u>System</u>

- Common LO and clock signals for all analyzers
- Master provides LO, 100 MHz digital clock, and Trigger Sync to MIMO Synchronization Unit
- MIMO Sync. Unit distributes a common LO, common 100 MHz clock, and synchronized Trigger to all units
- Signal sampling alignment within ±1 nsec

<u>Form Factor</u>

- 28/2920: 3U high, ½ rack width
- MIMO Sync. Unit: 1U high, full-rack width

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Conclusions

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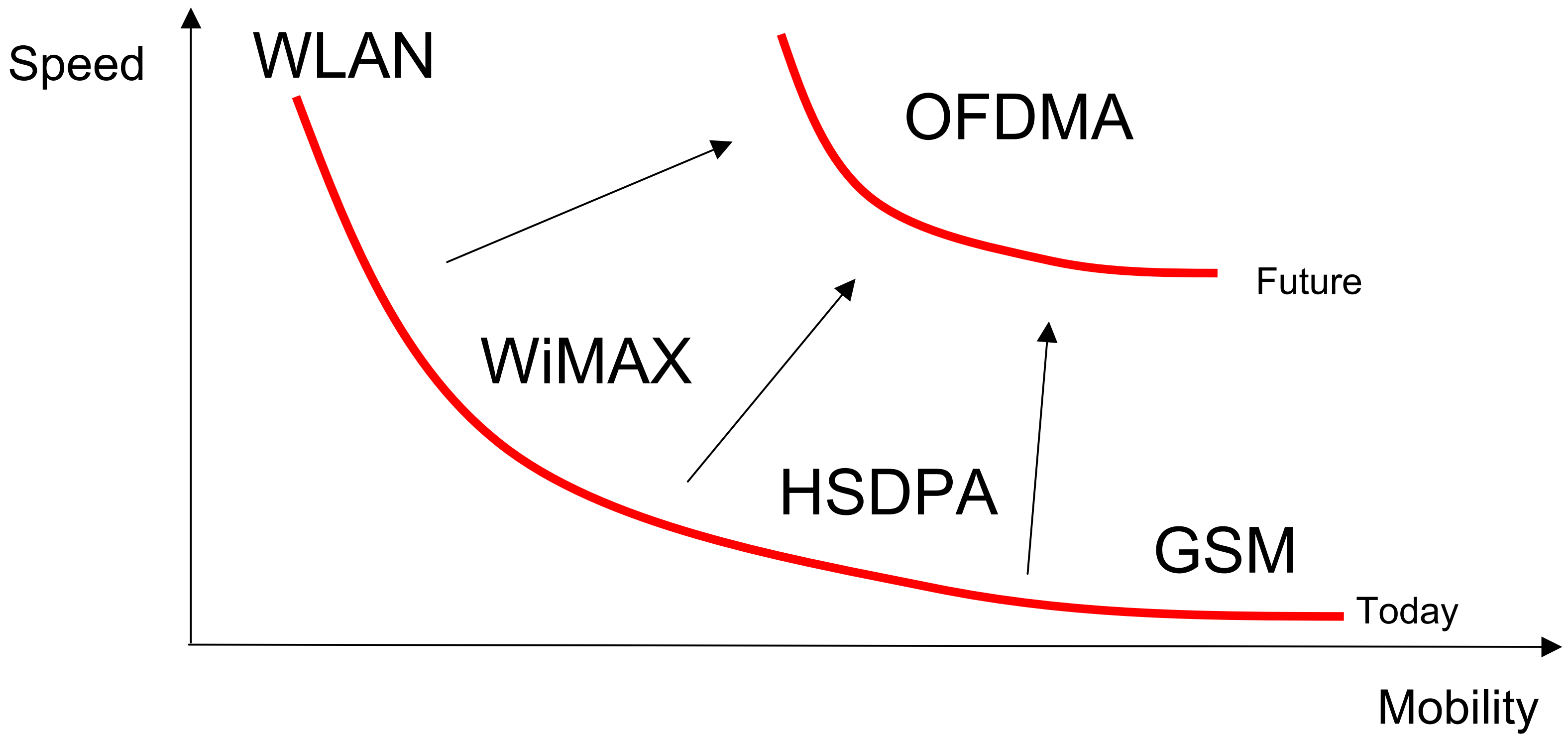
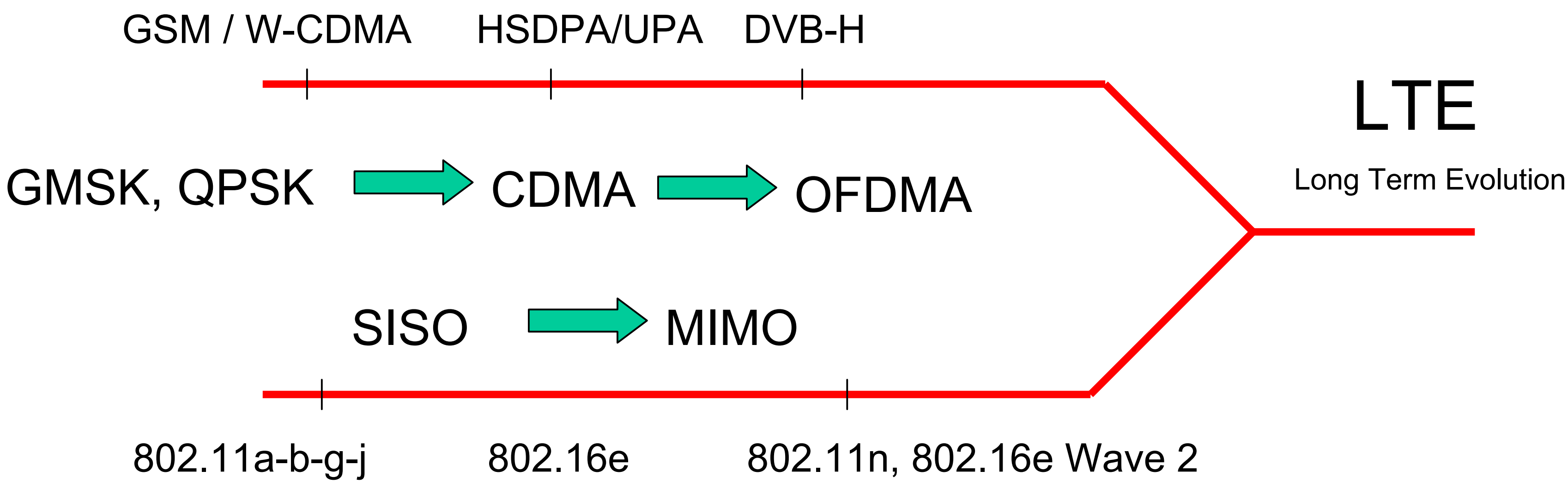
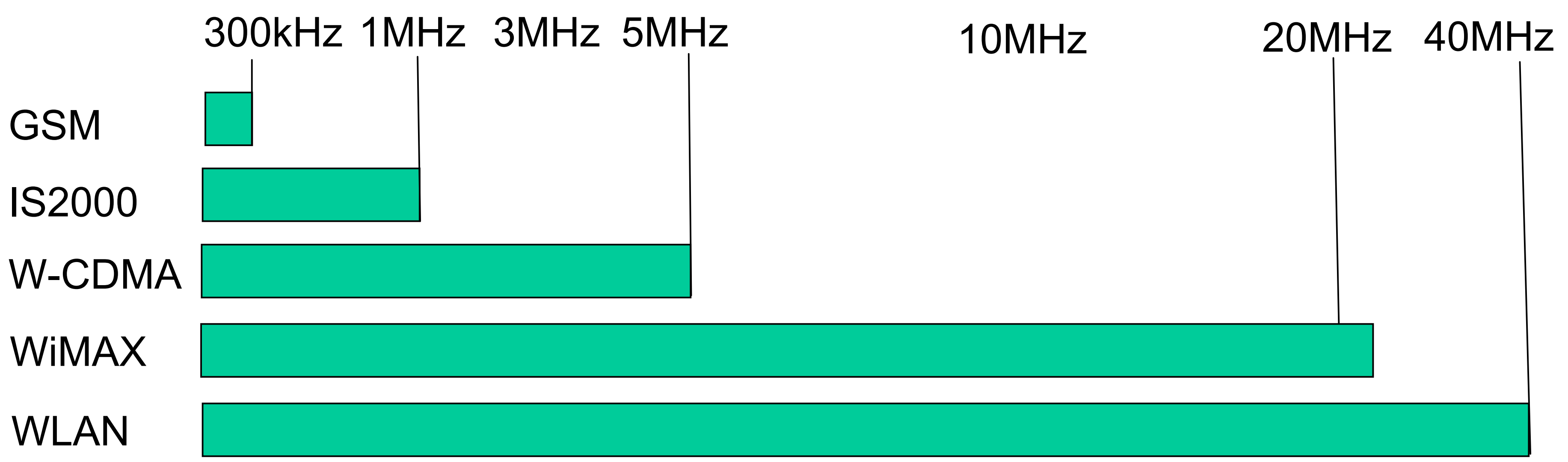
Speed vs. Mobility



The Long Term Evolution of Wireless



Instrument Bandwidth Requirements



Keithley instruments have 40MHz BW as standard.

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Summary

- OFDM and SISO radio configurations
- OFDM and MIMO radio configurations
- OFDMA
- WLAN, WiMAX and the evolution to 4G

Industry's Leading 4x4 MIMO RF Test System

- **Industry-Leading Performance**
  - Flexible 2, 3, or 4-channel configurations
  - 40MHz signal bandwidth
  - 1 nsec signal sampler synchronization
  - 1 nsec peak-to-peak signal sampler jitter
  - 1° peak-to-peak RF-carrier phase jitter
  - High-performance: -40dB EVM (Error Vector Magnitude)
  - Uses standard MIMO-ready instruments
  - Industry leading signal analysis MIMO software