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RFCM 201: WLAN Fundamentals

Agilent Technologies

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RFCM 201: WLAN Fundamentals

Welcome to RFCM 201, on the fundamentals of WLAN. This would take you about 45 minutes to study. We strongly recommend that you study RFCM 102 – Introduction to Digital Communications, if you are not completely familiar with digital wireless communications.

Agenda

- •WLAN Technology Overview
- •MAC Layer Briefly…
- •Analyzing Transmitter Performance
- •Testing Receiver Performance
- •Summary of Measurement Solutions
- •Q&A

This seminar gives the engineer a deep perspective on the PHY layer of wireless LAN as described in IEEE 802.11. The tests on PHY layer are described and measurement solutions proposed.

What Is Wireless Local Area Network?

A Wireless Local Area Network (WLAN) is a **high bandwidth**, two-way data communications network.

It operates over a **limited geographic area** using radio as the transmission medium, rather than optical fiber or copper cable.

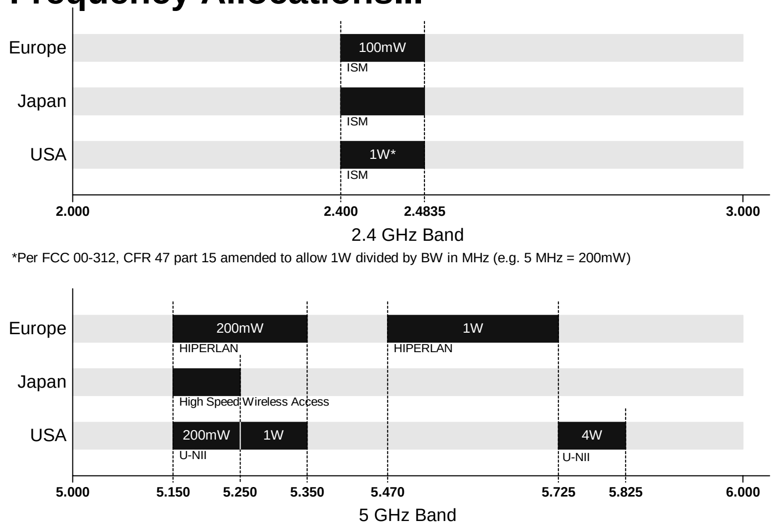
It serves as an extension to, or as an alternative for, a wired LAN.

It combines data connectivity with **user mobility**.

What is Wireless Local Area Network?

Wireless Local Area Network technologies emerged in the 1980s as a high bandwidth, two-way data communications network operating over a limited geographical area. By using radio as the transmission medium, Wireless LAN serves as an extension to, or as an alternative for, a wired LAN. It combines data connectivity with user mobility. By using wireless LAN, users can access shared information without having to look for a place to plug in.

The Frequency Allocations...



ISM = Industrial, Scientific and Medical
HIPERLAN = HIgh PERformance LAN
U-NII = Unlicensed National Information Infrastructure

WLAN systems operate in one of the frequency bands shown here. The maximum transmit powers are also shown. Transmit Power Control and Dynamic Frequency Selection, which are part of the HiperLAN/2 specification, will be added to 802.11a operation to satisfy regulatory requirements in Europe.

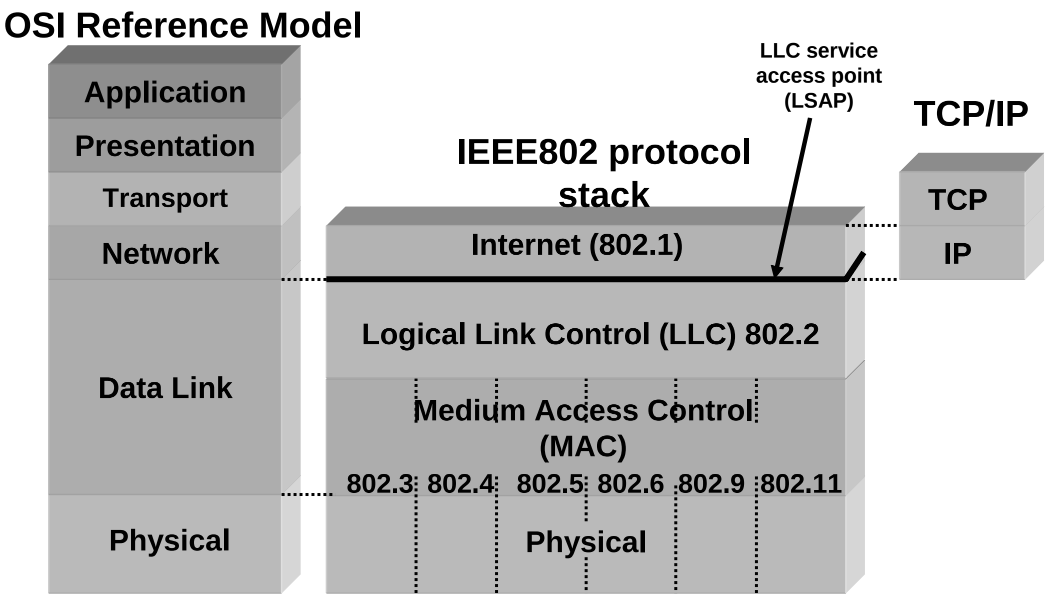
Summary of Wireless LANs Standards

Standard	Modulation	Data rates	Comments
IEEE802.11	2-GFSK or 4-GFSK FHSS BPSK or QPSK DSSS	1 or 2 Mbps	Multiple PHY including Infra red
IEEE802.11b	CCK	5.5 or 11 Mbps	Corporate favorite
IEEE802.11g	64 OFDM + BPSK, QPSK, 16QAM, 64QAM	6, 9, 12, 18, 24, 36, 48, 54 Mbps	In development, 48 and 54 Mbps will need new RF design
IEEE802.11a	64 OFDM + BPSK, QPSK, 16QAM, 64QAM	6, 9, 12, 18, 24, 36, 48, 54 Mbps	ETSI TGj/IEEE working on coexistence strategies
HIPANLAN 1	GMSK, FSK	23.5 Mbps or 1.5 Mbps	Europe only, no product, non-existence now
HIPANLAN 2	64 OFDM + BPSK, QPSK, 16QAM, 64QAM	6, 9, 12, 18, 24, 36, 48, 54 Mbps	ETSI TGj/IEEE working on coexistence strategies

Summary of Wireless LANs Standards

A summary of the modulation techniques, the data rates and some comments associated with each Wireless LAN standard is shown in this slide.

IEEE802 Protocol Layers Vs OSI Reference Model



IEEE 802 Protocol layers Vs OSI Model

Here is a comparison of the evergreen OSI Reference Model and the IEEE802 protocol stack. From the lowest layer, the IEEE802 protocol Physical layer corresponds to the OSI Physical layer. The Physical layer specifies the transmission medium, modulation and access technique as well as the topology. The IEEE802 protocol breaks up the Data Link layer into two sub-layers; Medium Access Control (MAC) and Logical Link Control (LLC) . section. The LLC user addresses are referred to as LLC Service Access Point (LSAP).

CCK Modulation: 802.11B

Form of Spread Spectrum Modulation

Extends 802.11 data rates to include 5.5 MBits/sec and 11 MBits/sec

There are three rates to keep track of:

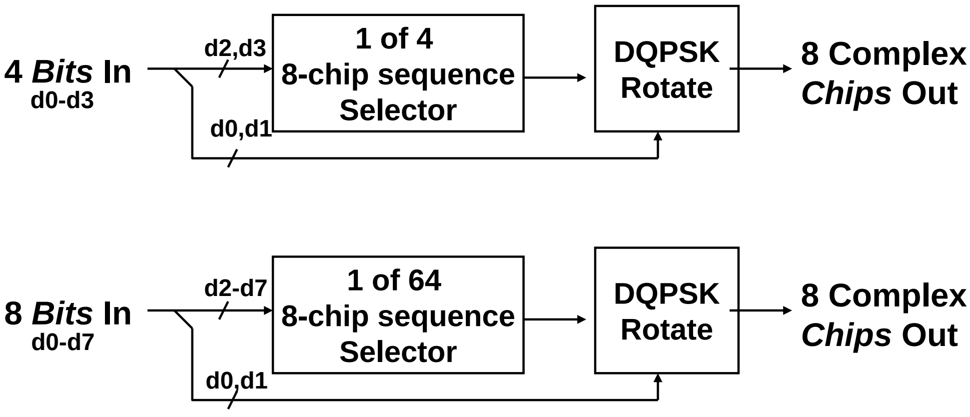
Chip Rate:	**11 MChip/sec -- always**
Bit Rates:	**1 MBit/sec DBPSK 11 chip Barker sequence**
	2 MBit/sec DQPSK 11 chip Barker sequence
	5.5 MBit/sec QPSK, 4 8-chip CCK spreading
	11 MBits/sec DQPSK, 64 8-chip spreading
Symbol Rates:	**1 MHz (11/11) and 1.375 MHz (11/8)**

At all rates, the signal looks like an 11 MHz BPSK or QPSK waveform

802.11B adds 5.5 and 11 Mbit/sec data rates to the 802.11 standard. In a rather odd twist, the progression of technology in the 802.11 standard is 802.11 to 802.11B to 802.11A., and eventually to 802.11G, which at the time of this writing, had not been defined. Many find the fact that 802.11B is slower than 802.11A confusing.

802.11B is designed for use in the 2.4 GHz "microwave oven" band. 802.11A, operates in the 5-6GHz U-NII bands, with data rates to 54 Mbits/sec. The technology behind 802.11B is direct sequence spread spectrum (DSSS). With spread spectrum technology, the chip rate can remain constant while the data rate changes to match conditions. The bit rate is varied by changing both the spreading factor and/or the modulation format. For example The 1MBit/sec rate has a spreading factor of 11 with a simple BPSK modulation. To double the bit rate to 2 Mbit/sec, QPSK is used instead of BPSK.

802.11 b Spread Spectrum Concepts
5.5 and 11 MBit/Sec

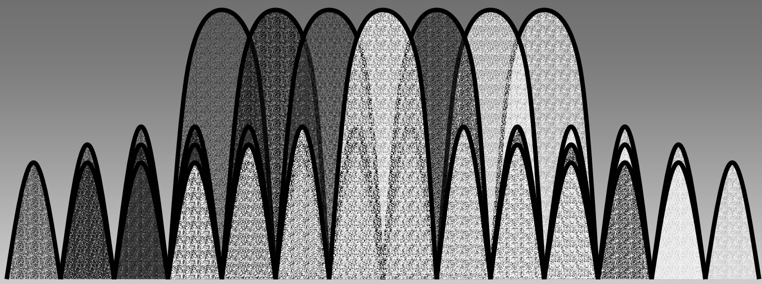


To achieve 5.5 and 11 MBit/sec rates, the spreading length is first reduced from 11 to 8. This increases the symbol rate from 1 Msym/sec to to 1.375 Msym/sec. To achieve 5.5 MBit/sec bit rates with 1.375 MHz symbol rates we need to transmit 5.5/1.375 or 4 bits/symbol. For 11 MBit/sec we obviously need 8 bits/symbol

The approach taken for 802.11B, which keeps the QPSK spread spectrum signal and still provides the required number of bits/symbol uses all but two of the bits to select from a set of spreading sequences and the remaining two bits to rotate the sequence.

One important difference between the sets of spreading sequences used here, and the single Barker code sequence used for the 1 and 2 Mbit/sec rates is that these sequences are complex. In other words, a DQPSK signal with QPSK spreading.

Orthogonal Frequency Division Multiplexing

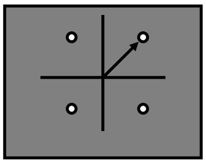


- Closely spaced carriers overlap
- Nulls in each carrier's spectrum land at the center of all other carriers for Zero Inter-Carrier Interference

The "O" in OFDM stands for orthogonal. 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.

Non-linear distortion and phase noise are the two largest contributing factors to a loss of orthogonality, creating inter-carrier interference. Poor frequency estimation in the receiver is another.

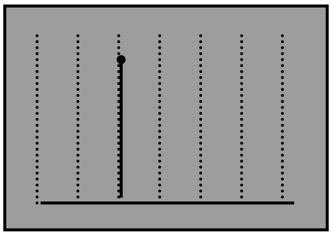
IFFT Used to Create Signal - One Carrier Example



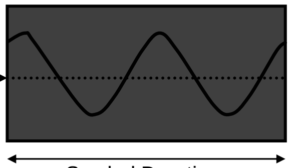
The constellation shows the magnitude and phase of the carrier.

Each FFT bin corresponds to a single carrier

1+j1



IFFT

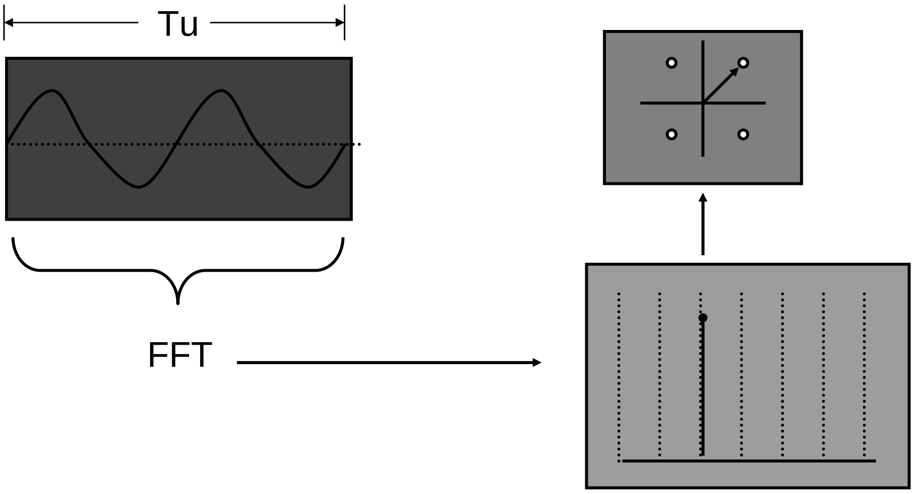


Symbol Duration
4usec

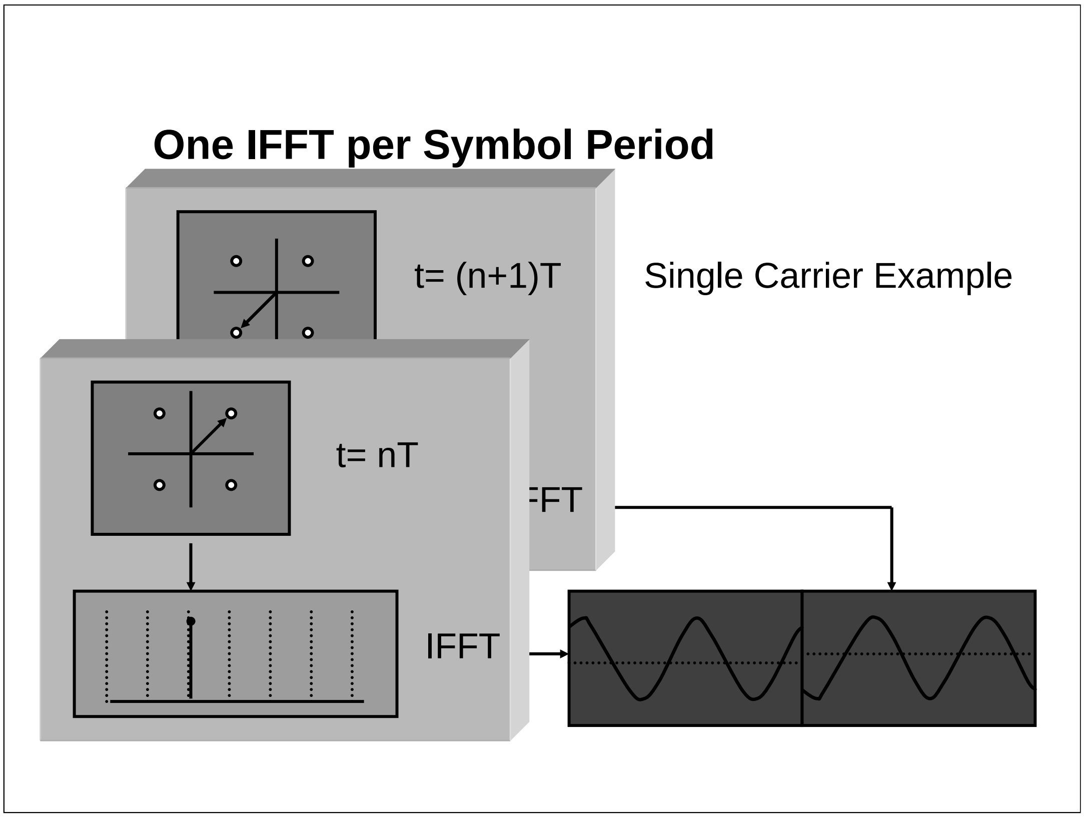
If you know a little about FFT's, the concepts behing OFDM should be very simple to understand. In this example we are going to create an OFDM signal with only one carrier. The magnitude and phase of the carrier are determined from the symbol to be transmitted, as shown in the constellation diagram. 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.

Receiving a COFDM Signal



At the receiver, ignoring channel affects, the time waveform is digitized and an then converted back to a symbol using an FFT.



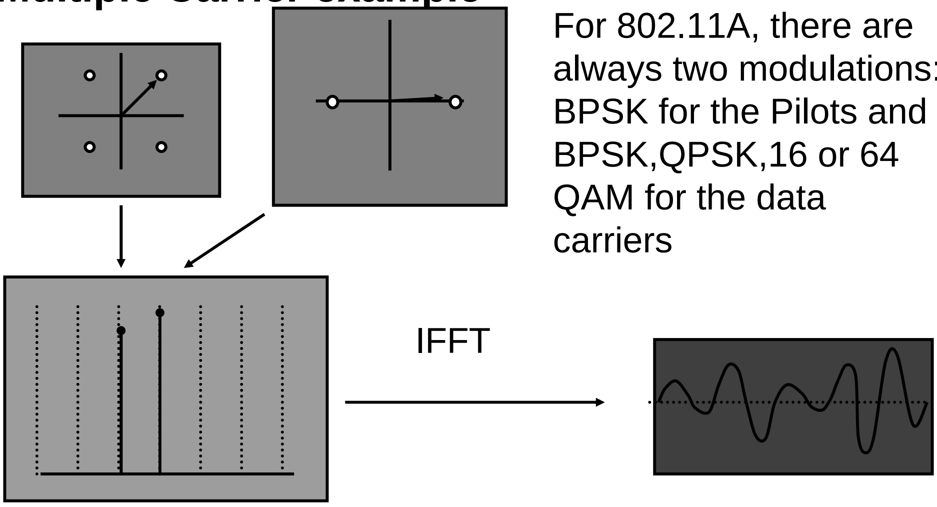
Continuing with the single carrier OFDM example, while the first pulse is being transmitted, the next symbol is loaded into the FFT buffer. Notice that the resulting pulse, when joined with the first, results in a discontinuity. This is normal. The resulting spectral splatter can be attenuated somewhat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

802.11 a – OFDM Physical Medium Dependent (PMD) Sublayer

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

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.

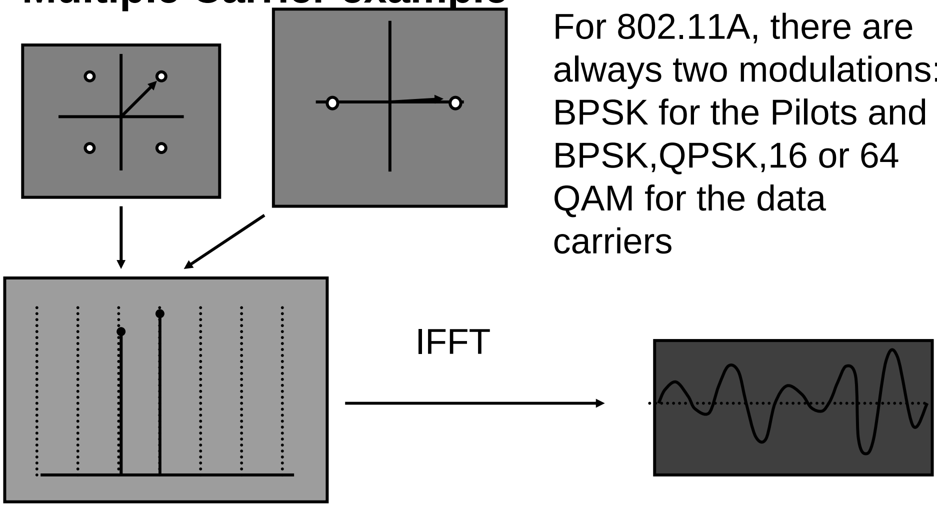
IFFT Used to Create TX Signal Multiple Carrier example



For 802.11A, there are always two modulations: BPSK for the Pilots and BPSK,QPSK,16 or 64 QAM for the data carriers

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.

IFFT Used to Create TX Signal Multiple Carrier example



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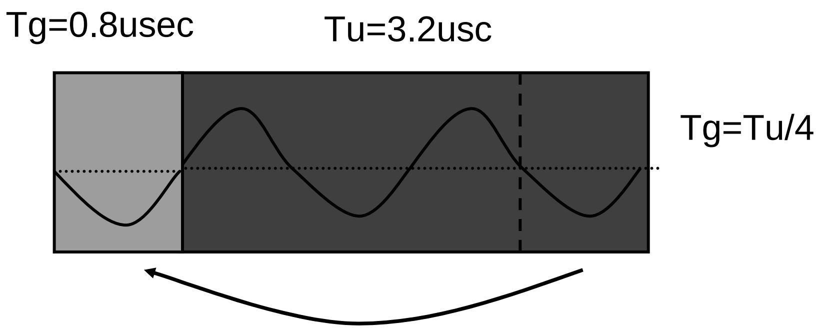
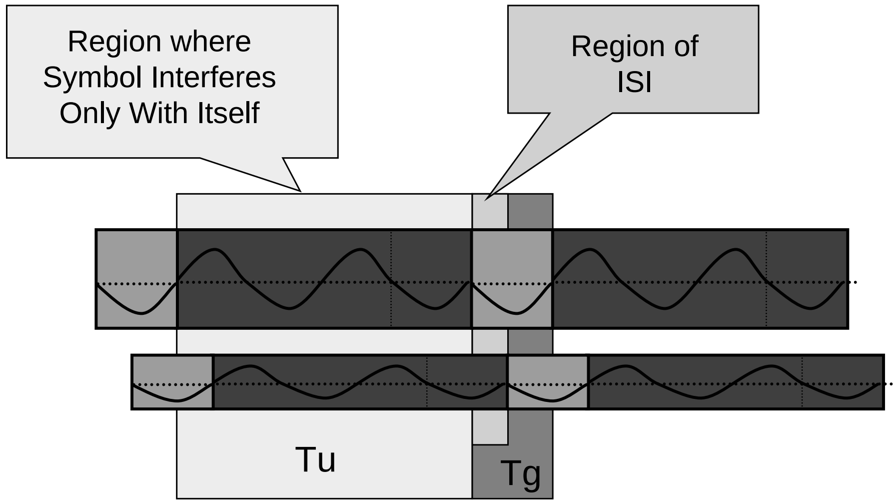
A *Guard Interval* is inserted before Transmission



The guard interval is often referred to as a “cyclic extension” . This signal

In the earlier example we ignored the effects of the channel and spliced the two pulses from subsequent symbols together. 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 1/4 of the pulse 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.

Dealing With Multipath
Two Paths/Transmitters

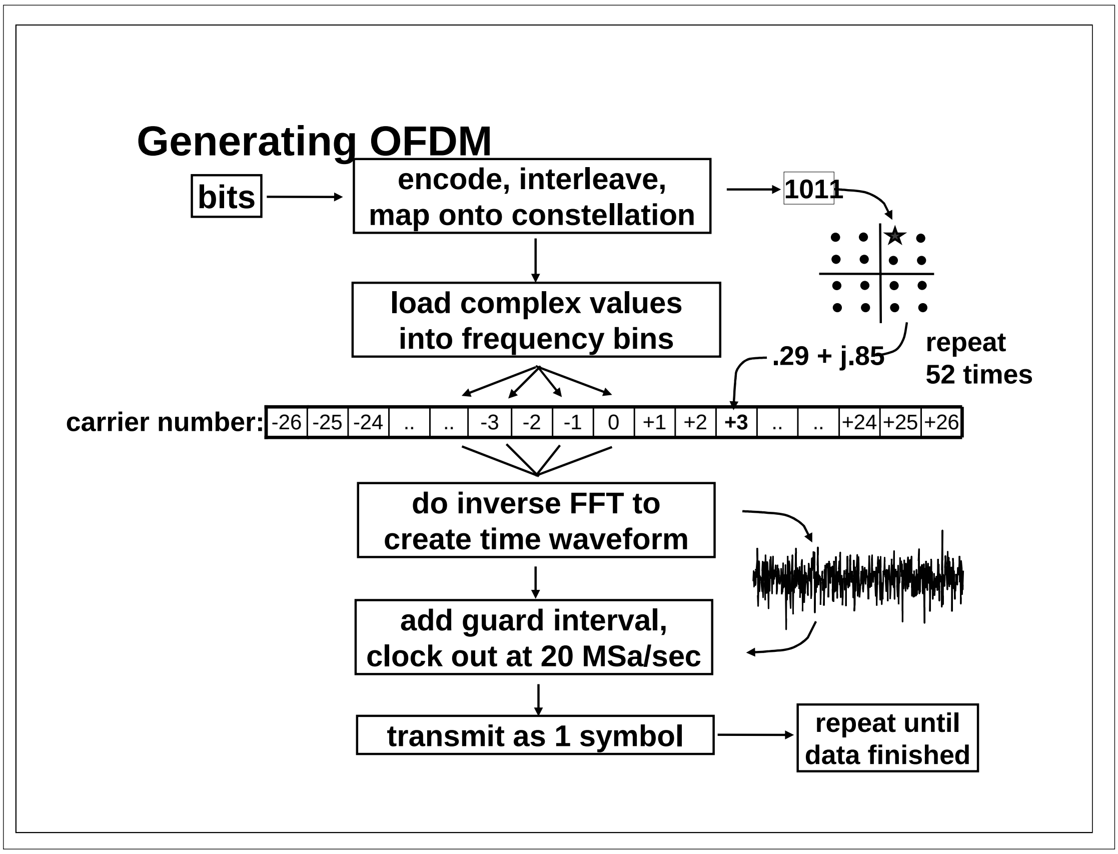


This drawing illustrates how the addition of a guard interval helps with ISI. Shown are two copies of the same signal. Each copy took a different path so they will arrive at the receiver at slightly different times where they will be combined in the receiver's antenna into a single signal. In the time interval denoted by the yellow box marked Tu, the signal 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.

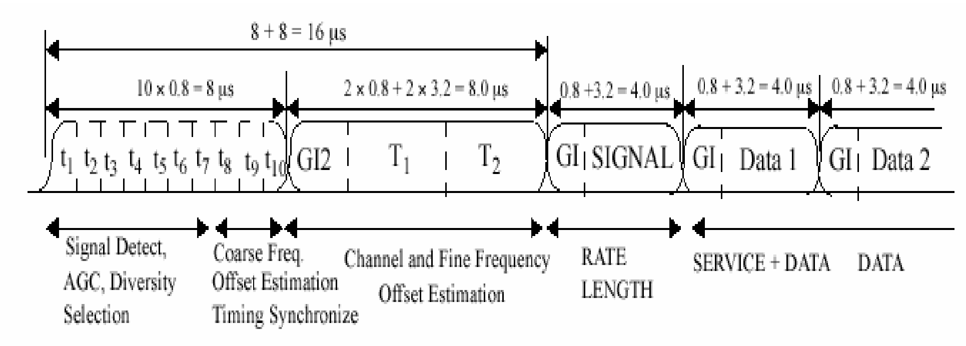
Delay spread is not limited to positive delays. In non line-of-site conditions, the shortest path may not be the strongest. The implications on OFDM receivers is that the FFT may not be perfectly aligned with the useful part of the burst (as it's often called). Instead the receiver will shift the FFT 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 modulation accuracy test, so linear distortion which introduces ISI within the useful part of the burst will increase EVM.



Generation of OFDM signals tends to require high performance DSP engines. The steps include:

- adding error correction codes and interleaving the input bit stream, and then mapping the resultant bits, “n” at a time, onto the transmit constellation. (Depending on the desired bit rate, the bits could be mapped one at a time onto a BPSK constellation, or up to 6 bits at a time onto a 64QAM constellation).
- in this example, the four bits “1011” correspond to a location on a 16QAM constellation whose I-Q coordinates are +0.29 +j0.85. This complex number is then loaded into the next bin in an array of 52 complex values. The process is repeated until 192 bits have been converted, and the entire array filled. (Four of the bins are “pilots”, and get their values from a slightly different source – described later).
- an inverse FFT is then performed on this complex array (to make the math easier, 0+j0 values are appended to either end of the array, so that it’s total length is 64).
- the result of the IFFT is a new array of 64 complex values. These values are clocked out at 20 MHz, yielding a signal burst 3.2 usec long. (In practice, the latter ¼ of the waveform is copied to the beginning of the burst, yielding a total length of 4.0 usec. This “cyclic extension” provides a guard interval, resulting in further multipath immunity).
- this 4 microsecond burst represents a single “symbol” containing (in this example) 192 bits of payload. Multiple symbols are joined together to create a single transmit “frame”.
- on the receiving end, an FFT is performed on each symbol waveform, recreating the original array of 52 complex values, which are then mapped back onto the constellation, converted back to bits, decoded, etc.

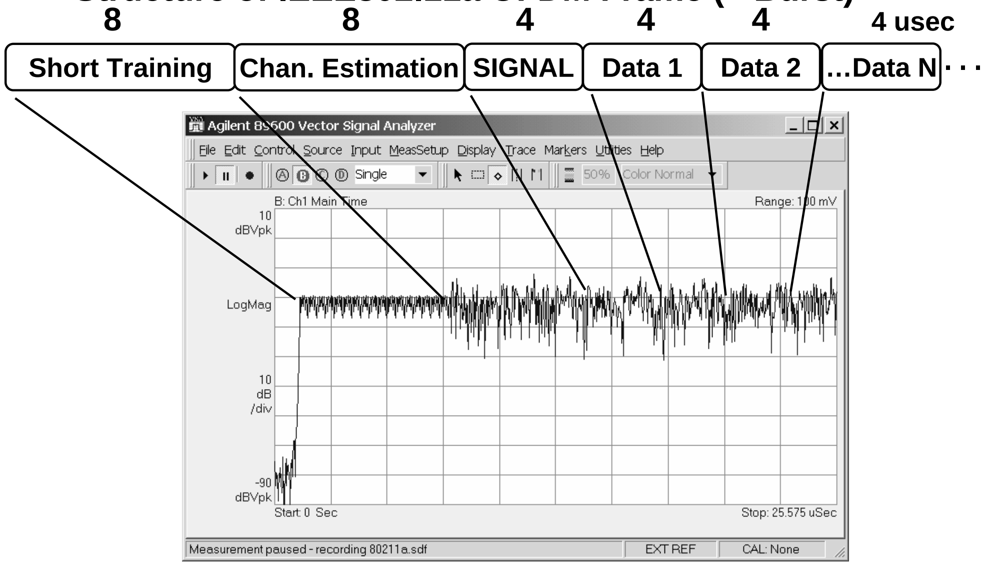
OFDM Training Structure



The 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.

Structure of IEEE802.11a OFDM Frame (= Burst)

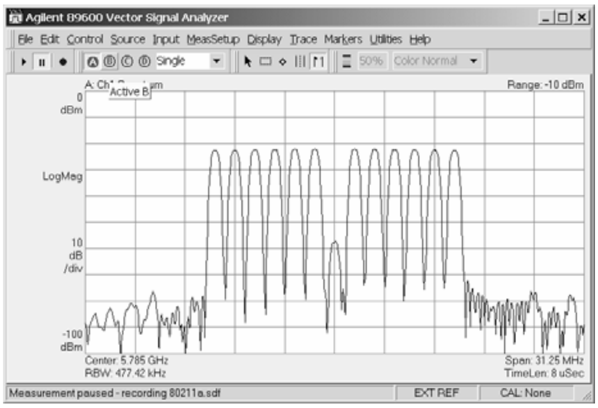


Looking at the structure of an 802.11a burst, there are three sections to every frame (a frame is an RF burst, and consists of multiple symbols):

- Short training sequence (double-length symbol)
- Channel estimation sequence (double-length symbol)
- Data symbols (up to 4096 of them)

Structure of IEEE802.11a OFDM Frame (= Burst)

[redacted] | **Chan. Estimation** | **SIGNAL** | **Data 1** | **Data 2** | **…Data N** · · ·



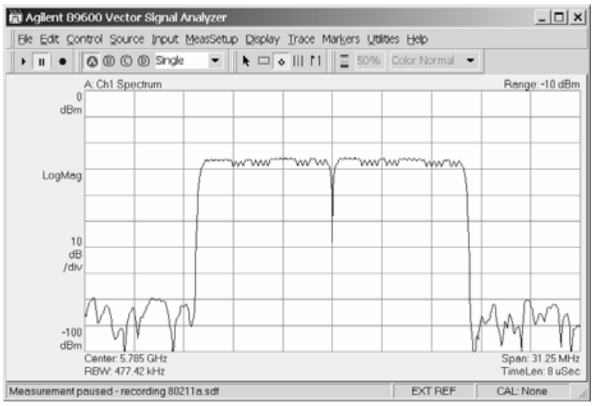
Short Training Seq.
- **8 uSec length**
- **Every 4th carrier, equal amplitude/phase**
- **Signal detect, AGC, timing synchronization, coarse freq. estimation.**

The short training sequence is a very simple signal, consisting of every 4th carrier transmitted with common phase and equal amplitude. It's designed to be easy for the receiver to detect and initially synchronize to.

This 89600 display represents a time-gated measurement, where the analyzer was configured to trigger on the RF burst envelope and then measure just the first 8 usec of the signal.

Structure of IEEE802.11a OFDM Frame (= Burst)

Short Training	Chan. Estimation	SIGNAL	Data 1	Data 2	…Data N	· · ·



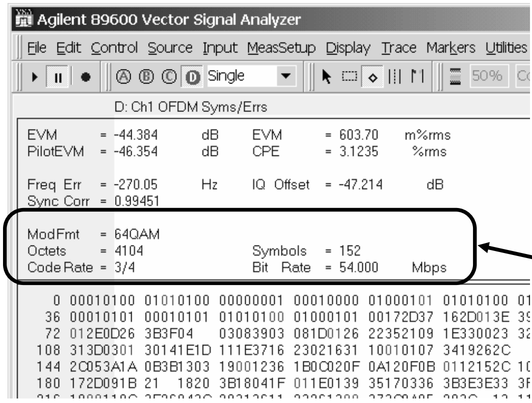
Channel Estimation

- **8 uSec length**
- **Every carrier, equal amplitude and phase.**
- **Channel equalization, fine freq. estimation.**

The second 8-usec block consists of all 52 carriers active, again at equal amplitude and phase. This signal is used by the receiver to fine-tune its estimate of the signal frequency and phase (crucial for ISI-free demodulation), and also to set its equalizer to compensate for any linear distortion (flatness, multipath, etc.) in the channel.

Structure of IEEE802.11a OFDM Frame (= Burst)

Short Training	Chan. Estimation	SIGNAL	Data 1	Data 2	…Data N · · ·



SIGNAL Symbol

- **4 uSec length**
- **Always BPSK.**
- **Describes this frame's rate, length.**

These parameters are read from signal under test. (IEEE802.11a only)

Next is the Signal symbol, a preamble that tells the receiver how to configure itself for the data symbols to follow. Of particular importance is its indication of the data rate (6-54 MBps), which defines the modulation format and coding rate being used. It also provides the number of symbols contained in this frame.

The Signal symbol is always transmitted in BPSK.

Structure of IEEE802.11a OFDM Frame (= Burst)

Short Training	Chan. Estimation	SIGNAL	Data 1	Data 2	…Data N · · ·

Data Rate	Mod. Format	Coding Rate	Bits per Symbol
6 Mbits/sec	BPSK	1/2	24
9	BPSK	3/4	36
12	QPSK	1/2	48
18	QPSK	3/4	72
24	16QAM	1/2	96
36	16QAM	3/4	144
48	64QAM	2/3	192
54	64QAM	3/4	216

Also: 54-108 – Atheros chipset"Turbo Mode"

Data Symbols

- **1 symbol =**
  - **4 uSec length**
  - **1 FFT**
  - **52 carriers (48 + 4)**
  - **52 constellation dots**
- **Format varies**
- **Coding varies**
- **Max 4096 bytes per frame.**
- ***MAC layer starts here.***

The 802.11a and HiperLAN/2 protocols allow the transmitter and receiver to negotiate a mutually agreeable bit rate, based on error performance.

- The following are a function of bit rate: modulation format, coding rate, max #symbols
- The following are not a function of bit rate: symbol rate (=250 kHz), number of carriers (=48+4), max. # bytes (=4096).

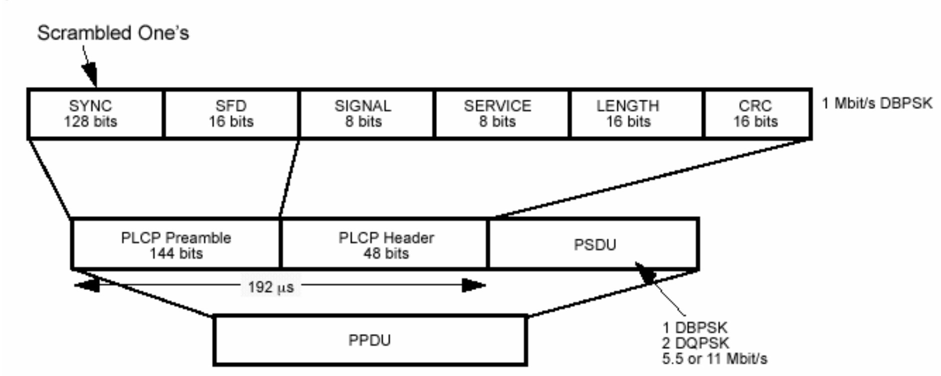
"Coding Rate" indicates the error-correction overhead added to the raw bitstream. For example, a coding rate of ¾ means that, for every 48 bits transmitted, 36 of them contain payload, and 12 contain error correction info.

An interesting twist on the IEEE standard is the proprietary "dual rate" scheme developed by chipmaker Atheros. This technique doubles the symbol rate, creating a doubly-wide signal with twice the spacing between carriers – and up to 108 MBps data rates (currently advertised as 72 MBps).

MAC Layer Briefly…..

To help understand setup of preamble and header while making measurements on a device PHY layer , we shall introduce briefly the MAC layer and explain how data transmission happens.

Long PLCP PPDU Format



For all 802.11B bit rates, the preamble and header are sent at the 1 Mbit/sec rate. The header is 192 usec long (192 bits). This translates to 2112 chips. The payload data as then appended using one of the four modulation rates

Acronyms:

physical medium dependent (PMD)

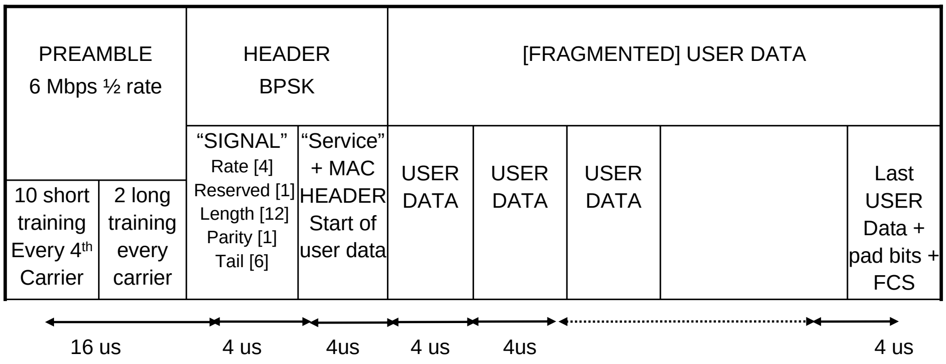
PHY convergence procedure(PLCP)

MAC sublayer protocol data units (MPDU)

PHY protocol data units (PPDU)

PLCP service data units (PSDU).

IEEE 802.11a frame structure



A WLAN device only transmits or receives at one point in time. Transmissions occur as bursts [frames] which vary in length and spacing, usually in the range of a few hundred microseconds to one millisecond. The 802.11b CCA receiver test draws attention to the longest possible 5.5Mbps frame being 3.65ms.

The preamble is used by the receiver to adapt to the input signal. This can involve frequency and phase error equalizing, and time alignment. The header contains a lot of information including the destination address and the format of the remainder of the burst. User data is transferred from the original packets, which are fed to the MAC layer. Long packets may be fragmented [broken up] if the radio determines this will improve the link performance.

IEEE 802.11b frame structure

PREAMBLE 1 Mbps DBPSK		HEADER 1 Mbps DBPSK	PSDU – [FRAGMENTED] USER DATA	
SYNC [128 bits] Scrambled 1s	Start Frame Delimiter (16 bits)	SIGNAL (8 bits) SERVICE (8bits) LENGTH (16 bits) CRC for header (16 bits)	Variable length	FCS CRC (32 bits)

192 us

PREAMBLE 1 Mbps DBPSK		HEADER 2 Mbps DBPSK
SYNC [56 bits] Scrambled 0s	Start Frame Delimiter (16 bit reversed)	SIGNAL (8 bits) SERVICE (8bits) LENGTH (16 bits) CRC for header (16 bits)

96 us

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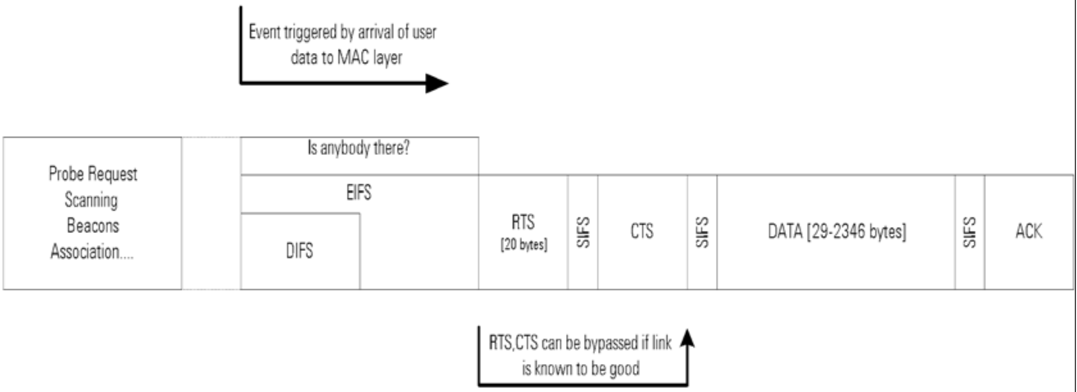
IEEE 802.11 timing intervals

TIME INTERVAL	802.11a	802.11b
SIFS- Short Inter Frame Space	16us	10us
SLOT	9us	20us
Priority IFS= SIFS + SLOT	25us	30us
Distributed IFS= SIFS + 2 SLOTS	50us	50us
Contention Window Min	15 slots	31 slots
Extended FS- much longer	Variable	Variable

There are five time periods in the 802.11 specification that determine the spacing between transmissions. The physical values vary according to the standard used, and are shown above

Data transmit process



The picture here shows the process to send data (an example)

Establish Contact

Starting from a device being powered up, the LLC software operating above the MAC layer needs to stimulate it to establish contact. Active or Passive Scanning are used. The IEEE specification allows for different implementations, so different characteristics will be noted between devices.

Active scanning is the fastest way to establish contact, but consumes more battery power. Having listened for a clear channel, a Probe Request transmission is sent from the device that wants to establish contact. If the Service Set IDentity matches, the recipient sends a Probe Response. The scanning device uses this information to decide if it will join the [I]BSS, but there is no further transmission at this point.

In Passive Scanning, Beacons & Probe Requests are used. After selecting a channel, the scanning device listens for Beacons or Probe requests from other devices.

A beacon is transmitted from an Access Point in a BSS or ESS. It contains information about the AP and a timing reference. Beacon transmissions occur on a 1024us time grid, and usually occur roughly every 100ms. Like other transmissions, they are subject to a clear channel test, and so may get delayed.

Before any user data can be transferred, the Sender and Receiver need to agree they are ready to talk. These are the authentication [has to happen first] and association processes. There are also several other processes, including random exponential transmission back-off, which are used if a device finds the channel is not clear when it wishes to transmit.

Earlier, a list of modulation rates was shown for the different standards. The IEEE specifications do not define how these are selected. Different designs will use proprietary algorithms. Currently, there is no Quality of Service information in the MAC frames to do it. However, the transmitting device is able to make some channel assessments using its own receiver, and can gauge the fidelity of the link from the regularity of ACK frames from the device it's transmitting to.

Data Exchange

When two WLAN devices are ready to exchange data, they choose between two methods. The decision depends on the expected performance of the radio link. The minimum transaction between devices when sending data is simply

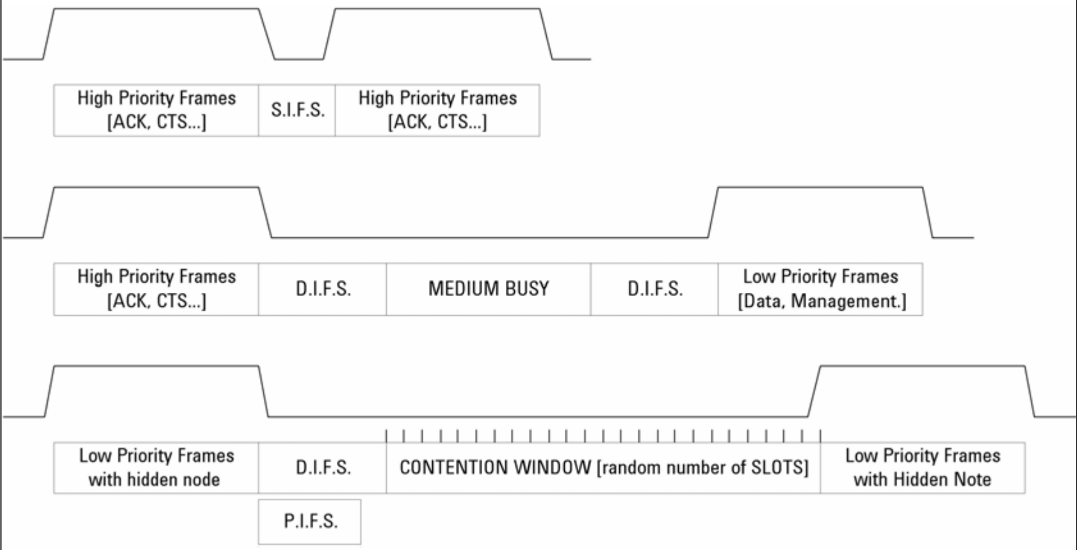
- Send
- Acknowledge

This is good for short packets, or a sparsely used RF environment. More usually it is a four-step process.

- Request To Send [RTS]
- Clear To Send [CTS]
- Send
- Acknowledge

This is used for long frames, when there is a higher likelihood of getting interfered with, or noisy environment. A special MAC signal [dot11RTSThreshold] is used to choose between frame lengths.

IEEE 802.11 frame timing



The picture here shows the major timing options.

Products and Resources

E4438C Vector Signal Generator
•Up to 6 GHz to cover 802.11a range
•Available in improved phase noise version.
•Internal baseband generator, with deep memory and internal disk drive for large waveform memory and length.
•External Signal Studio software to generate 802.11a and 11b specific signals.

89600 Series Vector Signal Analyzer
•Industry's widest bandwidth signal analyzer (36 MHz)
•Fast and powerful modulation analysis
•Up to 6 GHz frequency range, higher when used with an Agilent PSA spectrum analyzer.

GS-8300 WLAN Manufacturing Test System
•Integrated system, in rack
•Electrical and RF cable integration
•Safety tested, CE certification available

That brings us close to the end of this module. If you are looking out for WLAN test solutions, please have a look at some of the products from Agilent for your R&D or manufacturing needs.

The ESG family of signal generators are ideal for R&D and manufacturing. They go up to 6 GHz in frequency, and offer high performance digital modulation capabilities. The powerful internal baseband generators are ideal for real-time I/Q generation (receiver test) and arbitrary waveform generation (component test). The powerful integrated baseband generator (model E4438C) helps build long waveform sequences without requiring an external arbitrary source. Internal and PC-based personalities give you format-specific modulations and channel coding.

The 89600 series of Vector Signal Analyzers are ideal for WLAN transmitter testing – they offer industry's widest bandwidth signal analysis (36 MHz). The 6 GHz frequency range ensures coverage for the 5 GHz range for 802.11a. Higher frequencies are possible when used with the Agilent PSA spectrum analyzers. The 89600 has personalities for WLAN specific measurements.

Agilent also offers customized test systems for WLAN manufacturing test. For more details, please contact your nearest Agilent office, or email us at tm_ap@agilent.com.

Products and Resources

Product Information:

- RF Signal Generators: www.agilent.com/find/sources and click on vector signal generators.
- Vector Signal Analyzer: www.agilent.com/find/89600
- WLAN solutions: wireless.agilent.com/find/wlan

Application resources:

- Agilent Wireless Industry Site: www.agilent.com/find/wireless
- WLAN products and applications: wireless.agilent.com/wlan

Need product literature or application notes? Email us at tm_ap@agilent.com

If you'd like more information on WLAN, test products, or application hints, please try some of the resources listed above.

Or, if you'd prefer to contact a trained engineer, please send us an email at tm_ap@agilent.com. Here, you can request product literature, quotations, or ask questions on product usage, application area and so on.

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This brings us to the conclusion of this module on WLAN basics. Thank you for your time and interest. We hope that it was useful.

For more information, please send us an email to the address listed above. If you'd like to learn about WLAN test or other Agilent products in more detail, please have a look at our training curriculum at the URL above. These are charged training conducted by our experts and give you the opportunity to learn in greater detail, as well as hands-on experience with the instruments.

Finally, please do visit us again at the eAcademy. You will may find new modules, materials, and may be even a special offer!

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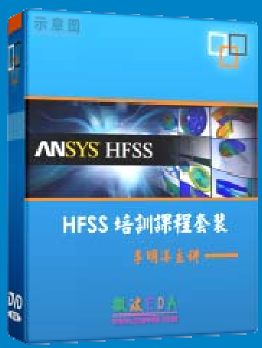
课程网址：http://www.edatop.com/peixun/cst/24.html



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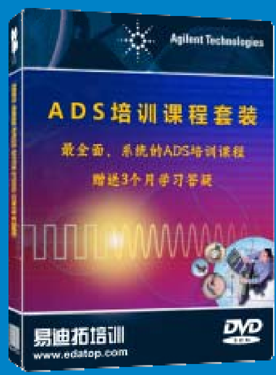

该套装是迄今国内最全面、最权威的 ADS 培训教程，共包含 10 门 ADS 学习培训课程。课程是由具有多年 ADS 使用经验的微波射频与通信系统设计领域资深专家讲解，并多结合设计实例，由浅入深、详细而又全面地讲解了 ADS 在微波射频电路设计、通信系统设计和电磁仿真设计方面的内容。能让您在最短的时间内学会使用 ADS，迅速提升个人技术能力，把 ADS 真正应用到实际研发工作中去，成为 ADS 设计专家...

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