#### Wireless LAN & OFDM

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# Topics

- Link Considerations
- Wireless LAN Specifications and Modulations
- OFDM Signal Processing

#### Link Considerations

#### License Free Bands

- 2.4 GHz
  - 83.5 MHz
  - 1Watt
  - Spread Spectrum
    - FHSS
    - DSSS
  - Fair Usage
    - CCK
    - OFDM
  - Point to point 18dBi antenna – 14dBW EIRP

- 5.15 GHz
  - 100 MHz  $\,$  2.5 mW/Hz  $\,$
- 5.25 GHz
  100 MHz 12.5 mW/Hz
- 5.725 GHz
  - 100 MHz  $\,$  50 mW/Hz  $\,$
  - 1 Watt
  - Point to point no reduction with antenna gain
- 60 GHz
  - 57 to 64 GHz

## Line of Sight Propagation –LOS

- $Pr = PtGtGr \lambda^2/(4\pi d)^2$
- Path Loss =  $\lambda^2/(4\pi d)^2$
- Path Loss Exponent = 2
- From experimental data at 5.8 GHz
  - Path Loss Exponent = 2
  - Standard deviation = 6.9 db
- Additional O<sub>2</sub> loss of 16 dB/km @ 60 GHz

# Non Line of Sight -- NLOS

- Sum of reflections from many objects
- Rayleigh distributed
   10 % of time 10 dB below nominal level
   1% of time 20 dB below nominal level
- Form experimental data at 5.8 GHz
  - Path loss exponent = 3.5
  - Standard deviation = 9.5 dB
- Combated with antenna diversity

## Bits per Hertz

- Baseband binary data
  - 2 bits/Hertz
  - Alpha  $\alpha$  is filter factor 0.25 gives 1.6 bit/Hz
- Binary phase shift keying BPSK
  - 1 bit/Hertz
  - Upper and lower sidebands as baseband
- Quadrature phase shift keying QPSK
  - 2 bits/Hertz

## More bits per Hertz

- 16 Quadrature Amplitude Modulation
   16 QAM
  - 4 bits/Hertz
- 64 Quadrature Amplitude Modulation
  - 64 QAM
  - 6 bits/Hertz
- In practice with FEC, protocol, shaping and guard 2/3 of the available bits/Hertz is good

# Energy per Bit / Noise Density

- E/N0 = Energy per bit / Noise density
- Additive White Gaussian Noise AWGN
- Un-coded error rate 10<sup>-4</sup>
- BPSK or QPSK 8.5 dB
- 16 QAM 15.5 dB
- 64 QAM 21.7 dB

#### Atheros Measured Range



### Atheros Measured Range



# An Example of Range

- 5.8 GHz U-NII band transceiver
- 70 MHz bandwidth, 64 QAM, 280 Mbps
- Power out RMS 13 dBm
- Line of sight
  - 1ft. Tr and Rx 20 dB gain antenna 3 miles
  - Omi Tr and 20 dB rx
  - Omi Tr and Rx 0.1 m
- Non line of sight 50 ft
  - 1ft. Tr and Rx 20 dB gain antenna 50 feet
- 0.5 miles 0.1 miles





### Multipath Delay



### Multipath Example



# Link Considerations Summary

- Bandwidth is limited.
- Bandwidth efficient modulations require high S/N
- NLOS propagation is brutal giving low S/N.
   High data rate LAN's are short range
- Multipath distorts waveforms.
  - Equalization
  - OFDM

### Wireless LAN & OFDM Part 2

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## Wireless LAN Specifications and Modulations

### 802.11 Specifications



## 802.11 Characteristics

Standard	802.11a	802.11b	802.11
Standard Approved	September 1999	September 1999	July 1997
Available Bandwidth	300MHz	83.5MHz	83.5MHz
Unlicensed Frequencies of Operation	5.15-5.35GHz, 5.725- 5.825GHz	2.4-2.4835GHz	2.4-2.4835GHz
Number of Non- Overlapping Channels	4 (Indoor) 4 (Indoor/Outdoor) 4 (Indoor/Outdoor)	3 (Indoor/Outdoor)	3 (Indoor/Outdoor)
Data Rate per Channel	6, 9, 12, 18, 24, 36, 48, 54 Mbps	1, 2, 5.5, 11 Mbps	1, 2 Mbps
Modulation Type	OFDM	ССК	FHSS, DSSS

# 802.11 FHSS Frequency Hopping Spread Spectrum

- Center frequency is selected from a large number of frequencies
- Processing gain is number of hopping frequencies.
- Slow hopper symbol rate is much higher than hopping frequency
- Effective against large narrow band interference

## 802.11 FHSS PMD Physical Medium Dependent

- Hopping set 79 in US
- 3 sets of 26 Hopping frequencies
- Separation 1MHz
- 1 Mbit/s two-level GFSK BWE = 1/80
- 2 Mbit/s four-level GFSK BWE = 1/40

# 802.11 DSSS Direct Sequence Spread Spectrum

- Carrier directly modulated by a code sequence.
  - Symbol rate is rate of data symbol 1MHz
  - Chip rate is rate of code sequence 11 MHz
- Processing gain Symbol rate/Chip rate 10 dB
- Effective against moderate interference levels.

# 802.11 DSSS PMD Physical Medium Dependent

- 11 MHz chip rate --11 chip symbols
- 1Mbps Differential binary phase shift keying BWE = 1/11
- 2 Mbps Differential quadrature phase shift keying BWE = 2/11
- Spreading uses a 11chip Barker code -+1,-1,+1,+1,+1,+1,+1,-1,-1.-1
  - Nearly impulsive autocorrelation

# 802.11b CCK Complimentary Code Keying

- Complementary codes are symbols having desirable correlation functions
- Symbol rate 11/8 = 1.375 MHz
  - Chip rate 11MHz
  - 8 chips per symbol
  - QPSK modulation
- 5.5 Mbps 4 bits or 16 codes per symbol
- 11 Mbps 8 bits or 256 codes per symbol

# 802.11b CCK PMD Physical Medium Dependent

- 11 MHz chip rate -- 8 chip symbols
- 5.5 Mbps data rate
   Four 8 chip codes
   QPSK modulated
- 11 Mbps data rate

BWE = 1.0

BWE = 0.5

- Sixty Four 8 chip codes
- QPSK modulated

# 802.11b PBCC Packet Binary Convolutional Coding

- Data is 1/2 rate convolutional coded
- 64 state convolutional coding -- 4 dB coding gain
- Data modulates carrier using pseudorandom cover sequence
  - At 11 Mbps data is QPSK BWE = 1.0
  - At 5.5 Mbps data is BPSK BWE = 0.5

## 802.11a OFDM Characteristics

- Split high data rate stream into a number of lower data rate streams that are transmitted over subcarriers
- Combats multipath Robust Equalization
- Forgiving to hardware frequency characteristics
- Flexible data rates
- Requires linear amplification

# OFDM Symbol



#### **OFDM FFT Interval**



## OFDM Symbol

OFDM Symbol



#### I Tone Values



### I Component of FFT Interval



## I Component of Four Symbols



### **QPSK Scatter Plot**



### 16 QAM Scatter Plot


## Motivation for OFDM

- Desired 54 Mbs in 20 MHz bandwidth in a 400 millisecond multipath enviroment
- Single carrier
  - Symbol length 50 nsec
  - 64 QAM
- OFDM
  - 64 Carriers
  - Symbol length 4 usec
  - 64 QAM

## 802.11a OFDM Parameters

- Total Number of Frequencies 64
- Number of Subcarriers Used 52
- Number of Pilots
- Number of Data Subcarriers
- Subcarrier Spacing
- -3 dB bandwidth
- Channel spacing

4 48 312.5 kHz 16.56 MHz 20 MHz

## 802.11a OFDM Parameters

- OFDM Signal Duration 4 usec
- Cyclic Prefix 800 nsec
- Complex sample rate 20 Msps
- Data Samples 64
- Guard Samples 16
- FFT Complex Tones 64

#### 802.11a OFDM Parameters

- Data Rate 6,9,12,18,24,36,48,54 Mbps
- Modulation BPSK,QPSK,16QAM,64QAM
- Coding Rate 1/2, 2/3, 3/4
- Number of Data Subcarriers 48
- Max Data Rate 48\*6\*(3/4)/4 = 54 Mbps BWE = 2.7
- Min Data Rate 48\*1\*(1/2)/4 = 6 Mbps BWE = 0.3

## 802.11g Unapproved

- Higher data rates for 2.4 GHz
- Mandatory OFDM as 802.11a
- Mandatory backward compatible with 802.11b
- Optional CCK/PBCC and CCK/OFDM
- Step towards dual band

## PBCC 802.11g Packet Binary Convolutional Coding

- Data is 2/3 rate convolutional coded
- Coded data is modulates carrier with 8 PSK
- Throughput of 2 information bits per symbol

#### PLCP Physical Layer Convergence Protocol

PLCP Preamble		PLCP Header			
Sync	Start Frame Delimiter	PLW	PSF	Header Error Check	Whitened PSDU

Sync	80 bit Alternating one zero			
Start of frame	0x0CBD			
PSDU	PLCP service data unit			
PLW	PSDU length word 12 bits			
PSF	PLCP signaling field 4 bits – data rate			
Header Error Check	16 bits			

## 802.11g CCK/PBCC CCK/OFDM Hybrid CCK and PBCC or OFDM

- Uses the CCK to transmit the header/ preamble portion of each packet
- PBCC to transmit the payload. PBCC supports data rates up to 33 Mbps.
- OFDM to transmit the payload. OFDM supports data rates up to 54 Mbps.

# Summary of 802.11 Modulation and Specifications

- 802.11
  - 2.4 GHz 1 or 2 Mbps FHSS or DSSS
- 802.11b
  - 2.4 GHz up to 11 Mbps CCK
- 802.11a - 5.8 GHz up to 5
  - Hz up to 54 Mbps OFDM
- 802.11g
  - 2.4 GHz up to 54 Mbps OFDM

## **OFDM Signal Processing**

#### Transceiver

- Point to point communications
- Full duplex 100+ Mbps payload
- License free 5.8 GHz
- Low cost using many WLAN components
- Software defined radio
- Robust OFDM modulation
- Time Division Duplexed

## Software Defined Radio

- I and Q modulation
- Any modulation can be used
- Any data rate limited by complex sample rate of 75 MHz
- Programmable
  - High speed processing in FPGA
  - Control in DSP

## **TDD** Characteristics

- Transmit and receive take turns on the same frequency.
- Adaptive asymmetrical service
- Simplifies RF hardware.
  - TR synthesizers have same frequency
  - No RF duplexer
  - No receive while transmit
- Reduces digital hardware. Single FFT
- Introduces latency

#### **TDD** Transceiver



TDD Transceiver

#### Modem



Modem

#### **OFDM Parameters**

- Sample rate -- I and Q --75 Msps
- Symbol length 300 samples 4 usec
- 256 FFT samples 30 preamble 14 postamble
- 210 data tones 42 guard 2-pilot- 2 dc tones
- Frame 552 usec 138 symbol slots per frame
- Frame 2 pilot 126 data 10 T/R Gap symbols
- 64 QAM modulation 6 bits per symbol
- 0.92 Turbo product code
- Full duplex payload of 125 Mbs each direction
- RF Bandwidth 62 MHz IQ 32 MHz

#### Frame Structure



## Oscillator Considerations

- Oscillators 3 ppm @ 5.25 GHz 15.75 kHz.
  Over 1 symbol 28 degrees of carrier shift.
  Requires carrier correction during symbol.
- Oscillators 3 ppm @ 75 MHz 225 Hz.
  - Over 1 symbol 1/1000 of a sample shift
  - No time correction during symbol.
  - Over a frame 1/100 of a sample shift.
  - Requires time correction during frame.

## Transmit Signal Processing



## FFT

- 256 point FFT
- Fixed point
- Execution in 1 symbol time
- Radix 4 implementation
- 5 symbol latency

## **Receiver Signal Processing**



## Hardware Recovered Data



## Initial Symbol Time Measurement

- Correlation measurement of pre and post fix
   Maximum at signal time
  - Reliable detection of signal presence
- Minimum least squares difference measurement of pre and post fix
  - Minimum at signal time
  - Accurate measurement of signal time

## OFDM Symbol



#### Initial Time Measurement



#### Initial Symbol Time Detection



## Received Signal Phase Estimation

- Received subcarrier phase is sum of nominal carrier phase, sample time and multipath.
  - Carrier phase adds to all subcarriers.
  - Time error adds phase of (n/N)\*2pi.
  - Multipath is function of geometry.

## **OFDM Sampling**



#### Pilot with Carrier Offset



#### Data with Carrier Phase Offset



## Carrier Tracking



#### Data -- Carrier Offset Removed



## **OFDM Sampling**



## Pilot with Time Offset



#### Data with Time Offset



## Symbol Time Tracking


## Data with Time Offset Removed



## Equalization

- Pilot transmitted first in each burst
- Pilot components filtered over multiple frames
- Data normalized by pilot components
- Pilot designed for easy detection

## Differential Loss



## OFDM Signal Processing Summary

- FFT is an efficient method of recovering multiple subcarriers
- Coherent detection of subcarriers requires
  - Carrier recovery
  - Symbol time recovery
  - Equalization
- FPGA implementation to OC-3 speeds