Agilent Technologies

Measurement Challenges For OFDM Systems

September 18, 2001

presented by:

Bob Cutler

OFDM

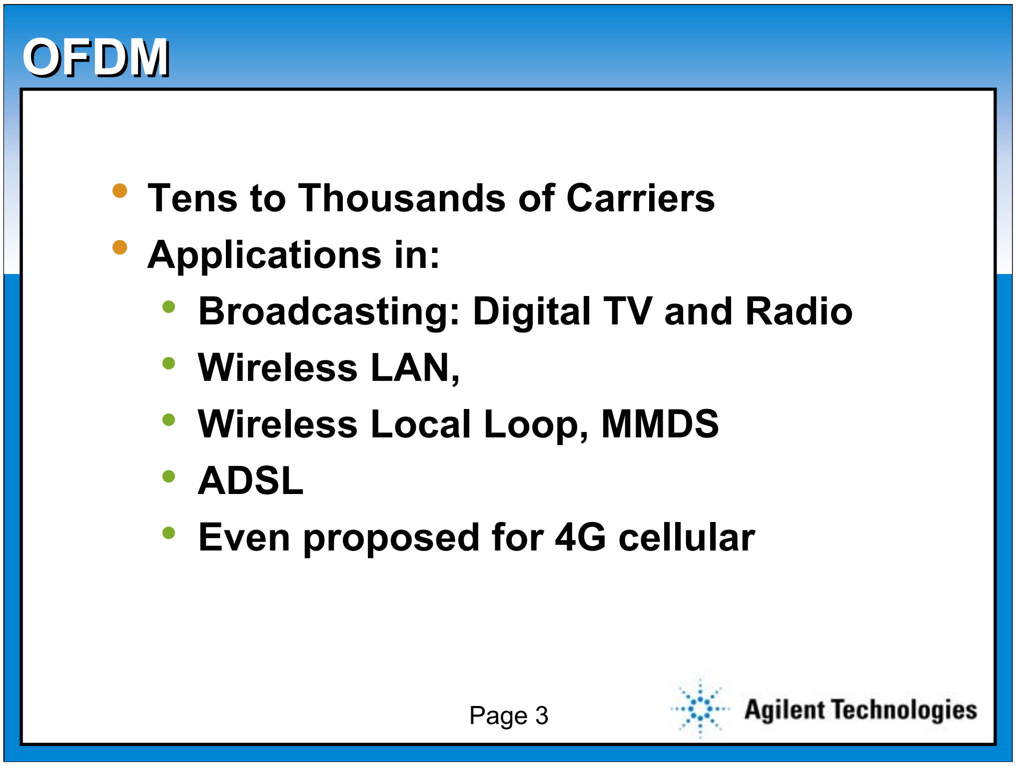
- OFDM: Orthogonal Frequency Division Multiplexing
- 802.11A, HiperLAN/II: Burst TDD
- COFDM: Coded OFDM
  DVB-T, ISDB-T: Continuous Downstream
- VOFDM: Vector OFDM (TX/RX diversity)
  BWIF: Cont. Downstream, Burst Upstream

OFDM is a technology who's time has arrived. It was first widely used in consumer products in Digital Audio and Digital Video Broadcasting and ADSL modems. It's now finding it's way into broadband internet access systems such as wireless LANs and Point-to-Multipoint distribution systems.

OFDM was first proposed as a way of dealing with multipath. One of the problems with single carrier modulations (SCM) is that, in a given environment, the symbol interval becomes much shorter than the delay spread as the symbol rate is increased. To solve this problem with multi-carrier modulation formats, the symbol rate is instead decreased, and the number of carriers is increased. The basic idea is that if you take a signal and send it over multiple low-rate carriers instead of a single high-rate carrier, then inter-symbol interference (ISI) is eliminated and multipath effects can be compensated with a much simpler equalizer.

As a modulation format, OFDM is very flexible in that it can be easily scaled to meet the needs of a particular application. For applications like VOFDM, the lack of ISI also greatly simplifies the implementation of diversity reception.

BWIF (uplink), 802.11A and Hyperlan/II are unique in that the OFDM is pulse modulated. While the specifics of BWIF are proprietary, the impact on WLAN products is the need for special synchronization techniques.

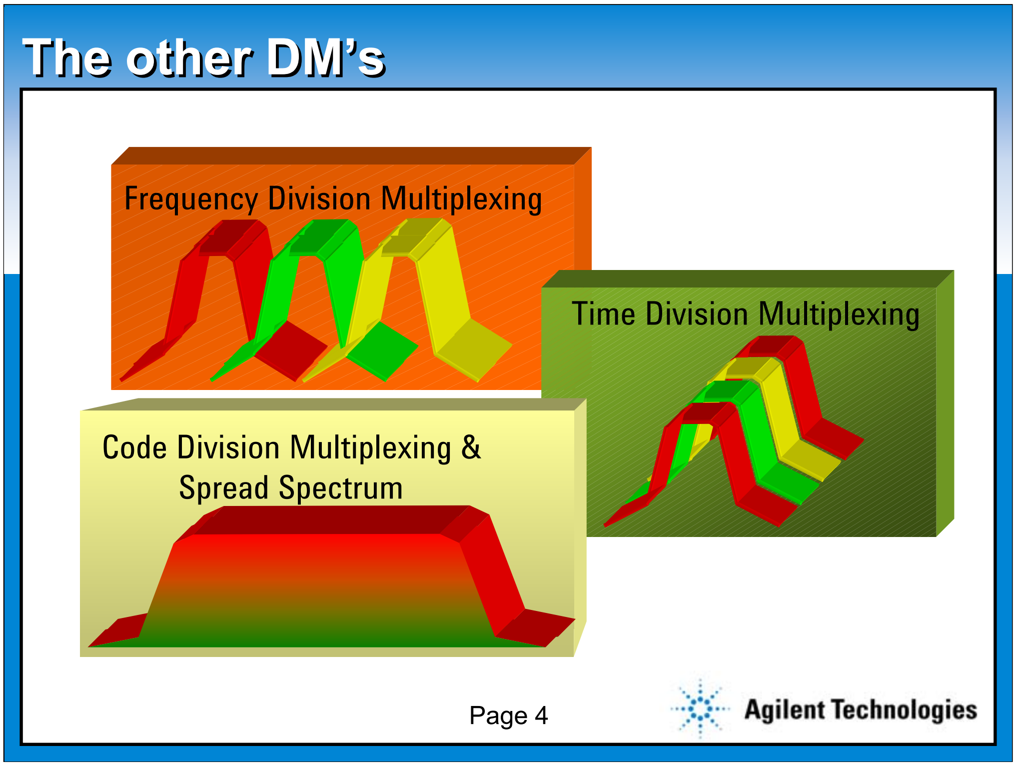


OFDM is a technology who's time has arrived. It was first widely used in consumer products in Digital Audio and Digital Video Broadcasting and ADSL modems. It's now finding it's way into broadband internet access systems such as wireless LANs and Point-to-Multipoint distribution systems.

OFDM was first proposed as a way of dealing with multipath. One of the problems with single carrier modulations (SCM) is that, in a given environment, the symbol interval becomes much shorter than the delay spread as the symbol rate is increased. To solve this problem with multi-carrier modulation formats, the symbol rate is instead decreased, and the number of carriers is increased. The basic idea is that if you take a signal and send it over multiple low-rate carriers instead of a single high-rate carrier, then inter-symbol interference (ISI) is eliminated and multipath effects can be compensated with a much simpler equalizer.

As a modulation format, OFDM is very flexible in that it can be easily scaled to meet the needs of a particular application. For applications like VOFDM, the lack of ISI also greatly simplifies the implementation of diversity reception.

BWIF (uplink), 802.11A and Hyperlan/II are unique in that the OFDM is pulse modulated. While the specifics of BWIF are proprietary, the impact on WLAN products is the need for special synchronization techniques.

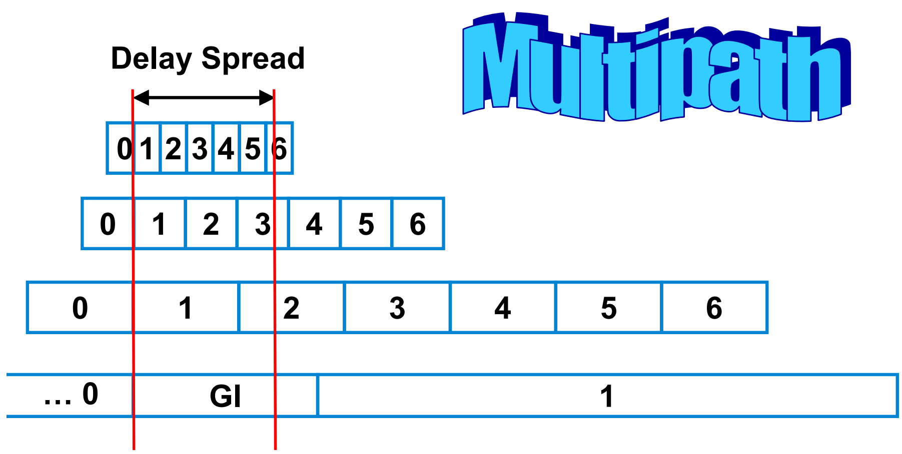


In FDM systems, the carriers don't interfere with one another because the carrier frequency spacing is close to the signal bandwidth. As we'll soon see, in OFDM the carriers can be heavily overlapped without introducing interference. This is not unlike CDMA where the carriers overlap 100%

Advantages of OFDM

- Increased efficiency because carrier spacing is reduced (orthogonal carriers overlap)
- Equalization simplified, or eliminated
- More resistant to fading
- Data transfer rate can be scaled to conditions
- Single Frequency Networks are possible (broadcast application)
- Now possible because of advances in signal processing horsepower

Motivation for OFDM



Disadvantages of OFDM

- Higher Peak-to-average
- More sensitive to phase noise, timing and frequency offsets
- Greater complexity
- More expensive transmitters and receivers
- Efficiency gains reduced by requirement for guard interval

The two biggest RF problems with OFDM are amplification, due to the higher crest factor, and frequency accuracy and stability (phase noise). The amount of additional power amplifier (PA) backoff, or headroom, required for OFDM is hotly contested. Some OFDM proponents believe that only 1-2 dB are required over single carrier modulations (SCM). Others believe the number is much higher. As with most requirements, it really depends on the assumptions. The amount of backoff is a strong function of adjacent channel considerations and to a lesser degree a function of in-channel distortion.

The carrier orthogonality is a strong function of the frequency accuracy of the receiver and the phase-noise performance of both TX and RX.

Tighter phase-noise requirements and linear PA's contribute to greater implementation costs.

Comparing OFDM Systems

- All use complex IFFT to generate symbol pulse
- All use the general concept of a guard interval, although there are some variations
- Some systems do not require equalizers in the receiver
- Some systems do not use a rectangular pulse
- Pilot and sync symbols (and carriers) vary from system to system

Comparing OFDM Systems

	DVB-T	DAB	802.11A
BW	8 MHz	1.5 MHz	18 MHz
Carriers	1705 6817	1536 384 192 768	48 4 (sync)
Carrier Spacing	4.464 kHz 1.116 kHz	1 kHz 4 kHz 8 kHz 2 kHz	312.5 kHz
Pilot/Sync Mod.	BPSK	QPSK	BPSK
Data Modulation	QPSK 16 QAM 64 QAM	DQPSK	BPSK, QPSK 16 QAM 64 QAM

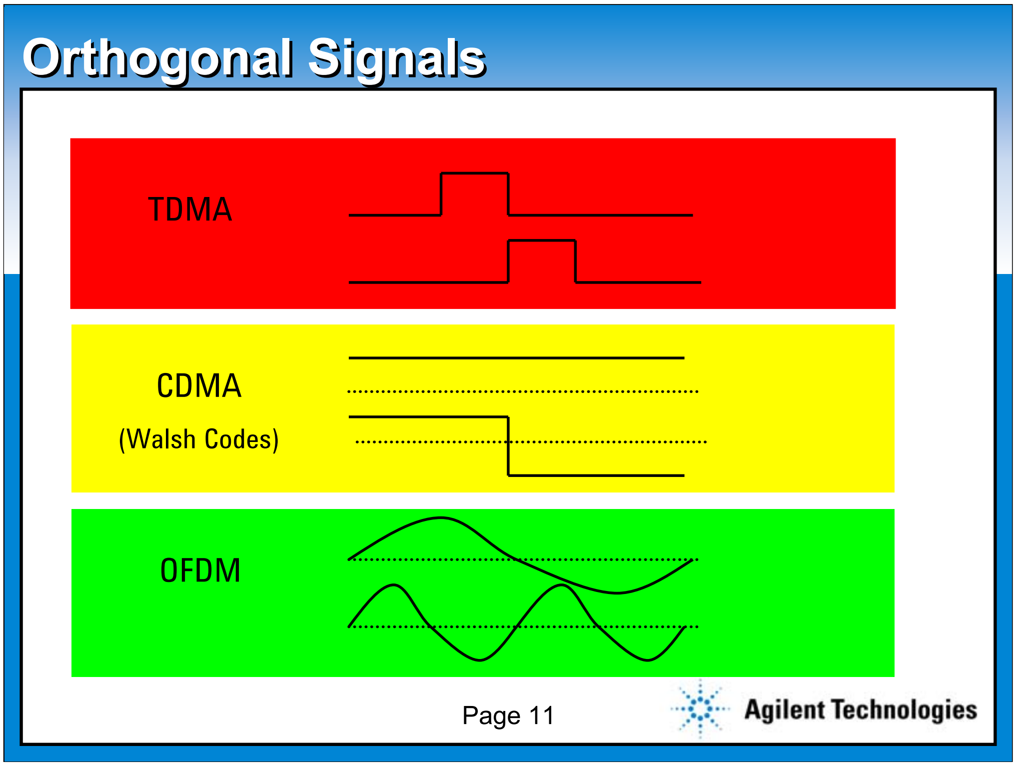
Agilent Technologies

While both DVB-T and 802.11A are both based on OFDM technologies they are quite different in implementation. The 802.11A signal has more than 2X the bandwidth, but only a small fraction of the carriers. Both use up to 64 QAM modulation on the data carriers. The 300x carrier spacing of 802.11A greatly reduces the phase-noise requirements relative to DVB-T.

Comparing OFDM Systems

	DVB-T	DAB	802.11A
Max Guard Interval (max delay spread)	56 usec (2k) 224 usec (8k)	246 usec 62 usec 31 usec 123 usec	0.8 usec
Equalizer	Yes	No	Yes
Pulse Shape	Rect	Rect	Raised Cosine
Pilot/Sync	Continuous and Scattered Pilots	Null and Phase Ref. symbols	Short and Long Training Symbols
Carrier at TX frequency	Yes	Yes, but not used	Yes, but not used

The guard interval duration gives a clear indication of the intended application. In DVB-T delay spreads of 200usec are anticipated, as would be expected in a terrestrial broadcast environment. For 802.11A and HIPERLAN/II the guard interval is only 800 ns. This is appropriate for an indoor environment.
It's interesting to note that the center carrier isn't used in either DAB or WLAN applications. Removing this carrier reduces the data capacity slightly, but also allows the requirements on carrier leakage to be relaxed.

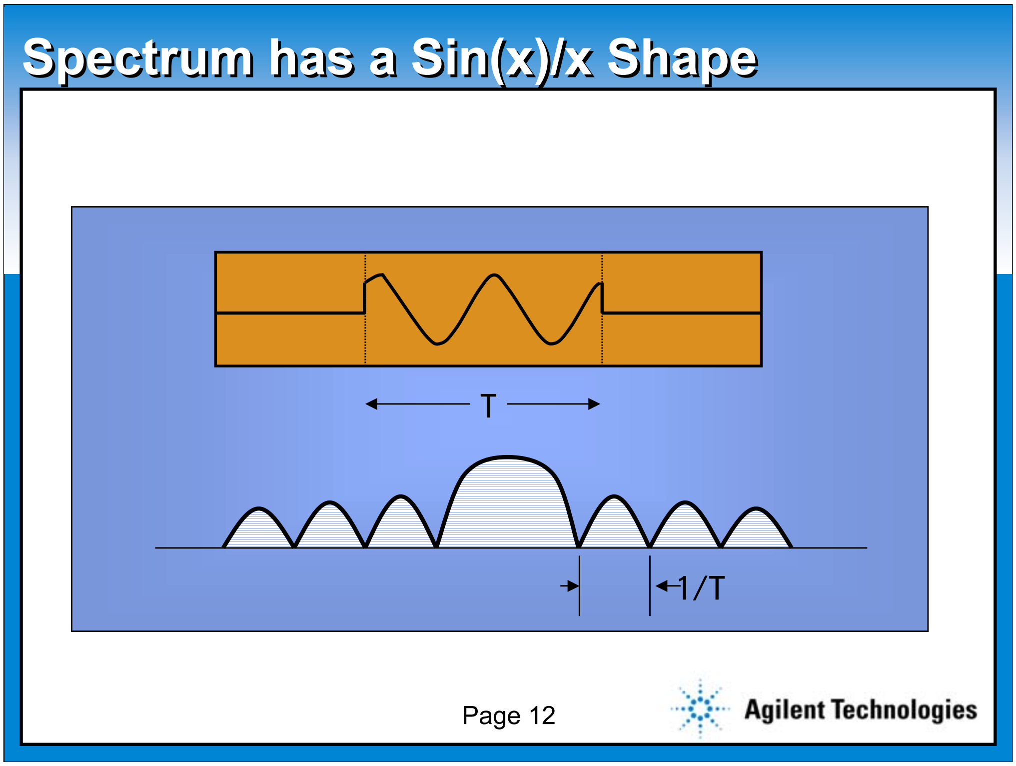


Two signals are orthogonal if their dot product is zero. That is to say that if you can take two signals, multiply them together and then integrate over some interval, and the result is zero, then they are orthogonal in that interval.

TDMA isn't normally considered an orthogonal coding scheme, however the idea applies if you consider the time interval to be the burst width. Over that interval, the other signal is zero, so the dot product is zero.

Walsh codes which are used in CDMA systems are orthogonal, and are probably the most common form of orthogonal signaling. For example in IS-95, length 64 Walsh codes provide 64 possible code channels.

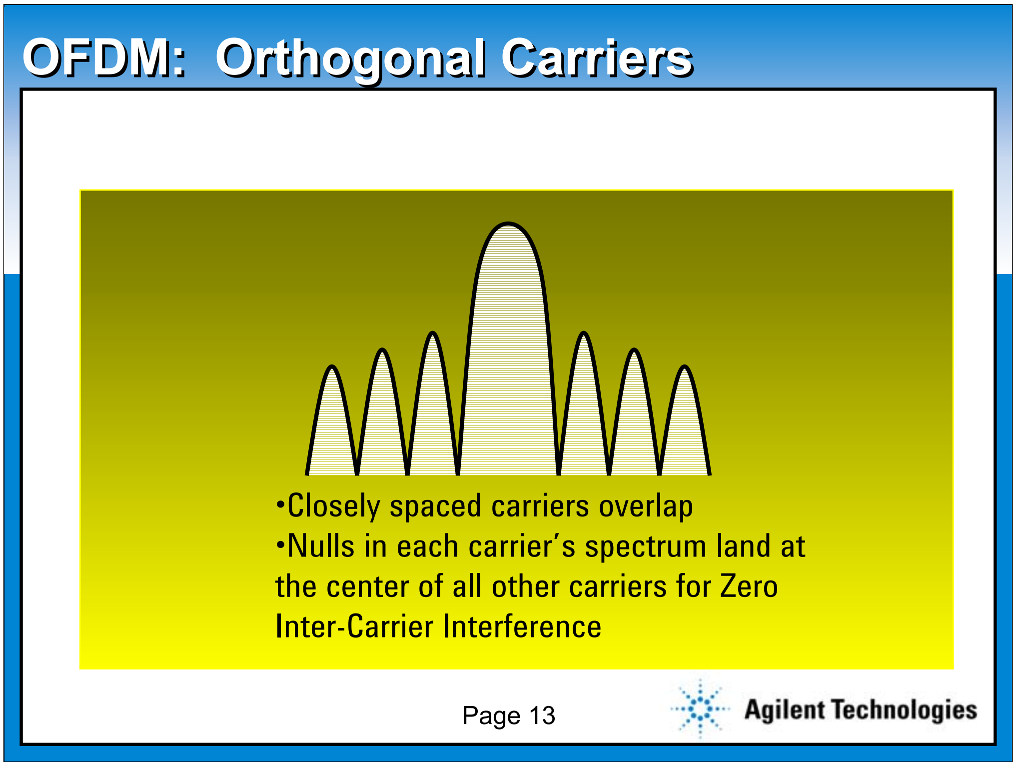
OFDM is actually very closely related to CDMA. Instead of Walsh codes, the basis functions are sinusoids. In a given period, the sinusoids will be orthogonal provided there are an integral number of cycles. The amplitude and phase of the sinusoid, which will be used to represent symbols, does not affect the orthogonlaity property. Using sinusoids instead of Walsh codes produces a spectrum where it's possible to associate a carrier frequency with a code channel.



For a single OFDM carrier, we can model the transmitted pulse as a sinusoid multiplied by a RECT function. In the frequency domain, the resulting spectrum has a sin(x)/x shape centered at the carrier frequency.

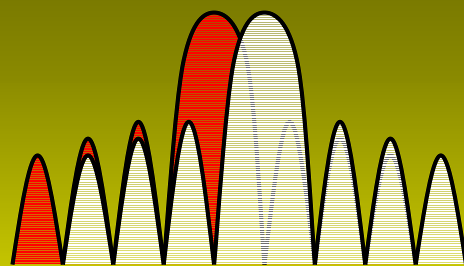
The sin(x)/x spectrum has nulls at adjacent carrier frequencies, provided the sinusoid is on frequency and has zero bandwidth, and the RECT function is the proper width. The RECT function can have the wrong width if the ADC/DAC sample rates are incorrect in either the transmitter or receiver. The zero-width assumption can be violated by phase noise, again in either the transmitter or the receiver.

Relative to SCM systens using Nyquist filtering, the OFDM carriers occupy a significant amount of spectrum relative to the symbol rate. This characteristic is not a problem given the carriers can overlap. The slow sin(x)/x rolloff is really only an issue at the edge of the channel. Standards like 802.11A allow the RECT pulse to be modified such the the rising and falling edges are softer. This helps constrain the spectrum without affecting data transmission.



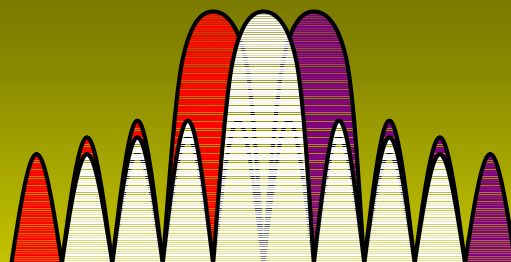
As was mentioned, in FDM systems, the channel spacing is typically greater than the symbol rate to avoid overlapped spectrums. In OFDM the carriers are orthogonal and overlap without interfering with one another. The idea is similar to that of Nyquist filtered SCM signals. The symbols in a single-carrier system overlap in the time domain, but don't interfere with one another because of the symbol (T) spacing of the zero crossings. For OFDM, the carriers have spectral null at all other carrier frequencies.

OFDM: Orthogonal Carriers



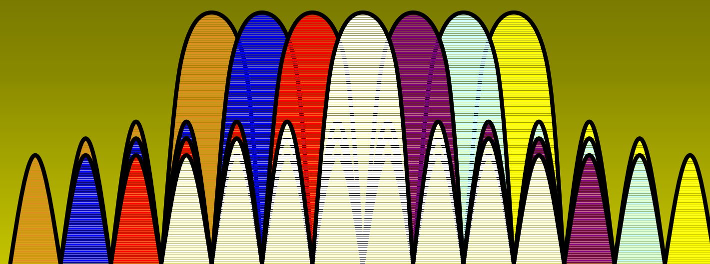
- Closely spaced carriers overlap
- Nulls in each carrier's spectrum land at the center of all other carriers for Zero Inter-Carrier Interference

OFDM: Orthogonal Carriers



•Closely spaced carriers overlap
•Nulls in each carrier's spectrum land at the center of all other carriers for Zero Inter-Carrier Interference

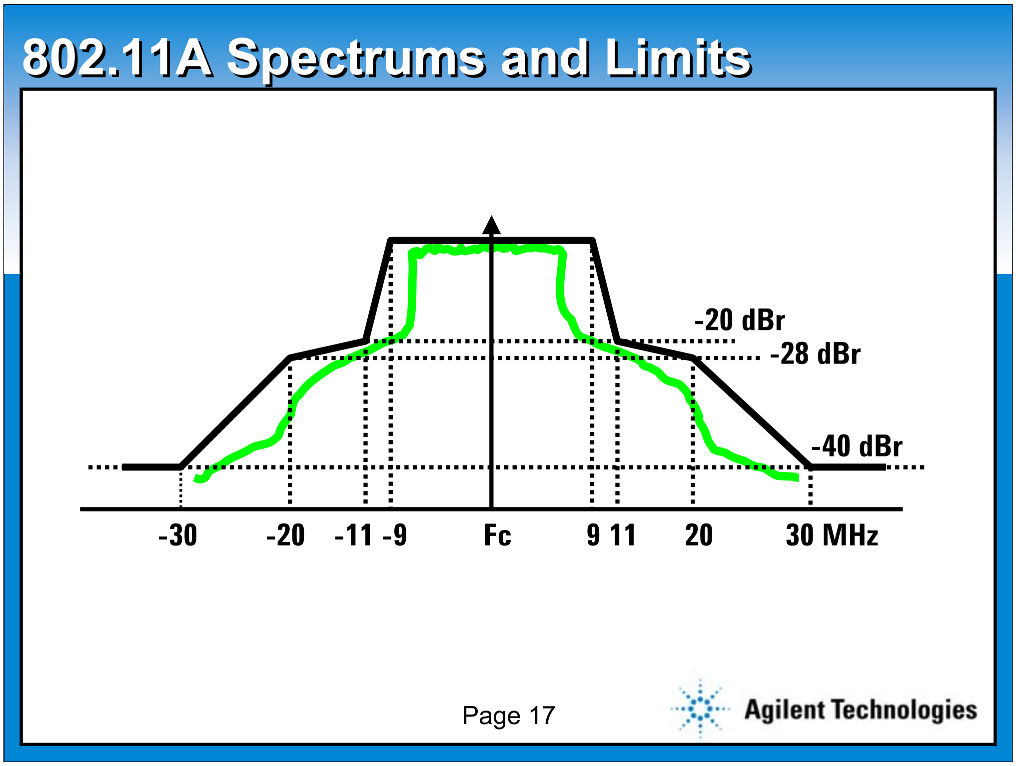
OFDM: Orthogonal Carriers



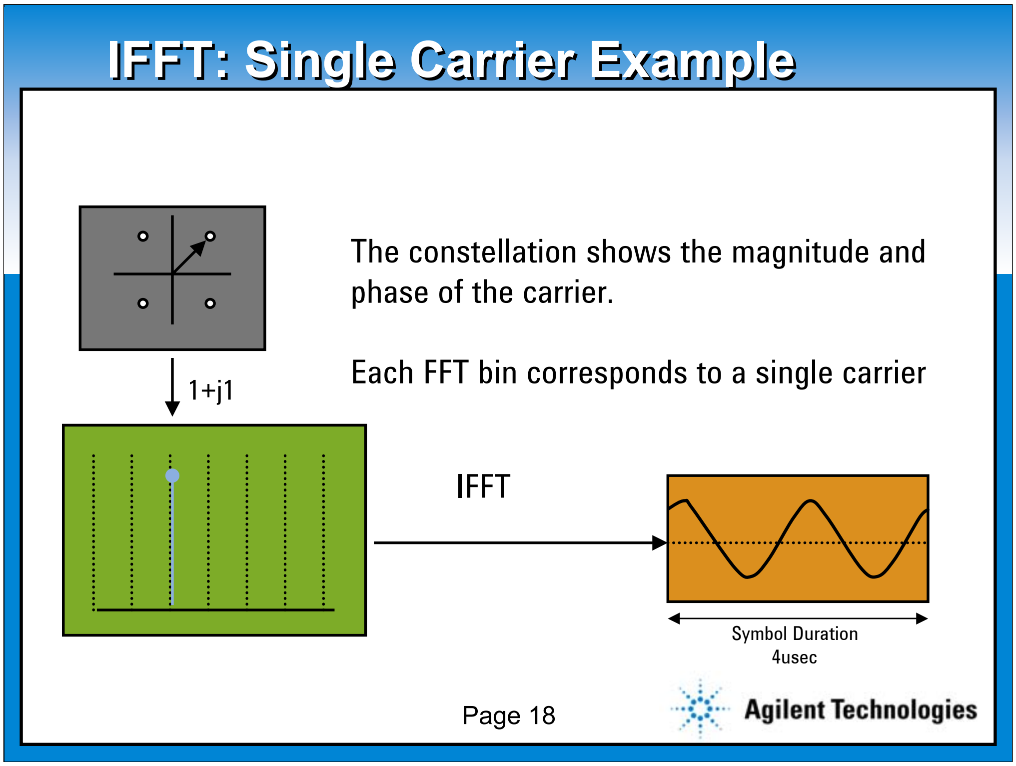
•Closely spaced carriers overlap

•Nulls in each carrier's spectrum land at the center of all other carriers for Zero Inter-Carrier Interference

Agilent Technologies

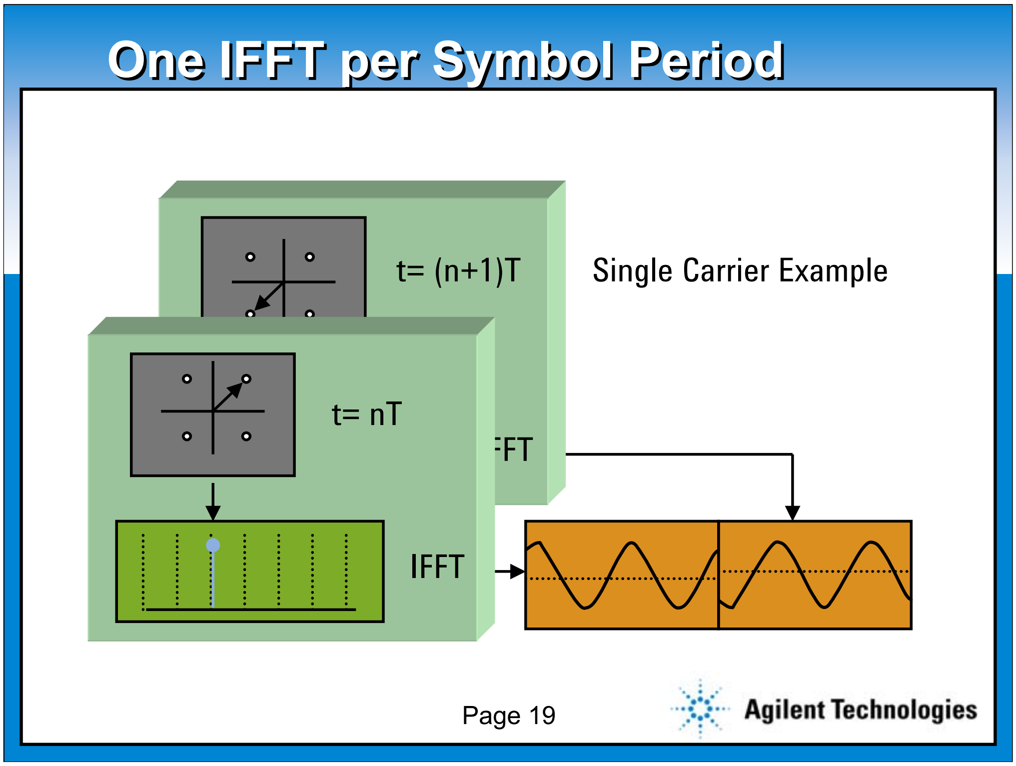


As you can see, the OFDM spectrum is very flat across the top. As drawn in the 802.11A standard, you might think the sidelobes were caused by third-order distortion. In fact, the sidelobe structure of this signal is part of the modulation as was shown in the previous slide.

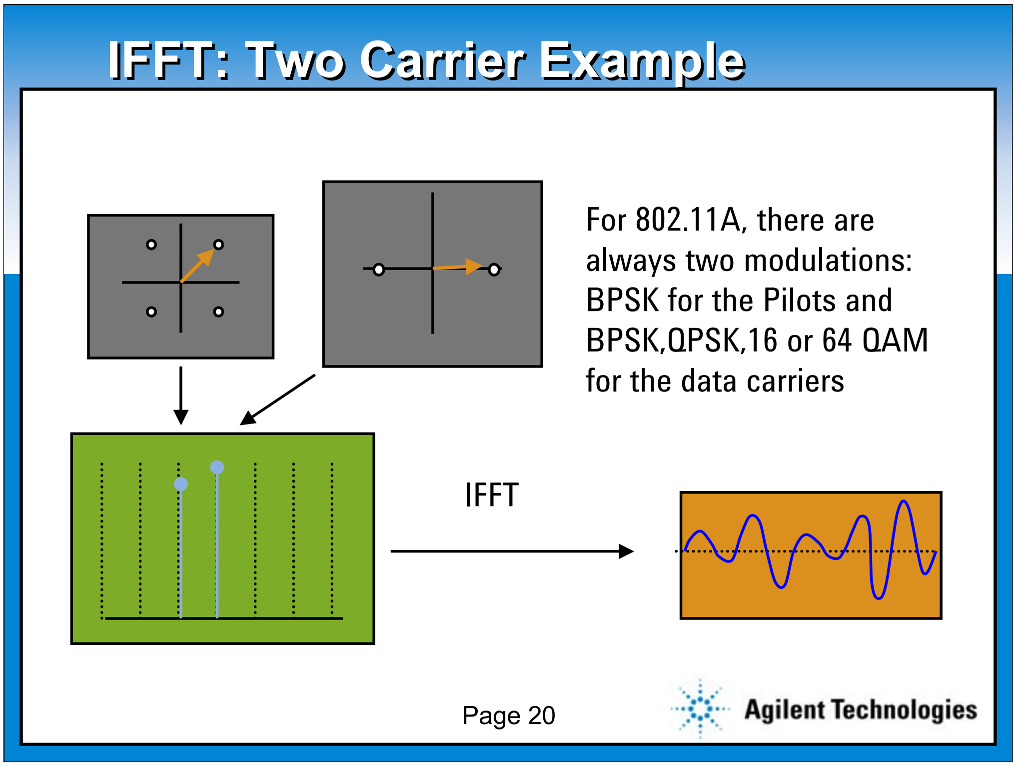


If you know a little about FFT's, the concepts behing OFDM should be very simple to understand. In this example we are going to create an OFDM signal with only one carrier. The magnitude and phase of the carrier are determined from the symbol to be transmitted, as shown in the constellation diagram. The complex number representing the symbol is loaded into an FFT buffer, and an inverse-FFT performed. This produces a set of time-domain samples. These samples are then transmitted.
In 802.11A and HIPERLAN/II the FFT size is 64. 52 of the FFT bins are loaded with data and pilots. After the IFFT, all 64 time samples are transmitted.

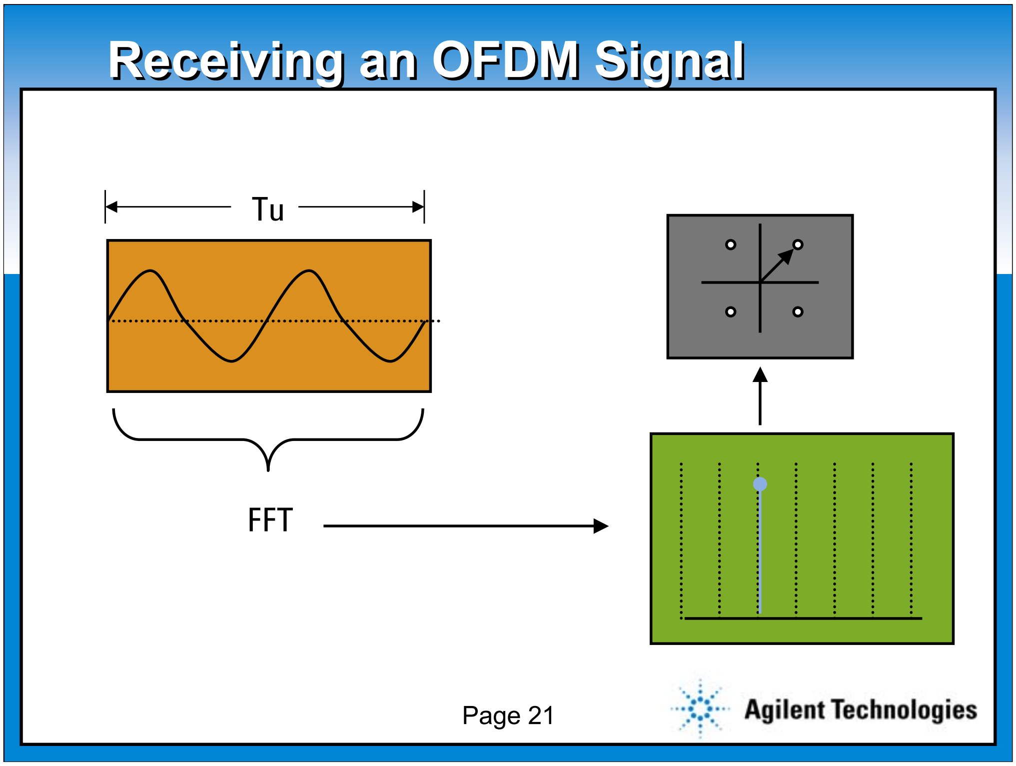
Note: For simplicity this is shown using a baseband FFT where the left most bin represents DC. In real systems, a complex IFFT is used where the center bin is DC and equates to the carrier frequency.



Continuing with the single carrier OFDM example, while the first pulse is being transmitted, the next symbol is loaded into the FFT buffer. Notice that the resulting pulse, when joined with the first, results in a discontinuity. This is normal. The resulting spectral splatter can be attenuated somewhat by windowing the data, as described in the 802.11A standard.



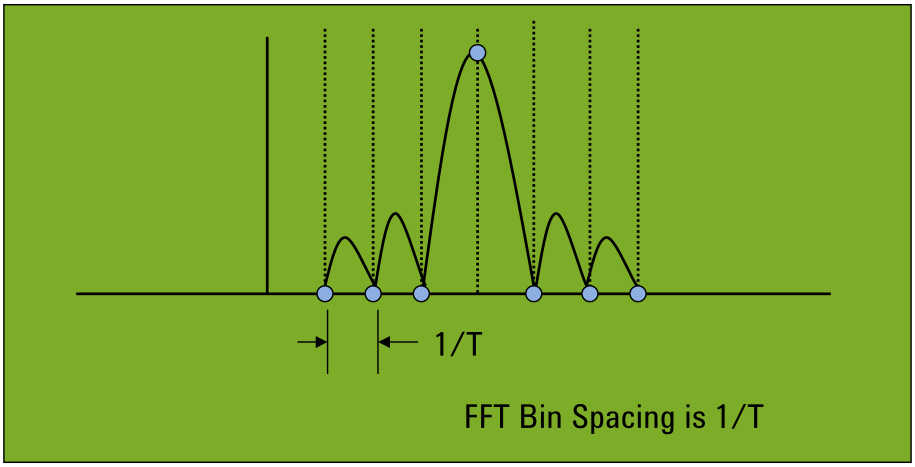
This diagram shows how a multi-carrier OFDM signal is generated, and how easy it is to have many different modulation formats. In the limit, every carrier could be different! As more carriers are added, the resulting time waveform becomes more complex. This is one of the problems with OFDM. As we'll show later, the addition of multiple carriers results in a signal with a high peak-to-average power ratio.



At the receiver, ignoring channel affects, the time waveform is digitized and an then converted back to a symbol using an FFT.
The FFT is a critical part of the demodulation scheme. When more than one carrier is present, it is the only practical method for recovering the data from overlapping carriers. It is not possible, for example, to use a single-carrier 64 QAM receiver to demodulate a 64 QAM carrier in an OFDM system.

Receiver FFT

Nulls are *On Bin* if the Tone is *On Bin*



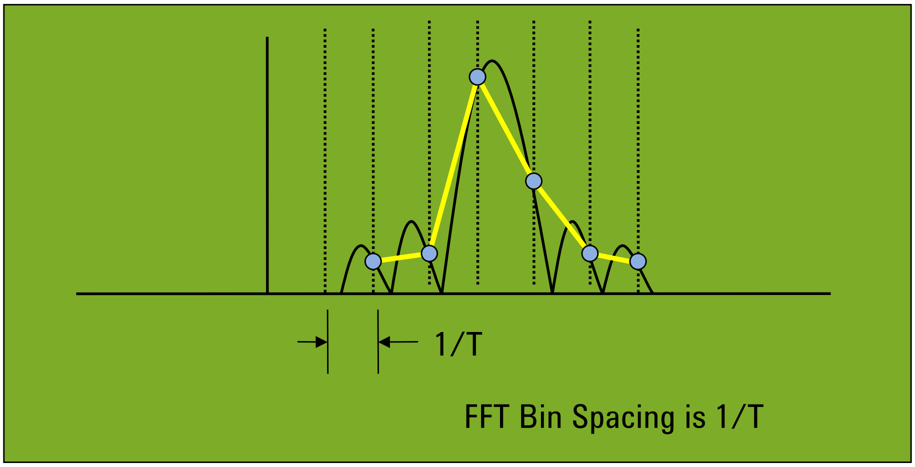
Agilent Technologies

There are many ways to consider the orthogonality properties in OFDM. Thinking in terms of FFT's, a signal that is perfectly periodic in the FFT time record has nulls in adjacent FFT bins.

The reason that OFDM is more sensitive to phase noise should now be obvious. The phase noise is an additional modulation which will modify the sin(x)/x spectrum, reducing the depth of the nulls, and creating interference to other carriers (not shown).

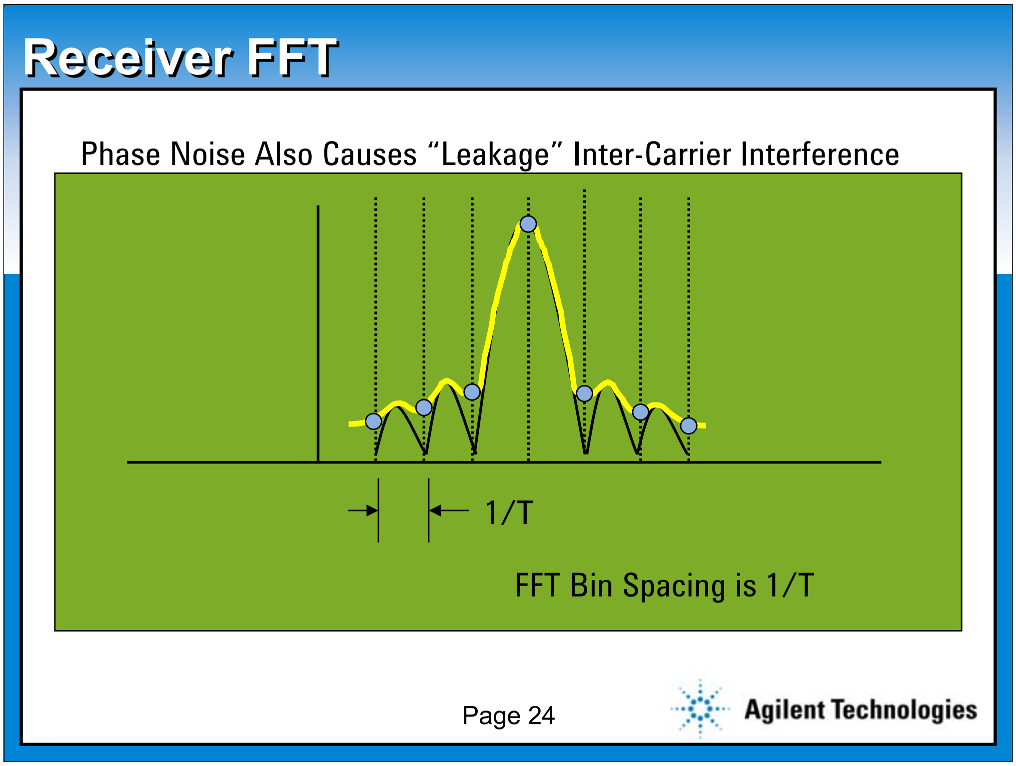
Loss of Carrier Orthogonality

Frequency Errors Cause "Leakage" or Inter-Carrier Interference



Agilent Technologies

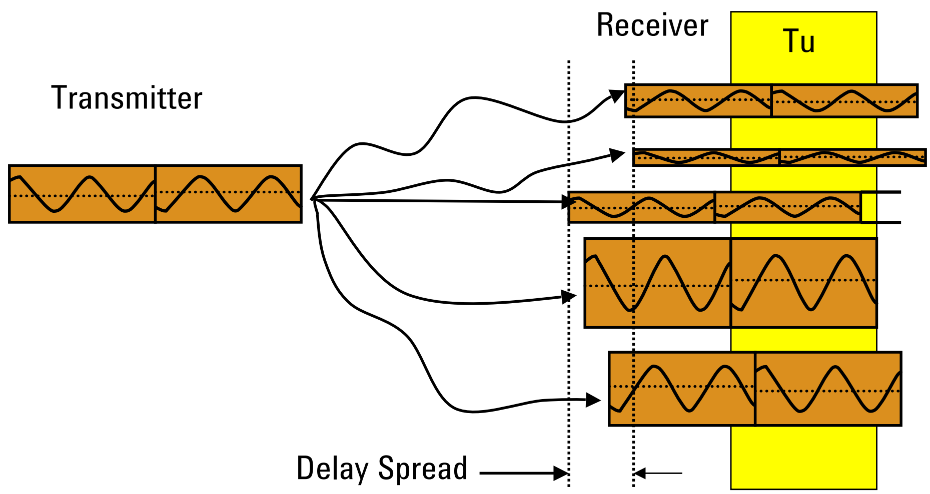
This diagram shows how critical receiver frequency tracking is. If the receiver is off frequency, then the nulls in each carrier won't land on an FFT bin. In FFT terminology this is called leakage. For OFDM, the result is inter-carrier interference.



There are many ways to consider the orthogonality properties in OFDM. Thinking in terms of FFT's, a signal that is perfectly periodic in the FFT time record has nulls in adjacent FFT bins.

The reason that OFDM is more sensitive to phase noise should now be obvious. The phase noise is an additional modulation which will modify the sin(x)/x spectrum, reducing the depth of the nulls, and creating interference to other carriers (not shown).

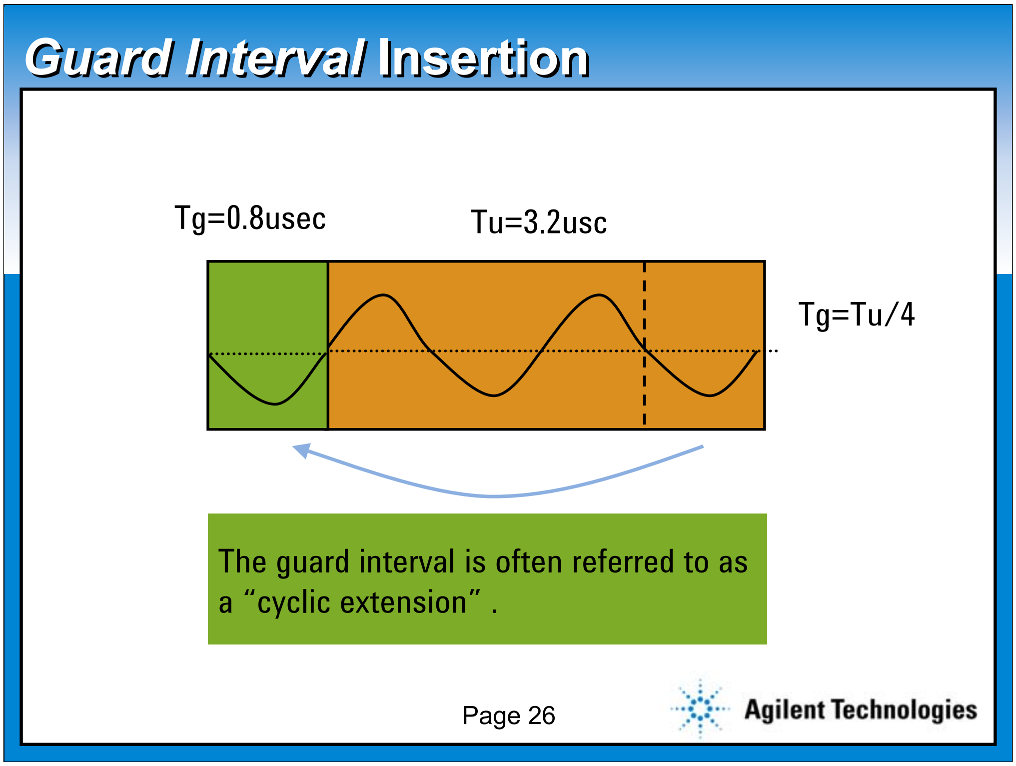
Dealing With Multipath



Page 25

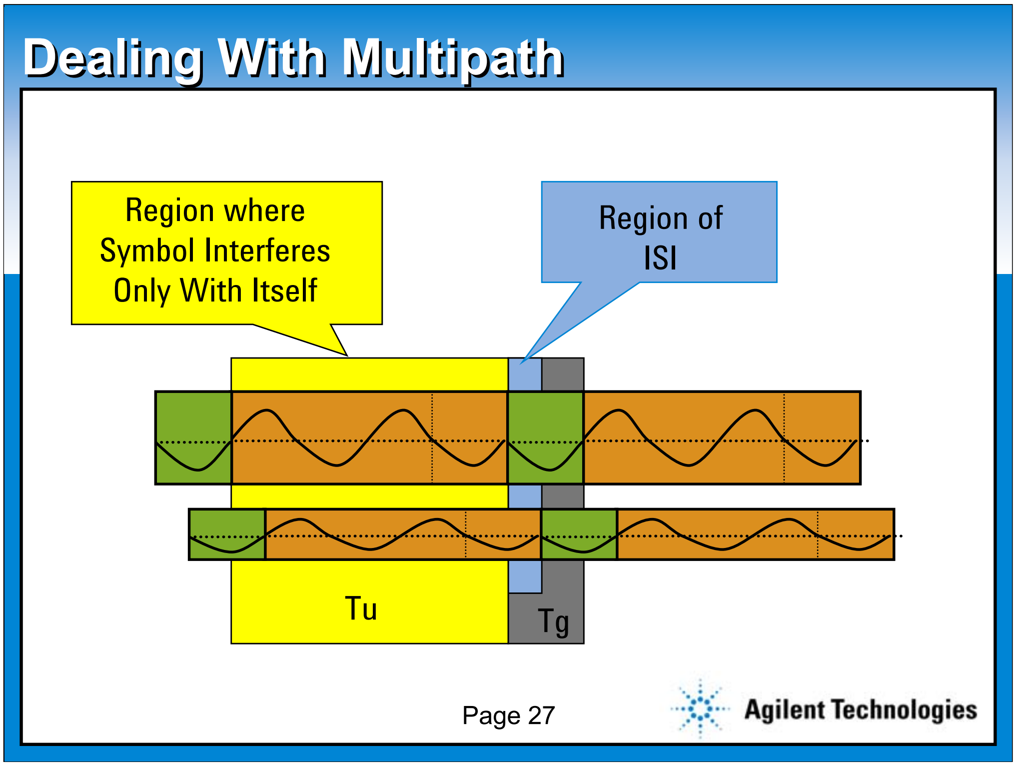
Agilent Technologies

Up to this point we've neglected the signal path. The simple OFDM signal that we've generated in this example won't work under multipath conditions. As you can see from the diagram, if we align the FFT with the biggest signal, then the other signal paths will introduce ISI.



We started by splicing the two pulses from subsequent symbols together. As we’ve shown, this won’t work in practice because the channel will still introduce ISI between pulses. To combat this problem, the pulse is modified by a technique know as ***cyclic extension***. In this process, the last part of the pulse (typically 1/16 to 1/4) is copied and attached to the beginning of the burst. Due to the periodic nature of the FFT, the junction at the start of the original burst will always be continuous. However, the signal will still suffer from discontinuities at the junctions between adjacent symbols.

As an aside, if this were a continuous pilot, this same symbol and extension would be repeated. Because there is only 1/2 of a cycle in the guard interval, the carrier is not phase continuous. If we were on a carrier with 4 cycles in the useful part, then a 1/4 guard interval would contain one complete cycle and the continuous pilot would also be phase continuous.



This drawing illustrates how the addition of a guard interval helps with ISI. Shown are two copies of the same signal. Each copy took a different path so they will arrive at the receiver at slightly different times where they will be combined in the receiver's antenna into a single signal. In the time interval denoted by the yellow box marked Tu, a symbol will only interfere with itself. This amounts to a scaling and rotation of the symbol, nothing more.

In the guard interval region(Tg), it's easy to see that the resulting signal will have contributions from both symbols -- ISI. The guard interval is ignored in the receiver, so the ISI does not degrade receiver performance.

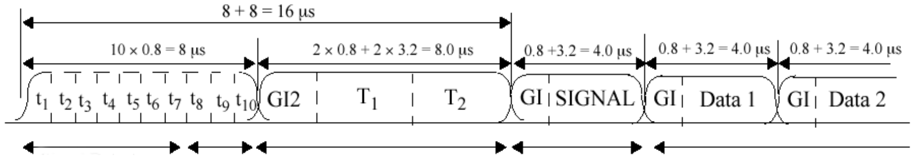
Obviously the guard interval needs to be larger than the delay spread, but not so long that throughput is lost. In the 802.11A standard, the guard interval is fixed at 1/4.

Delay spread is not limited to positive delays. In non line-of-site conditions, the shortest path may not be the strongest. The implications on OFDM receivers is that the FFT may not be perfectly aligned with the useful part of the burst (as it's often called). Instead the receiver will shift the FFT location to the left using part of the guard interval instead of the end of the useful part. In some OFDM standards, a cyclic post-fix is explicitly added. This shifting does not appear to be allowed in the 802.11A modulation accuracy test, so linear distortion which introduces ISI within the useful part of the burst will increase EVM.

Synchronization and Equalization

- **DVB-T Pilots: Spaced in frequency and time. The equalizer is a 2-D filter**
- **802.11A uses training symbols at the beginning of the burst transmission.**
- **DAB uses DQPSK so channel gain and phase is not an issue. No equalization required!**
- **In systems with pilots, the *Common Phase Error* of is used to track close-in phase noise**

802.11A OFDM Training Structure



Signal Detect
Coarse Freq.
AGC
Diversity

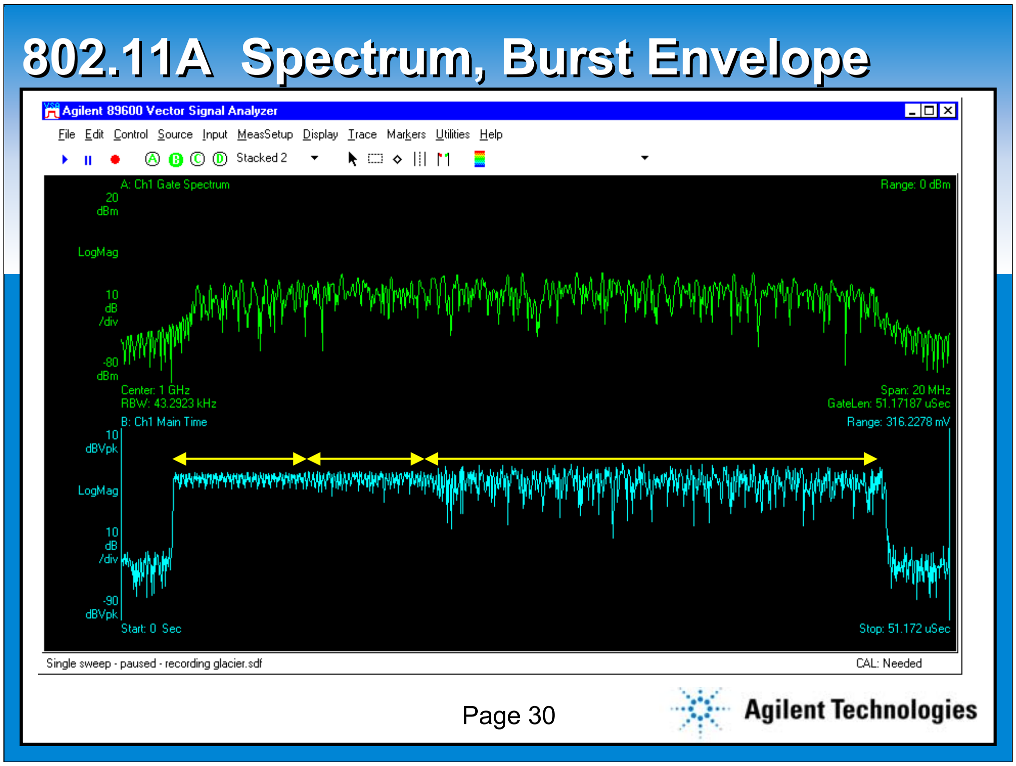
Channel Est.
Fine Freq.

Rate
Length

Data...

Note Raised Cosine Pulse Shaping

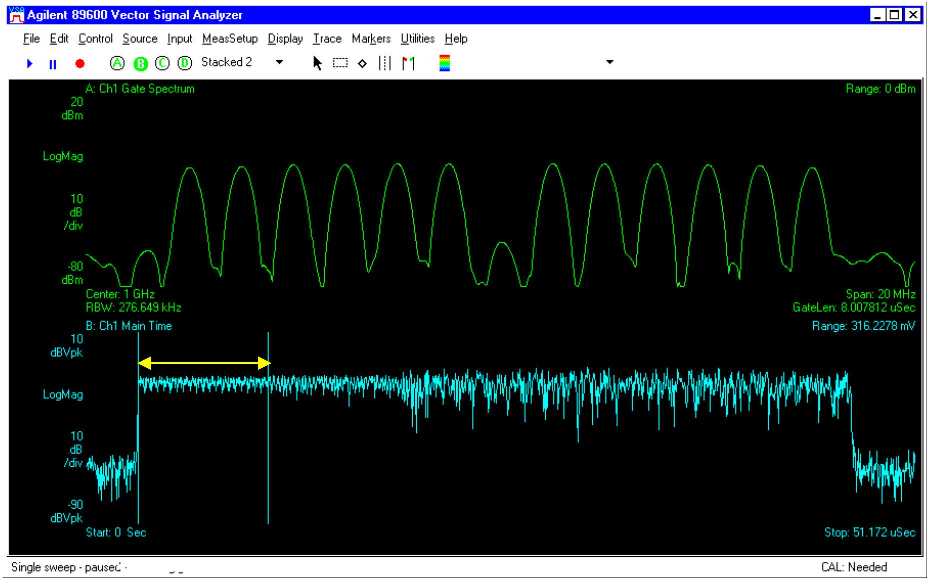
The 802.11A OFDM burst actually has four distinct regions. The first is the *Short training sequence*. This is followed by a *Long training sequence* and finally by the *Signal* and *Data symbols*.
From an RF standpoint the Signal Symbol and the rest of the OFDM symbols are similar.



This measurement shows an 802.11A burst. The sidelobe structure caused by the sin(x)/x spectrums of the individual carriers is clearly visible in the spectrum plot. Note that spectrum is not very uniform. This is caused in part by the preambles, but mostly by the data being transmitted.

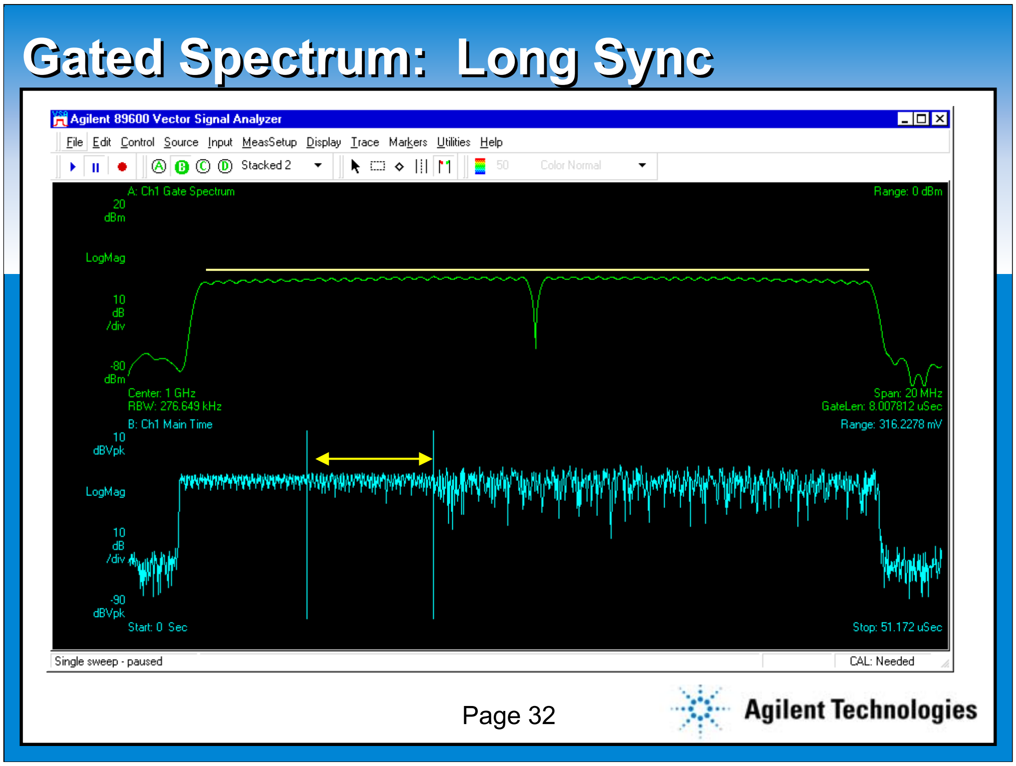
In the power-verses-time (PvT) plot in the lower trace, three distinct regions of the burst are visible.

Gated Spectrum: Short Sync

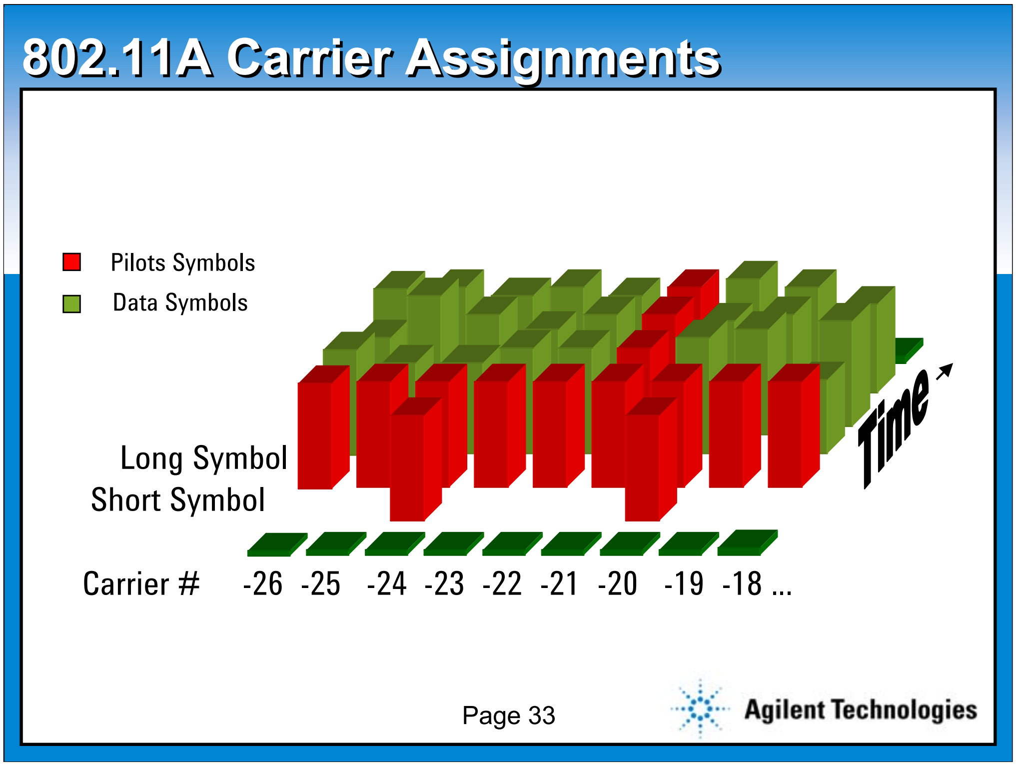


Agilent Technologies

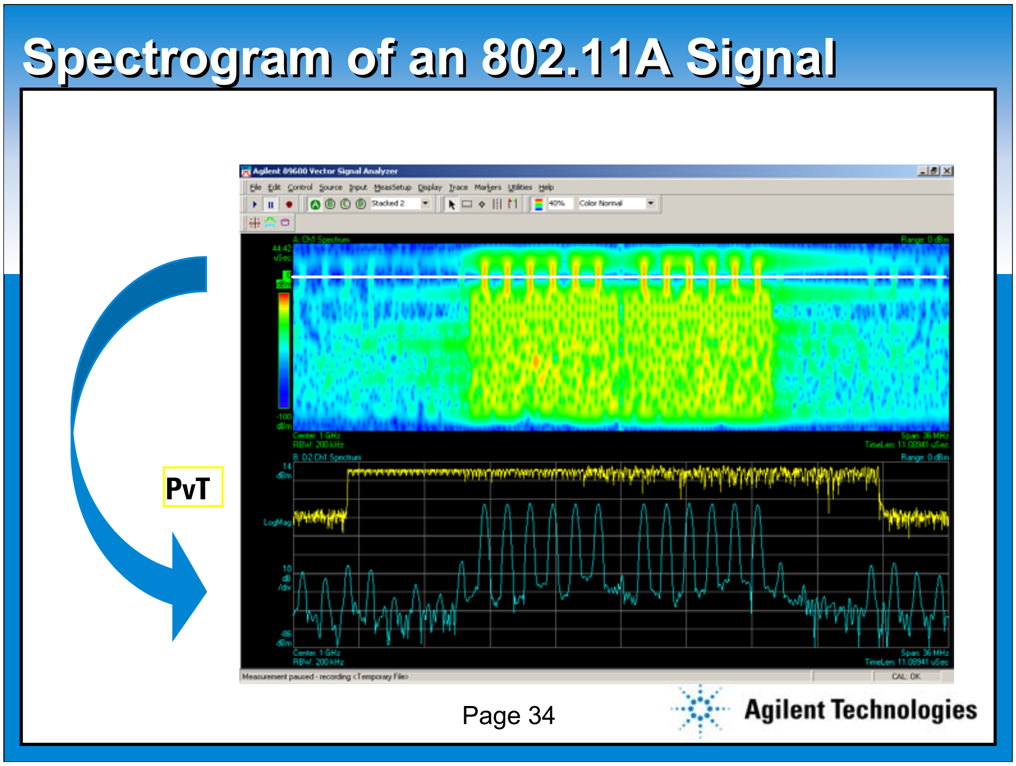
Using the gate markers we can look at the spectrum of the short training symbol. This symbol uses every 4th carrier so the carriers are widely spaced. The wide carrier spacing of the short symbol makes the short-training symbol interval ideal for easy carrier leakage measurements.



Moving the gate markers over to the long training symbol we see that the spectrum is nice and flat (or it should be). For this symbol, all of the carriers (save the one in the center which isn't used) have the same amplitude. The signal flatness is easily measured using the long training symbol interval.



It useful to consider OFDM from a 2-dimensional standpoint. Here we can see the short sequence, which uses every fourth carrier, followed by the long sequence and finally be the data carriers. In 802.11A four of the 52 carriers in the data portion of the burst are pilots (only one is shown here). The data carriers change in power level on a symbol-by-symbol basis when 16 or 64 QAM is used.



Using spectrograms, we can actually observe the spectral characteristics of the OFDM signals as a function of time. The lower trace shows the spectrum at a point in time indicated by the horizontal line in the upper trace. The top of the upper trace corresponds to the beginning of the burst.

The short sequence using every fourth carrier is clearly visible, as is the discrete tones in the resulting sidebands. Also visibile is the spectral splatter caused by the discontinuities between symbols. The later is most visible at the junction between the short and long syncs. For reference, the power-verses-time plot is show in the upper part of the lower grid.

Given the adjacent channel characteristics of this signal, it would be dangerous to model the effects on an adjacent channel signal assuming AWGN.

OFDM

Table 78—Rate-dependent parameters

Data rate (Mbits/s)	Modulation	Coding rate (R)	Coded bits per subcarrier (N_{BPSC})	Coded bits per OFDM symbol (N_{CBPS})	Data bits per OFDM symbol (N_{DBPS})
6	BPSK	1/2	1	48	24
9	BPSK	3/4	1	48	36
12	QPSK	1/2	2	96	48
18	QPSK	3/4	2	96	72
24	16-QAM	1/2	4	192	96
36	16-QAM	3/4	4	192	144
48	64-QAM	2/3	6	288	192
54	64-QAM	3/4	6	288	216

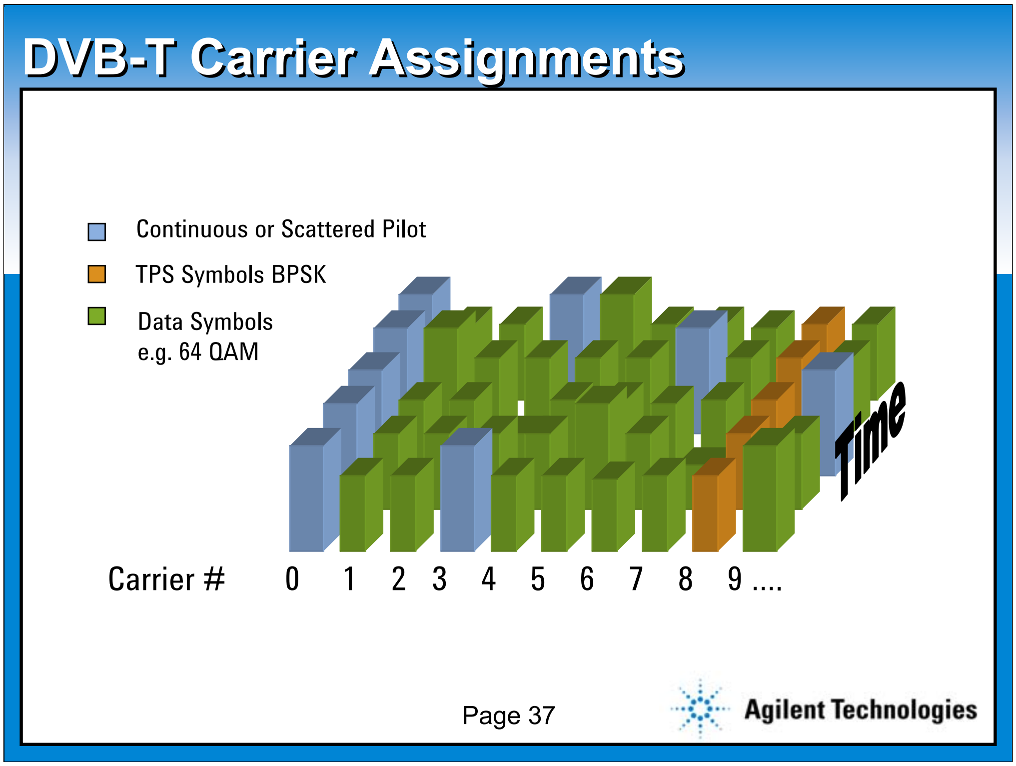
Agilent Technologies

In 802.11A, the data carriers can be BPSK, QPSK, 16QAM and 64QAM modulated. In some standards you'll find all of these transmitted at the same time! In 802.11A, only two modulation formats are used simultaneously -- BPSK and one of the previously mentioned formats.

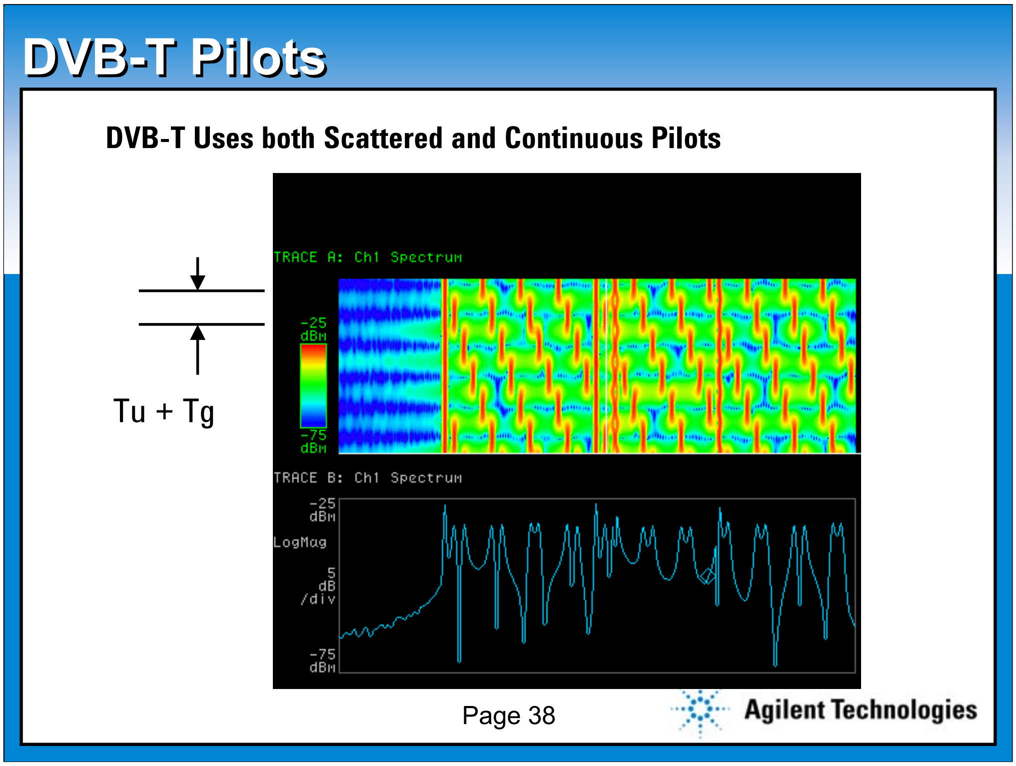
DVB-T Carrier Types

- Continuous Pilots: BPSK, a given carrier always transmits the same symbol
- Data Carriers: Various forms of QAM up to 64 QAM
- Data + Scattered Pilots: Data as above, Scattered pilots are BPSK
- TPS: Transmit system information on BPSK carriers, lower power than pilots

DVB-T makes more extensive use of pilots. Unlike 802.11A, the DVB-T pilots provide a continuous sampling of the channel in both time and frequency.
The pilots are BPSK modulated, as are the TPS carriers which transmit system information. The power levels between the two types of BPSK are different.



Using a diagram similar to the one used for 802.11A you can see the continuous pilots along the left edge and scattered pilots throughout.



To create this plot, the data carriers were turned off. The following characteristics are clearly visible:

-- The spectral splatter caused by phase discontinuities between symbol intervals

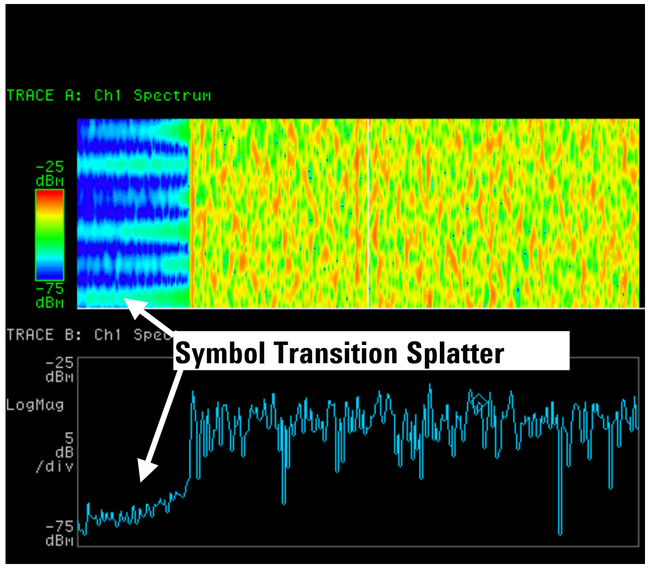
-- The phase continuous, continuous pilots

-- The phase discontinuous, continuous pilots

-- The scattered pilots.

Recall that a phase discontinuous, continuous pilots is a pilot where the same symbol is continuously transmitted, but because the guard interval doesn't contain an integer number of cycles, is not phase continuous between symbol intervals.

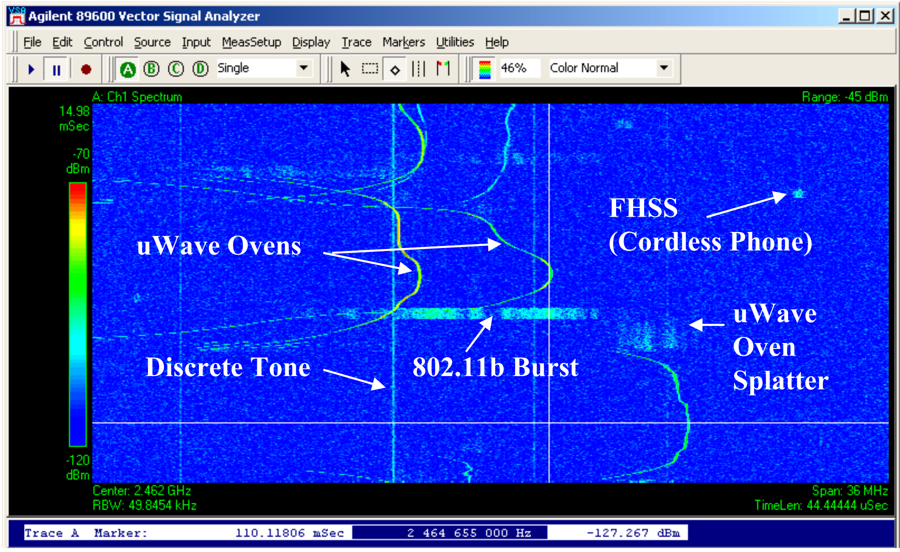
DVB-T Signal with Data & Pilots



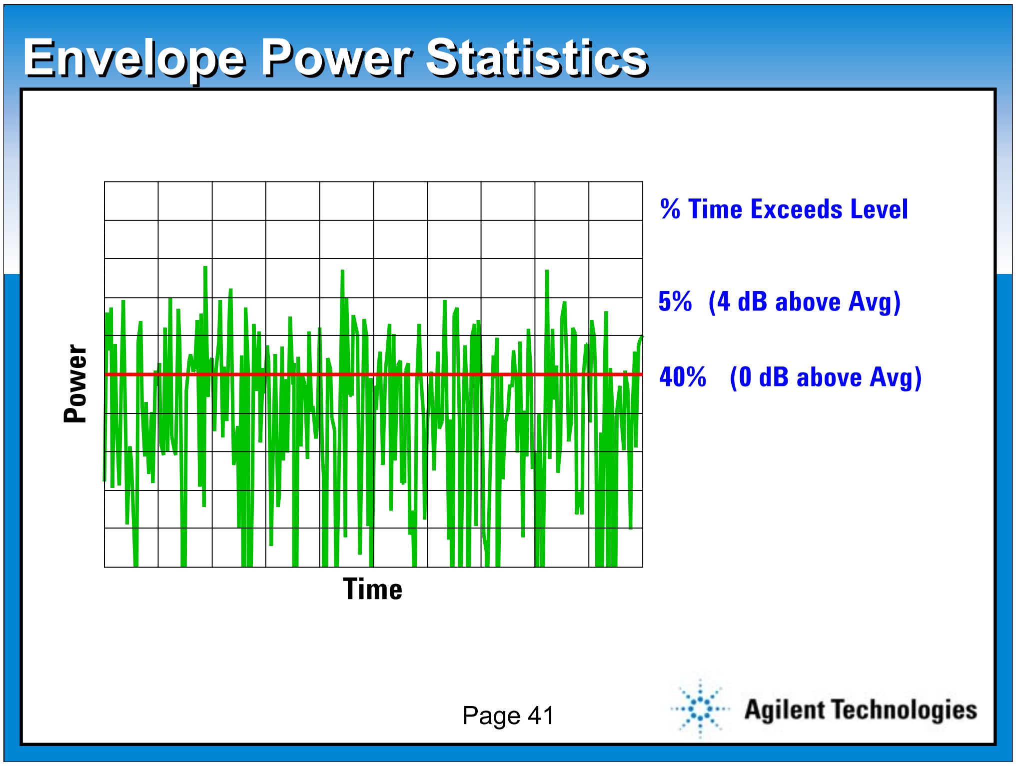
Agilent Technologies

This spectrogram plot is the same as before except with the data carriers enabled. The periodic splatter at the symbol transitions is still clearly visible. Less visible are the continuous pilots. Scattered pilots are now impossible to detect.

OFDM at 2.4GHz??

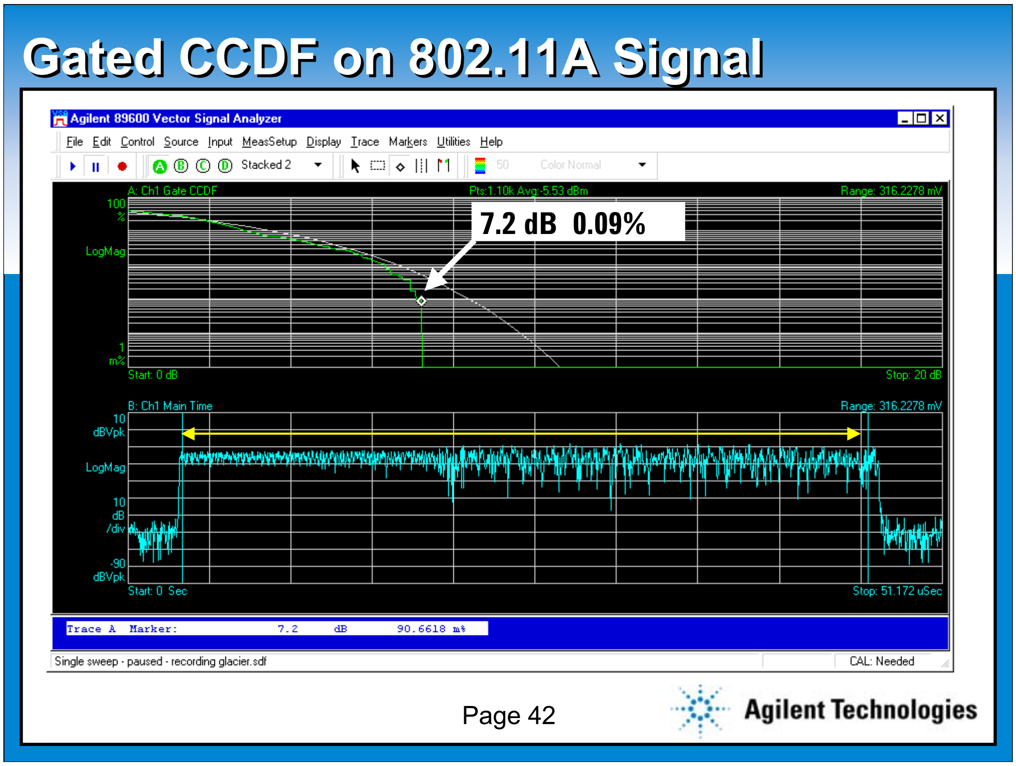


Agilent Technologies



The OFDM signal represents the vector additions of a large number of relatively uncorrelated carriers. For this reason the power envelope of an OFDM signal is not constant. Often a single metric, peak-to-average ratio (PAR) is used to describe the amount of headroom required in an amplifier. For OFDM signals, this metric is not very useful as the “real peak”, whatever that is, may not occur very often.

It’s usually more meaningful for OFDM signals to associate a percentage probability with a power level. For example, in the plot shown, the signal exceeds the average power (red line) 40% of the time. (It would be 50% only if the mean and median were identical). It exceeds a level that is 4 dB above the average, 5% of the time. In other words, if we ran this particular signal through a PA with 4 dB of headroom, or back-off, the signal would clip 5 % of the time. This is more useful than knowing that the peak-to-average for this signal is 8dB.

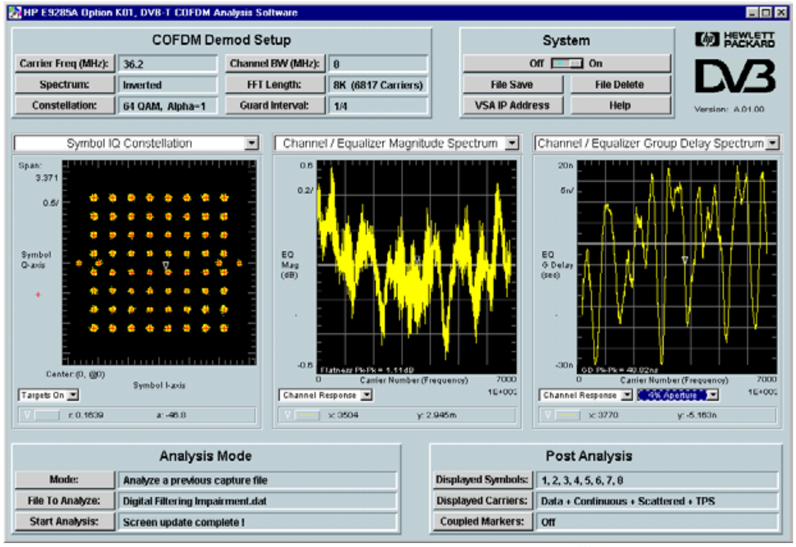


The best way to look at power statistics is with the complementary cumulative distribution function (CCDF). In this measurement, the gate markers are used to select the active portion of the 802.11A burst. If this wasn't done, the periods when the burst is off would bias down the average power calculation.

The CCDF, which is simply the more common CDF subtracted from 1.0, shows dB above average power on the horizontal axis, and percent probability on vertical axis. The marker shows that, for this one burst, the signal exceeds 7.2 dB above average 0.09% of the time. Normally, the CCDF measurement would be made over several bursts to improve the confidence interval on the low probability peaks.

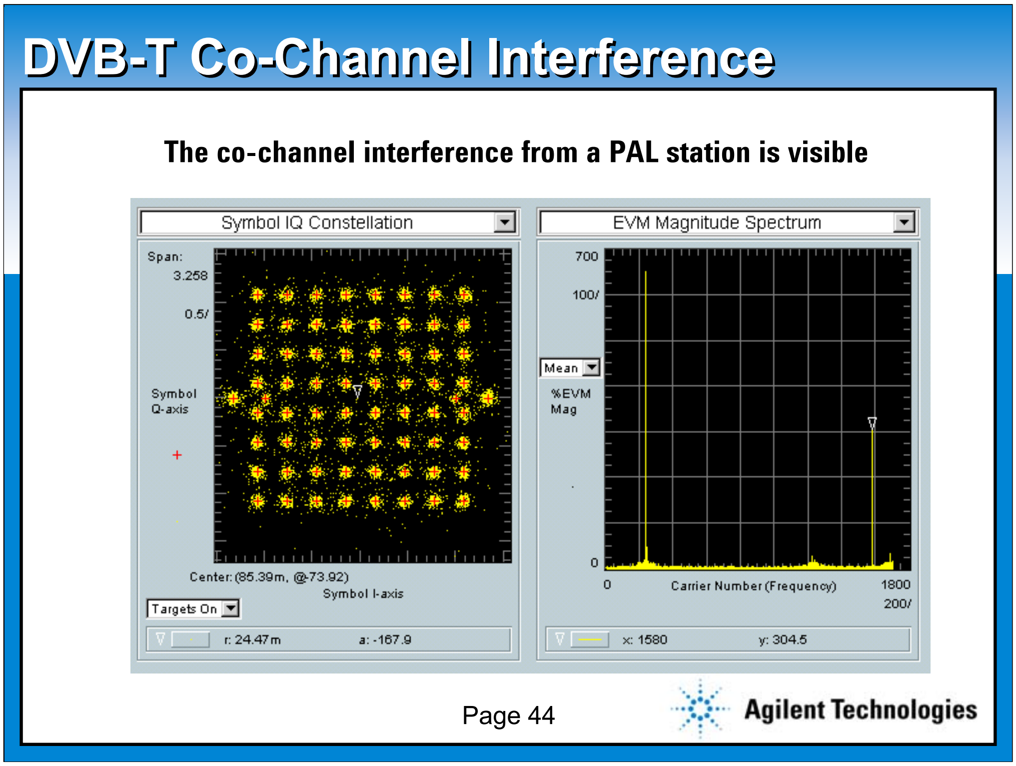
The curved graticule line represents the statistics for Gaussian noise. Most OFDM signals will have statistics that follow that line very closely.

DVB-T Measurement Software



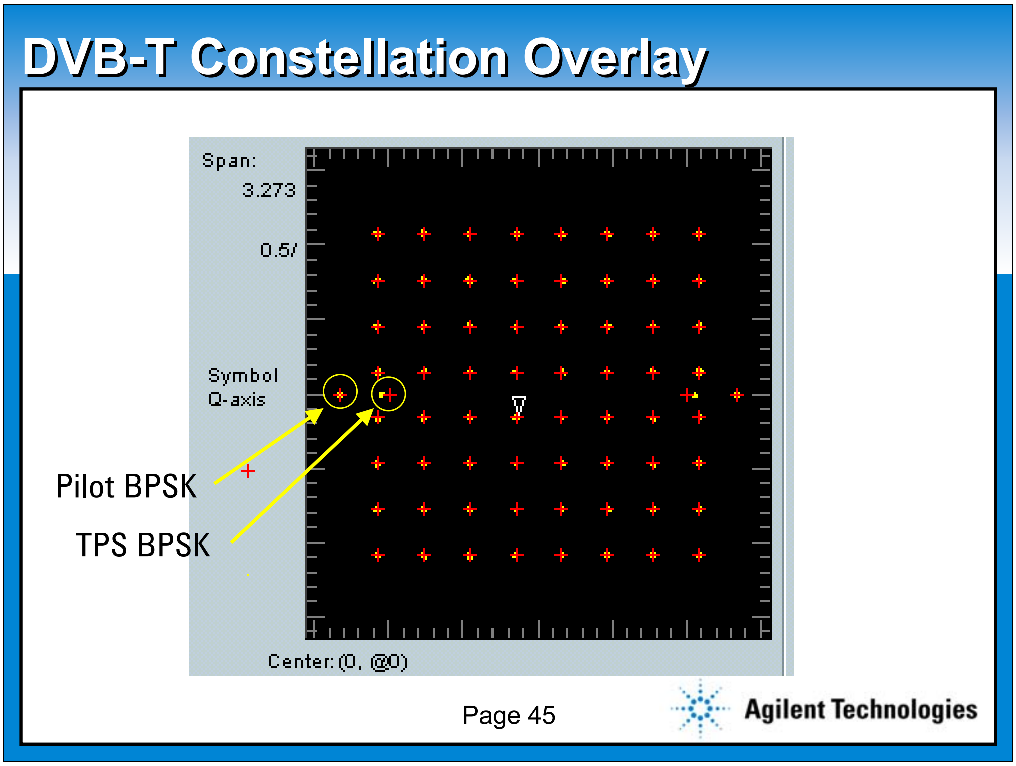
Agilent Technologies

When measuring OFDM signals, it's often useful to look at the constellation and the adaptive equalizer coefficients. The constellation display shows symbols for all carriers over a number of symbol intervals. Since all carriers are shown, you can see the 64 QAM signal, as well as the BPSK pilots, and the lower power level TPS BPSK carriers.



Another measurement result which can be very useful for troubleshooting is the EVM spectrum. This is a plot of the error as a function of frequency. Here the picture, sound and chroma carriers of an analog television signal on the same channels as this OFDM signal, are clearly visible.

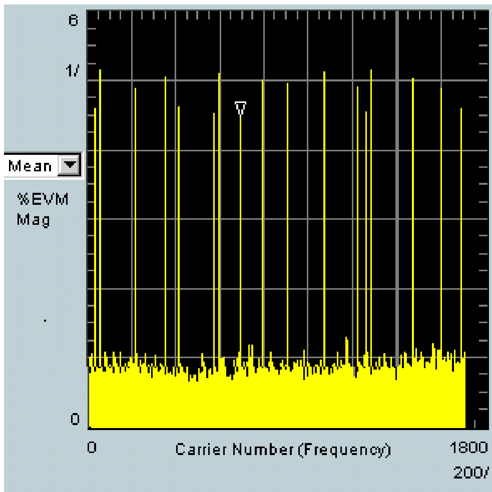
Even though the picture carrier of the analog station is quite strong, the OFDM signal is easily demodulated. The co-channel interference only interferes with a few of this OFDM signals 1700 carriers.



In both 802.11A and DVB-T, the pilots serve as a reference for scaling the signal. It's very important that the scaling for the data carriers to be correct with respect to the pilots. Here the TPS carriers are shown to have the wrong scaling.

EVM Spectrum

Spikes are TPS carriers

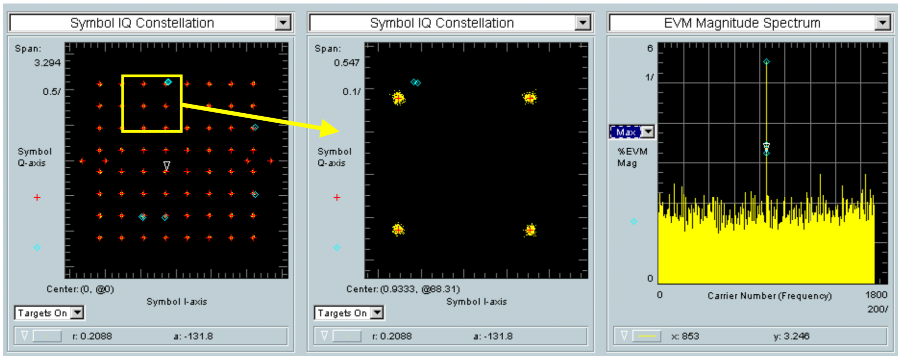


TPS carriers have a large error because they are at the wrong amplitude in this particular signal

Agilent Technologies

The improper scaling of the TPS carriers makes those carriers easy to find in the EVM spectrum plot.

DVB-T Carrier Leakage

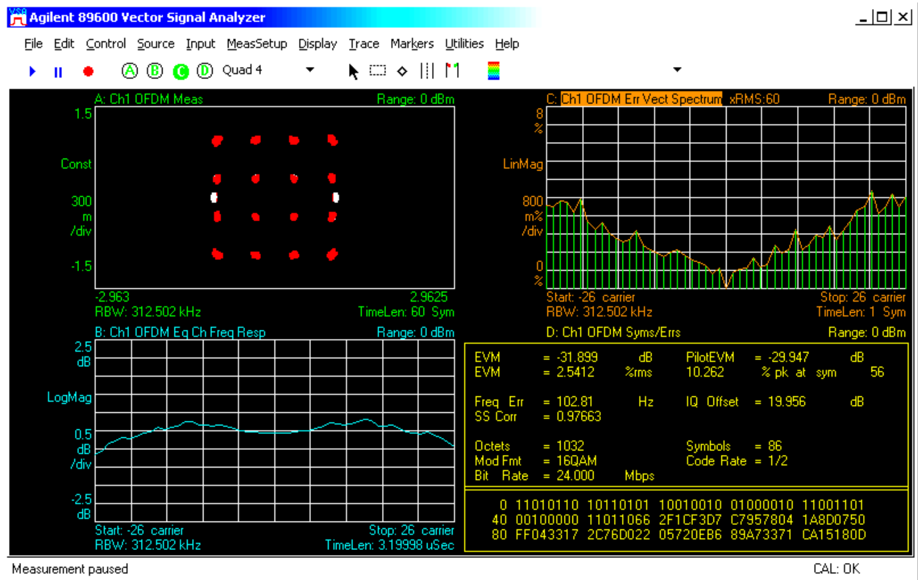


The markers are at the peak errors, which all occur on the center carrier. Note that LO leakage is a DC term, so the errors are all in the same direction

Agilent Technologies

Unlike 802.11A, DVB-T uses the center carrier to transmit information. This carrier is susceptible to interference from carrier feedthrough, or DC signals in an analog IQ modulator.

New! Demod Analysis for WLAN



Agilent Technologies

This plot shows an 802.11A OFDM constellation in the upper trace. As was done for the DVB-T signal, this is a composite plot of all carriers over all symbols. The constellation is a composite of the BPSK carriers and the 16QAM carriers. Also show ,in the lower trace, is the adaptive equalizer response. In 802.11A, the long training symbol is used to train an equalizer. This is a required step in the measurement process. The complex equalizer result can be viewed as magnitude, phase or group delay. The magnitude and phase responses are shown above. The equalizer result is a good measure of transmitted flatness and carrier power levels.

Summary

- OFDM is displacing SCM in many applications because of its performance under multipath conditions, and the ease with which it adapts to smart antenna technology
- The format requires more linearity in the amplifiers because of the higher peak-to-average ratio

Agilent Technologies

Summary (Cont)

- Better phase noise performance is required because of the closely spaced, overlapping carriers
- Measurement tools are available which can help design and troubleshoot OFDM signals and systems.