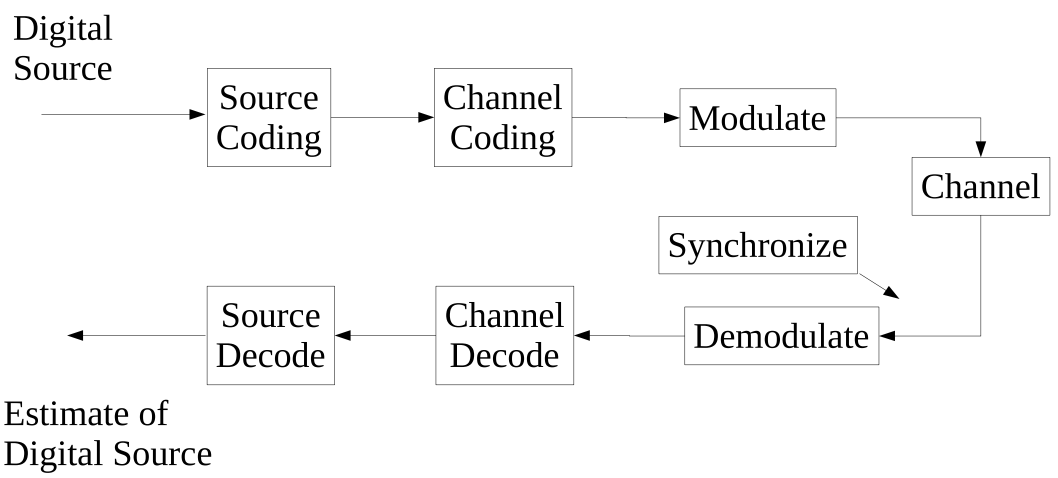
TSTE17 System Design, CDIO

- Lecture 6
  - Packet detection
  - Synchronization

Components of a digital communication system



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Example standard (802.11a)

- Title:

  IEEE Standard for Information technology--Telecommunications and information exchange between systems Local and metropolitan area networks--Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications

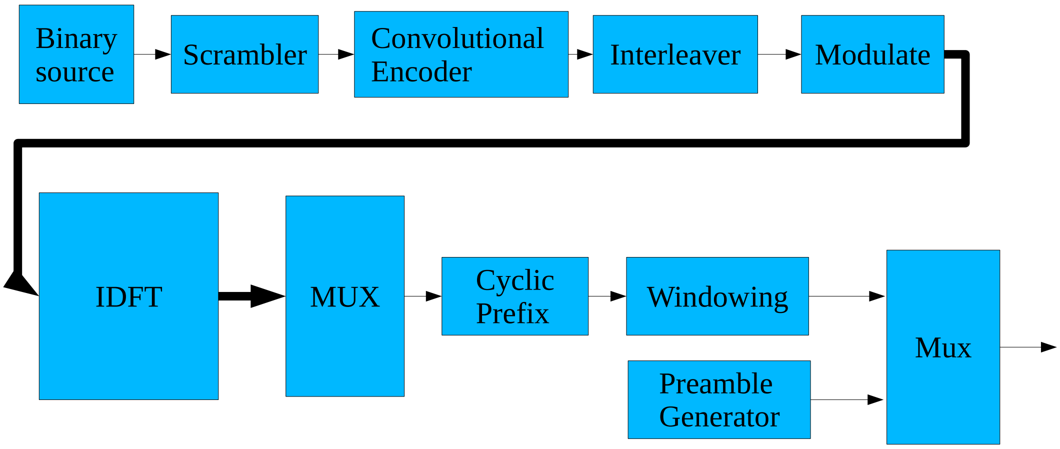
- Standard document downloadable from library
  - Search for IEEE Xplore database
  - search for 802.11 standard, 2016 version

Example standard (802.11a), cont.

- Chapter 17 is the 802.11a PHY standard
  - OFDM up to 54MBit/s in 5 GHz band
- Chapter 18 is the 802.11g PHY standard
  - DSSS + OFDM in 2.4GHz band

802.11a & HiperLAN/2 Transmitter Details

- Excluding interpolation, A/D, and RF circuits

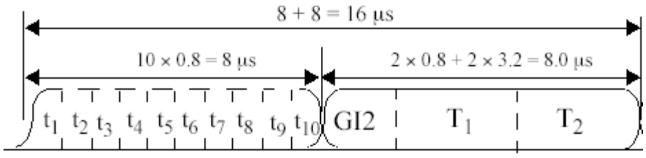


Synchronization

- Coherent modulation => Must synchronize carrier frequency
- OFDM works with frames => Must detect start of frame
- Channel is slowly changing => Must correct for changes

Preamble components

- t1 to t10 are short training symbols
  - Identical 16 samples long
- G12 is a cyclic prefix
  - 32 samples long
- T_1 and T_2 are long training symbols
  - Identical 64 samples long



Packet synchronization

- Use only in packet sending applications
  - Broadcasting system does not need them
- Task: Find start of the preamble of an incoming packet
- Two possible values
  - H_0 packet not present
  - H_1 packet present

Packet Detection

- Usual test
  - H_0 : m_n < Th => Packet not present
  - H_1 : $m_n \geq$ Th => Packet present
  - m_n is a decision variable
  - Th is a threshold

Packet detection performance

- Probability of detection P_D, should be as large as possible
- Probability of false alarm P_{FA}, should be as low as possible
- Want high P_D and low P_{FA}, but increasing P_D generally increases P_{FA}
- Generally worse with low P_D

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Packet detection algorithms

- Received Signal Energy Detection
- Double Sliding Window Packet Detection
- Using the preamble structure

Packet detection algorithms

- Received Signal Energy Detection

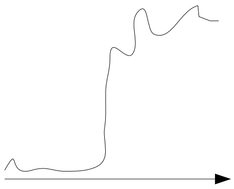
$$m_n = \sum_{k=0}^{L-1} r_{n-k} r^*_{n-k} = \sum_{k=0}^{L-1} |r_{n-k}|^2$$

- L samples added to reduce influence of noise
- The change of noise indicates start of packet

Received Signal Energy Detection

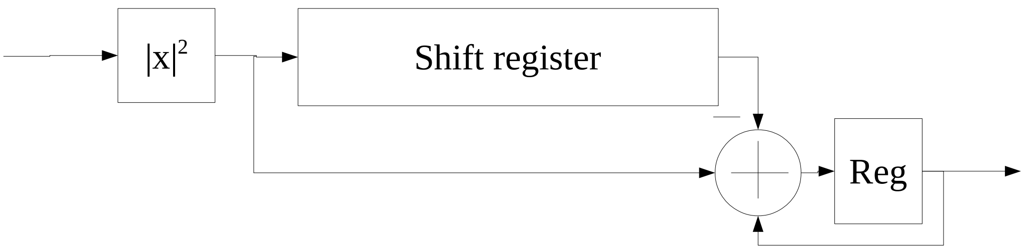
- Moving sum of signal energy

$$m_{n+1} = m_n + |r_{n+1}|^2 - |r_{n-L+1}|^2$$



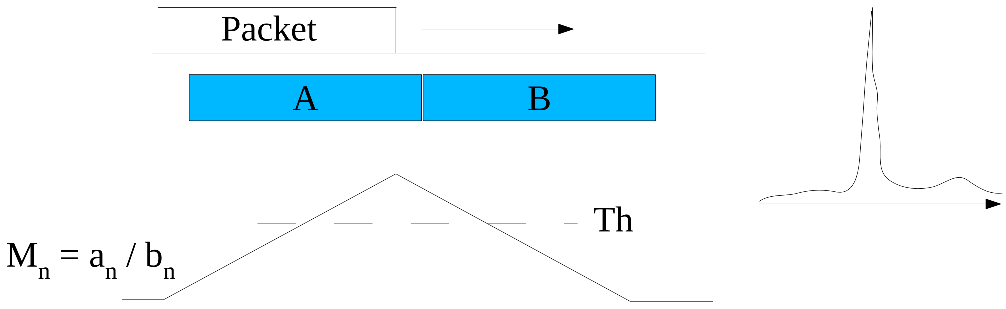
- One complex multiplication/sample, L samples stored in memory
- Drawback: Threshold depends on signal energy!

Moving Sum Implementation



Double Sliding Window Packet Detection

- Compute m_n as ratio between two consecutive sliding windows



Double Sliding Window Packet Detection

- Two sliding windows
  - One complex multiplication, one division, storage for all values

$$m_n = \frac{a_n}{b_n} = \frac{\sum_{m=0}^{M-1} r_{n-m} r_{n-m}^*}{\sum_{l=1}^{L} r_{n+l} r_{n+l}^*} = \frac{\sum_{m=0}^{M-1} |r_{n-m}|^2}{\sum_{l=0}^{L} |r_{n+l}|^2}$$

Double Sliding Window Packet Detection

- Can be used to estimate the received SNR

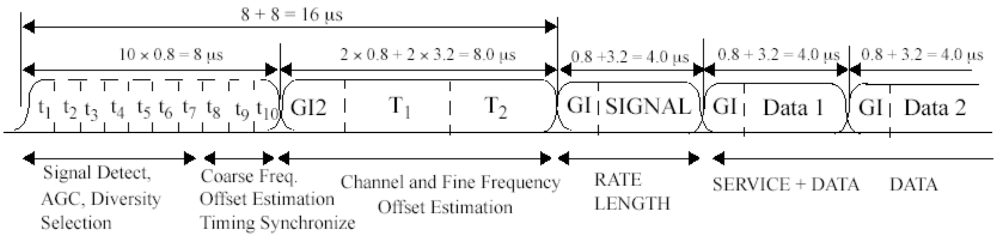
$$m_{peak} = \frac{a_{peak}}{b_{peak}} = \frac{S+N}{N} = \frac{S}{N} + 1$$

$$\widehat{SNR} = m_{peak} - 1$$

- Does not use known information about expected format of the preamble

Using the Structure of the Preamble

- Use as much information as possible
- Preambles in IEEE802.11a and HIPERLAN/2 have been designed to ease detection



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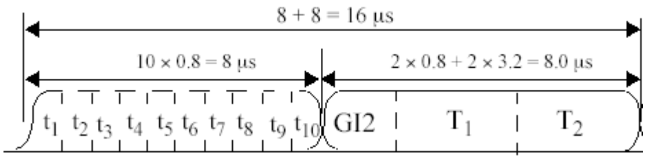
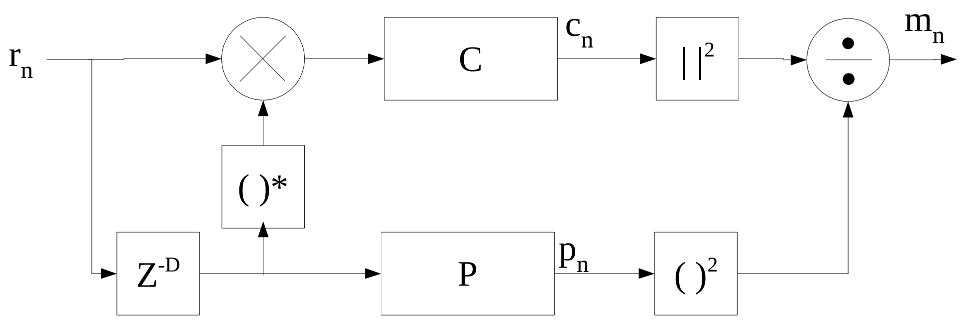
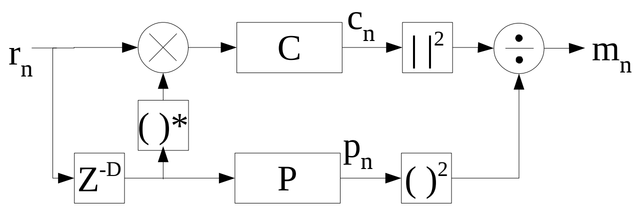


Delay and Correlate Algorithm

- Take advantage of periodicity of the short training symbols
  - Correlate two consecutive short symbols (c_n)
  - Normalize with signal power (p_n)



Delay and Correlate Algorithm



$$c_n = \sum_{k=0}^{L-1} r_{n-k}\, r^{*}_{n+k+D}$$

$$p_n = \sum_{k=0}^{L-1} r_{n+k+D}\, r^{*}_{n+k+D} = \sum_{k=0}^{L-1} \left| r_{n+k+D} \right|^2 \qquad m_n = \frac{|c_n|^2}{(p_n)^2}$$

HiperLAN/2 Preambles

- Multiple preambles, different lengths
- General structure
  - Two waveforms A and B
  - Inverted versions of the waveforms IA and IB
- Broadcast packet preamble

A	IA	A	IA	IA	B	B	B	B	IB	CP	C	C

Generates a zigzag detection output

- Encodes information in preamble

HiperLAN/2 Preambles

- Downlink packet preamble (stations already synchronized)

CP	C	C

- General uplink preamble

B	B	B	B	IB	CP	C	C

- Long uplink preamble (antenna diversity)

B	B	B	B	B	B	B	B	B	IB	CP	C	C

Symbol Timing

- Determine start of the OFDM symbol
- WLAN must find symbol start before first OFDM symbol
- Broadcasting systems may examine multiple symbols before finding symbol start

Symbol Timing in WLAN

- Refine packet start estimate given by packet detector

$$\hat{t}_s = \arg\max_n \left| \sum_{k=0}^{L-1} r_{n+k} t_k \right|^2$$

- t_k is a known reference, e.g., end of short training symbols
- Possible to implement using only sample signs in computation (quantizing to 1 bit values)

Optimizing Symbol Timing in a Multipath Channel

- Estimated start of the symbols will vary slightly
- Fig. 2.10 shows three symbols, including CP and estimated DFT window
- Problem if estimation gives a late result
  - The frame start a few sample into the symbol
  - The end of the frame will contain samples from the next symbol (CP is the end of the next symbol)

Optimizing Symbol Timing in a Multipath Channel

- Solve problem with late estimations by moving estimation earlier
  - The complete CP before the frame is useful
  - Rule of thumb for 802.11a: 4-6 samples earlier
  - Generates a small rotation error in the subcarriers
- Possible to get samples from the previous symbol due to channel impulse response length
  - This contribution is weak as the last taps of the channel are small

Further Optimization of Multipath Reception

- Correlation will pick largest tap in the channel impulse response
  - The first tap is not always the strongest (no Line-of-Site)
  - Not choosing the first tap leads to drop in received signal energy
- Optimize detection to select first tap
  - Increase signal energy
  - Increase SNR

Continuous Transmission System Symbol Timing

- Do not have a preamble
- Data-aided systems
  - Inputs known training symbols in the data
  - Called Pilot Symbol
- Nondata-aided system
  - Use cyclic prefix for synchronisation
  - Can use same algorithm as for packet detection (delay and correlate)

Sample Clock Tracking

- Two different clock domains
  - Sample clock drifts relative to eachother
- Slow shift in the symbol timing point
  - Rotates the subcarriers
- Loss in SNR due to ICI
  - Incorrect sample instants causes loss of orthogonality of the subcarriers

Sample Clock Error

- T and T' transmitter and receiver sampling period

$$t_\Delta = \frac{T' - T}{T}$$

$$R_{l,k} = e^{j2\pi k t_\Delta l \frac{T_s}{T_u}} X_{l,k}\, sinc(\pi k t_\Delta) H_{l,k} + W_{l,k} + N_{t_\Delta}(l,k)$$

l : OFDM symbol index, k : subcarrier index

T_s : Duration of total OFDM symbol

T_u : Duration of the useful data portion

$W_{l,k}$: additive white noise

$N_{t\Delta}(l,k)$: additional interference

Sample Clock Error

- Outermost subcarriers most severly affected by the last term $N_{t\Delta}$
  - Power grows proportional to $(kt_\Delta)^2$
- Degradation of SNR in db:

$$D_n = 10\log_{10}\left(1 + \frac{\pi^2}{3}\frac{E_s}{N_0}(k t_\Delta)^2\right)$$

- WLAN has few subcarriers and small t_Δ => usually ignore $N_{t\Delta}$ effects
  - $kt_\Delta << 1$

Sample Clock Error

- More significant problem

$$e^{j2\pi k t_{\Delta} l \frac{T_s}{T_u}}$$

- Result in rotation of all subcarriers, with different amount in each one
- Rotation increases with consecutive OFDM symbols

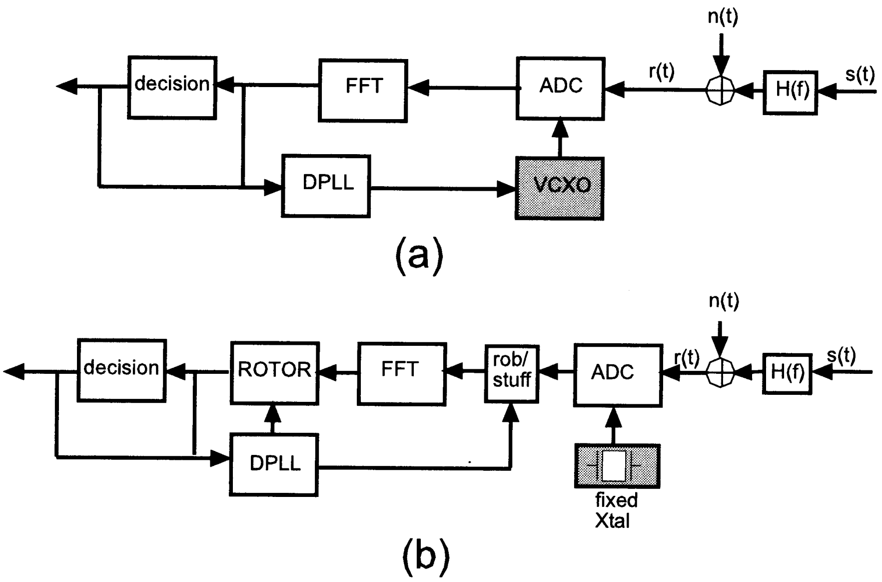
Estimating the Sampling Frequency Error

- Use the pilot subcarriers
  - Data sent on these are know
  - These subcarriers are distributed in the symbol
- Use the knowledge about the linear relationsship between phase rotation and subcarrier index

Correcting the Sampling Frequency Error

- Two methods
  - Change the sample clock rate using a VCO
  - Compensate using digital solution, allowing for use of fixed clock rate
- Fig 2.12 (next slide) shows the alternatives
  - Digital solution preferred
  - Analog solutions are costly

Structures for Correcting Sampling Frequency Errors



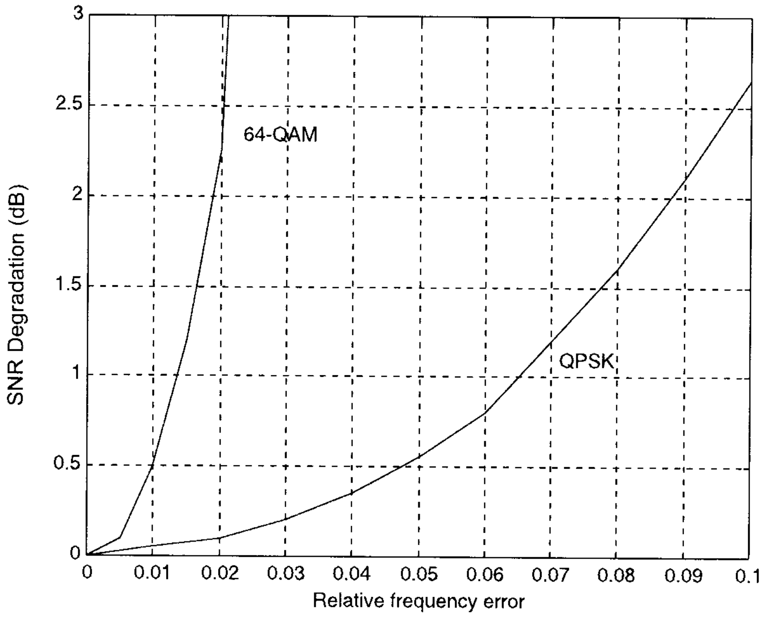
Frequency Synchronization

- Carrier frequency synchronisation
  - OFDM is sensitive to errors in carrier frequency
  - Errors results in reduced amplitude of the subcarriers plus ICI from neighbouring carriers

$$SNR_{Loss} = \frac{10}{3 \ln 10} (\pi T f_{\Delta})^2 \frac{E_s}{N_0} \quad dB$$

f_{Δ} : frequency error as a fraction of the subcarrier spacing
T : Sampling period

Frequency Error, Graphic View



Frequency Synchronization

- Estimation algorithms for carrier frequency offsets
  - Data-aided algorithms, based on special training information embedded in the transmitted signal
  - Nondata-aided algorithms, analyzing the received signal in frequency domain
  - Cyclic prefix based algorithms, use the inherent structure in OFDM provided by the cyclic prefix

Time domain approach

- Requires two consecutive repeated symbols
  - Both short and long training symbols can be used in the 802.11a standard
  - frequency error estimated as

$$\hat{f}_{\Delta} = \frac{-1}{2\pi D T_s} angle\left(\sum_{n=0}^{L-1} r_n r^*_{n+D} \right)$$

D is distance between identical samples

  - Calculation similar to delay and correlate preamble detection

Time domain approach

- Operating range
  - Defines how large frequency error can be estimated
  - Important property
  - Related directly to length of the symbol

$$\textit{angle in range} +/- \Pi$$

$$|f_{\Delta}| < \frac{\pi}{2\pi D T_s} = \frac{1}{D T_s}$$

Time domain approach

- One OFDM symbol
  => frequency error max 1/2 f_s
- Maximum frequency error in 802.11a (specified in the standard)
  - 20 ppm error in rec or trans. 40 ppm total @ 5.3 Ghz gives max error 212 kHz
- Within limits for short training symbol (D=16)
- To large if long training symbol is used

Post DFT approach

- Uses at least two consecutive repeated symbols
- Frequency error appears as equal phase shifts on all subcarriers (K = number of subcarriers)

$$\hat{f}_{\Delta} = \frac{-1}{2\pi} angle\left(\sum_{k=-K}^{K} R_{1,k} R_{2,k}^{*} \right)$$

- Similar to time domain

Post DFT properties

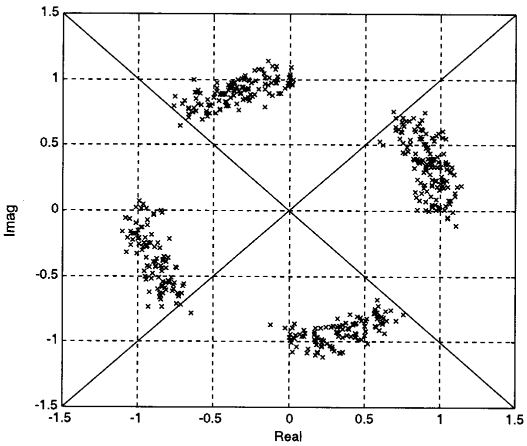
- Same limit as for time domain
- ICI introduced by DFT with frequency offset is useful information
- Usually use a two stage estimation
  - First short symbols give course estimate
  - Second long symbols improves the estimate
- Time domain is preferred as it is simpler to calculate (do not require DFT)

Alternative techniques for frequency error estimation

- Improve the limit on ± 0.5 subcarriers
- Use the correlation of the channel frequency response between adjacent subcarriers
- Autocorrelaton of the channel frequency respons will have a peak at lag corrsponding to the frequency offset

Carrier phase tracking

- Residual frequency error generates constellation rotation (same on all subcarriers)
  - Example:
    10 Symbols
    QPSK modulation
    3 kHz frequency error



Data aided carrier phase tracking

- Use pilot subcarriers
- Requires a channel estimate

$$\hat{\Phi} = angle\left(e^{-j2\pi n f_{\Delta}} \sum_{k=1}^{N_p} |H_k|^2 \right)$$

- Use of pilots removes the [-л,л) limit

Nondata-aided Carrier Phase Tracking

- All subcarriers get the same phase error
- Look at the angle between the hard decisions and the received data
- Angle increases from symbol to symbol
  - Biggest error at the end of the packet

Channel estimation

- Find the frequency response of the radio channel
  - Usually described as a discrete time FIR filter
- Channel is quasi stationary
  - Channel does not change during one data packet
- Channel estimation mandatory for OFDM systems using coherent modulation

Channel estimation

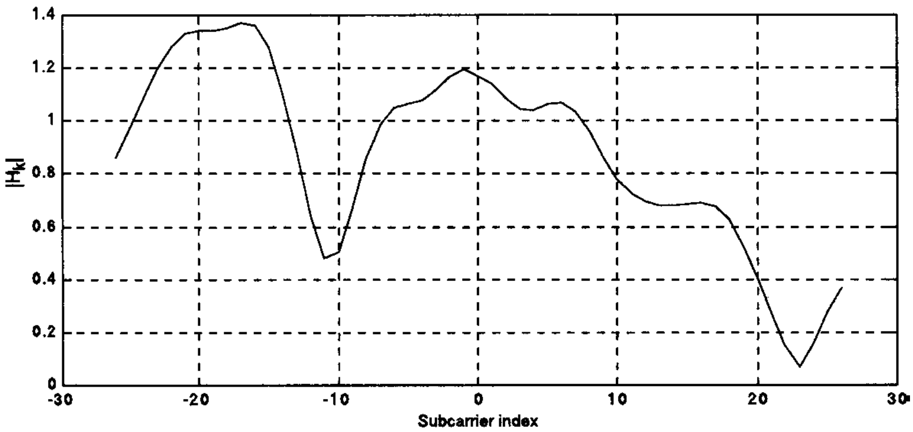
- Frequency domain
  - Using Training data
  - Using Pilot subcarriers and interpolation
- Time domain
  - Improved performance if impulse response length much less than the number of subcarriers
  - Requires additional computations

Training data based estimation

- Post DFT method
- Long training symbols
  - Sequences of +1 and -1
  - Calculate inverse of each
  - Use for every new symbol received
  - Use averaging of 2 training to reduce noise
  - Fixes initial error in guess of symbol start!

Channel amplitude response

- Neighboring channels are correlated



Clear Channel Assessment

- Used to synchronize a network
- Related to packet detection
- 802.11a:
  - 90% probability of detection of a preamble within 4 µs observation a signal at -82 dBm
  - 90% probability of detection without a preamble within 4 µs observation a signal at -62 dBm
- Receiver measures total received energy and tests limit

Signal Quality (SNR)

- Double sliding window give too good quality figures
  - Does not include fading properties
- Use distance information from viterbi decoder to perform estimation

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Other useful information

- Simulink communication toolbox demos
  - IEEE 802.11a WLAN Physical layer
    - Lacks some aspects such as synchronization
    - Includes support for multiple data rates
    - Fixed number of symbols
    - Useful to get hints on how to implement various features
  - Hiperlan/2 physical layer
    - Similar to 802.11a standard
  - Tail-Biting Convolutional Coding
    - Example use of Viterbi decoder