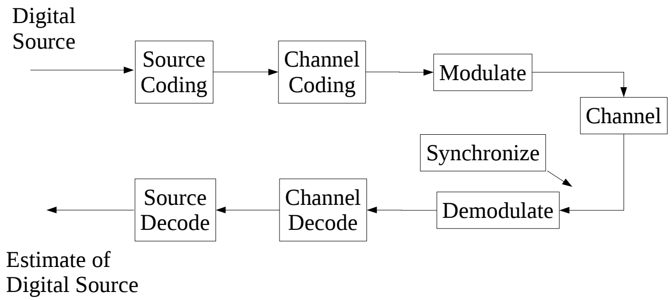
TSTE17 System Design, CDIO

- Introduction telecommunication
- OFDM principle
- How to combat ISI
- How to reduce out of band signaling

Components of a digital communication system



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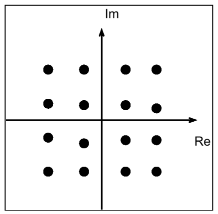
Quadrature Amplitude Modulation (QAM)

- Modulate both amplitude and phase
- Use equal distance between all points

16-QAM



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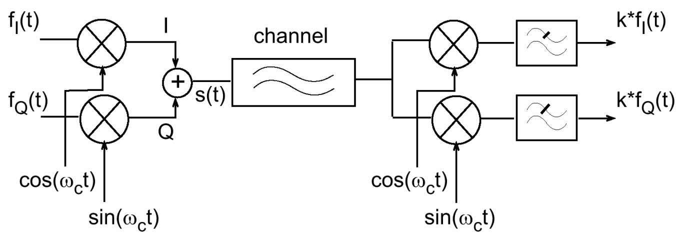
Creating the modulated carrier



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Wireless communication, cont.

- High data rate => Large bandwidth (BW)
- BW >> Coherence bandwidth => frequency selective fading
  - Coherence bandwidth = $1/T_m$ (multipath spread)
- Possible solutions
  - Use multiple narrow carriers
  - Use equalizer to even out effect (inverse of impulse response)

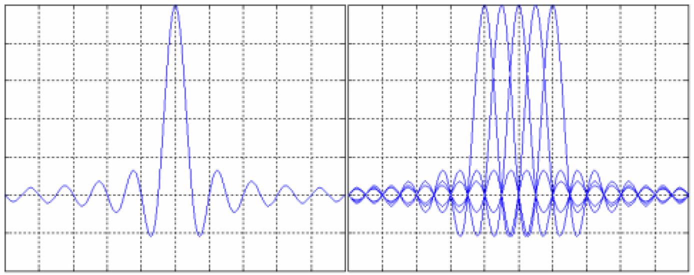
Multi-carrier Multiplexing

- Reduce effects of frequency selective fading by use of multiple carriers
- Each carrier must be non-overlapping with the other carriers to enable detection of data
- Leads to inefficient use of bandwidth

OFDM

- Use orthogonal carriers => better use of frequency spectrum
- Use integer number of periods for each carrier (carrier spacing $1/T_{symbol}$)
- Require that spectral peak of each carrier must coincide with the zero crossing of all other carriers

OFDM cont.



Single carrier frequency respons   Overlapping orthogonal carriers

Discrete Fourier Transform

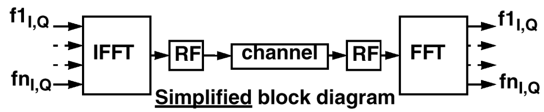
$$X(k)=\sum_{n=0}^{N-1} x(n)\mathrm{e}^{-j2\pi kn/N}$$

$$x(n)=\frac{1}{N}\sum_{k=0}^{N-1} X(k)\mathrm{e}^{j2\pi kn/N}$$

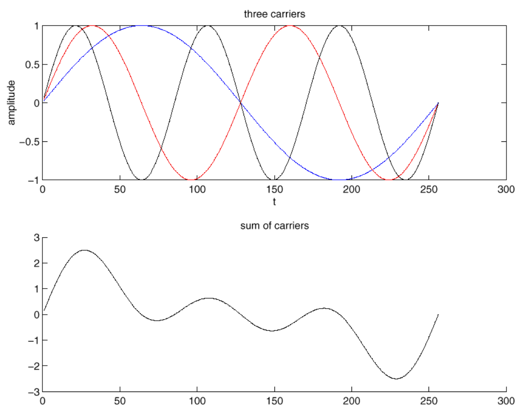
- Implemented using IFFT
  - O(nlogn) complexity

OFDM cont.

- Let inputs to the IFFT be the constellation points
  - Each coefficient controls the phase and amplitude of the subcarrier
- Requires the IFFT and FFT to be synchronized



IFFT subcarriers, example

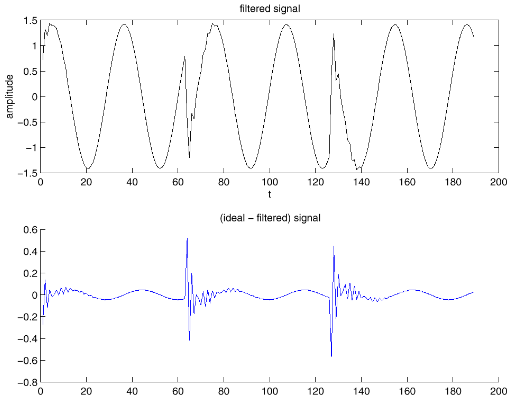


Avoiding Delay spread errors

- Inter Symbol Interference (ISI) caused by delay spread
  - Must avoid receiving multiple symbols
- Solution: Guard Intervals, do not send a new symbol until all delayed versions of the previous symbol has reached the reciever.
  - Empty transmission leads to Inter Carrier Interference (ICI)
- Guard interval > channel impulse respons length

Without Guard Interval

64
Point
IFFT



Without guard interval

- Adding scaled delayed versions of sinusoids
- Addition gives only a scaled and delayed signal
- Only works if the symbol length is increased without changing contents (frequency components)
- Remember the Discrete Fourier transform is cyclic!

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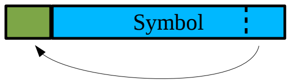
Guard Time

- Multipath => Mixing of two subsequent symbols in reciever
- Avoid mix by extending the symbol
  - Cyclic prefix



  - Same information found independent where inside the symbol
    - Varies in phase only depending on start

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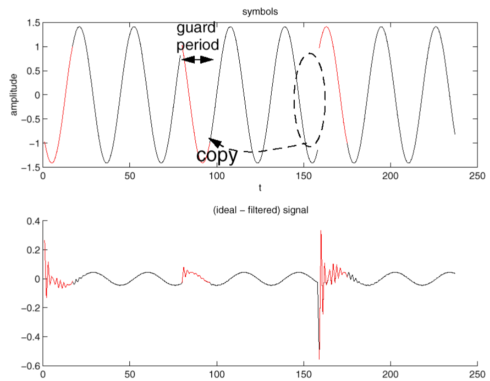
With Guard Interval using Cyclic prefix



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Cyclic prefix

- Two ways to increase symbol length
  - Prefix: Add copy of the end of the symbol to the front
  - Postfix: Add copy of the start of the symbol at the end
- Always gives a loss in data rate
  - Can be viewed as a reduction of power for each sent symbol
- Prefix can be changed to postfix by input rotation

Selection of parameters

- Dependency between cyclic pre/postfix length, delay spread, and number of subcarriers
  - Pre/post fix length > delay spread
  - Pre/post fix length / Symbol length
  - Symbol Time = 1/subcarrier distance
  - Ncarriers * Subcarrier frequency = BW
  - Datarate on subcarrier = Total datarate / Ncarrier

Parameter example

- T_m = 300 ns, Datarate = 50 Mbit/s, BW = 10 MHz, prefix/symbol length < 0.1
- Prefix at least 300 ns. Select guard interval = 4*300 = 1.2 us (to be safe)
- Symbol time = 6 * guard time = 7.2 us => guard time loss < 1 db
- Subcarrier distance = 1 / (symbol time – guard interval) = 1/(7.2 – 1.2) us = 167 kHz
- Maximum number of subcarriers = BW / subcarrier distance = 10 / 0.167 = 60

Parameter example, cont.

- 50 Mbit/s, 7.2 us symbol time => $50\cdot10^6 * 7.2\cdot10^{-6}$ = 360 bits/symbol
- 360/60 = 6 bits / subcarrier. The modulation required would be 64-QAM
- Final design: 64 QAM modulation, 64 point IFFT (60 subcarriers used for data), f_{sample} = $167\cdot10^3*64$=10.67 MSamples/s, 5 samples cyclic prefix, 69 samples long symbol.
- The above example could be modified to use lower datarate on a larger number of subcarrier

OFDM System

- Serial data stream to parallel data frames
- Modulate N subcarriers with BPSK, QPSK or QAM using the data frame
  - Data is in frequency domain (phase and amplitude for each subcarrier)
- Use IFFT for modulation (orthogonal subcarriers)
- Send the time domain signal

IFFT Algorithm

- Application of Divide and Conquer on the DFT transform
- Two approaches
  - Division in time
  - Division in frequency
- Complexity O(nlogn)

IFFT Algorithm

- Different ways to divide the input/output => different basic operation (butterfly)
  - Radix-2
  - Radix-4
  - Radix-8
- Tradeoff between number of operations and complexity of each operation

IFFT frequency map

- The input vector in frequency domain

  [DC, f_c, $2f_c$, ..., $(N/2-1)f_c$, $(N/2)f_c$, $-(N/2-1)f_c$, ..., $-2f_c$, $-f_c$]

  T : Symbol duration
  fc = 1/T : Subcarrier distance

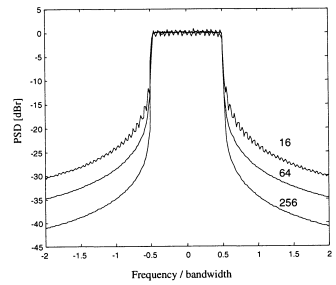
- DC and highest frequencies are usually not used
  - Requirements on A/D, D/A and mixers

Tricks with the IFFT

- Reciever FFT and IFFT can be designed simultaneously
  - Swap real and imaginary parts on input and swap real and imaginary parts on output
  - Rearrange order: 0, N-1, N-2, ... 2, 1
- Oversampling direct in the IFFT
  - Increase size of the IFFT, zero non-used channels
  - Increased computational load (n log n complexity)

Out of band spectrum

- IFFT generates unfiltered QAM subcarriers
- Transition between symbols generates out of band spectrum
- Reduced using windowing



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Windowing

- Smooth the symbol transitions
- Common type
  - Raised cosine window

$$w(t)=\begin{cases} 0.5+0.5\cos(\pi+t\pi/(\beta T_s)) & 0\leqslant t\leqslant betaT_s \\ 1,0 & \beta T_s\leqslant t\leqslant T_s \\ 0.5+0.5\cos((t-T_s)\pi/(betaT_s)) & T_s\leqslant t\leqslant(1+\beta)T_s \end{cases}$$

  - T_s Symbol interval < Total symbol duration

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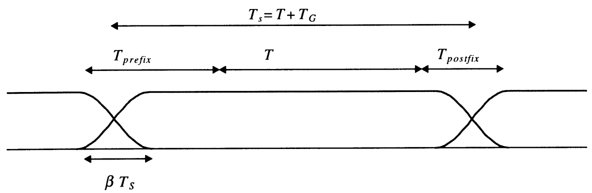
Windowing, cont.

- Windowing algorithm
  - T_{prefix} and/or $T_{postfix}$ samples added
  - Multiply by raised cosine window w(t)
  - Add to output of previous symbol



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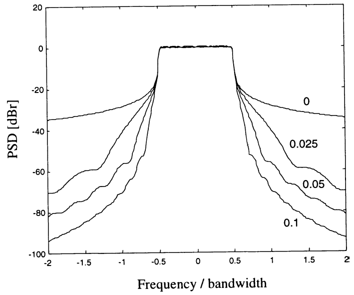
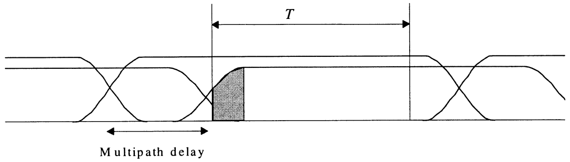
Windowing, cont.

- Small rolloff factor β gives large improvement



Windowing, cont.

- Large rolloff factor β reduces delay spread tolerance



Windowing, alternative

- Conventional filtering also possible
  - Convolution in time domain
- Must avoid ripple
  - Long ripple reduces delay spread tolerance
- Complexity higher
  - Windowing: a few multiplications per symbol
  - Filtering: a few multiplications per sample

OFDM Parameter Selection

- Input parameters
  - Bandwidth, bit rate, delay spread
- $T_{guard} \approx [2,4] * T_{delayspread}$
- $T_s \approx 5 * T_{guard}$
  - 1 dB SNR loss due to guard time
  - Longer symbol time => more subcarriers => more complex design & more sensitive to noise and frequency offsets

OFDM Parameter Selection, cont.

- Number of subcarriers
  - 3dB bandwidth / subcarrier spacing = 3dB bandwidth * ($T_s - T_{guard}$)
- Alternative
  - Bit rate / bit rate per subcarrier
- Both alternatives depends on the modulation used
  - Comparison of modulation and channel coding

OFDM Parameter Selection, cont.

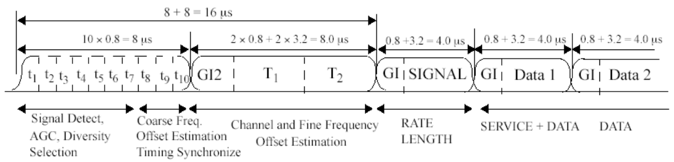
- Also important
  - Integer number of samples within the FFT/IFFT interval and symbol interval
  - Want the FFT/IFFT to be a power of 2
  - Need some of the subcarriers in the IFFT to be zero (oversampling)
  - May need to change some parameters slightly

Packet vs Continous

- Continous packet transmission
  - Digital Audio Broadcast (DAB)
  - Digital Video Broadcast (DVB)
  - No limit on synchronisation time
  - No multiaccess (sending data)
- Packet data transmission
  - Require fast synchronisation
  - Uses special training symbols (preamble)

802.11a Preamble

- Used to detect start of packet
- Used to synchronize receiver
- 10 short symbols + 2 long symbols



802.11a OFDM Parameters

- Bit rate 6, 9, 12, 18, 24, 36, 48, and 54 Mbps
- Modulation BPSK, QPSK, 16-QAM, 64-QAM
- Coding rates 1/2, 2/3, 3/4
- Number of subcarriers 52 (4 pilots)
- OFDM symbol duration 4 μs (800 ns guard interval)
- Signal bandwidth 16.66 Mhz
- Subcarrier spacing 312.5 kHz

802.16 WirelessMAN-OFDM

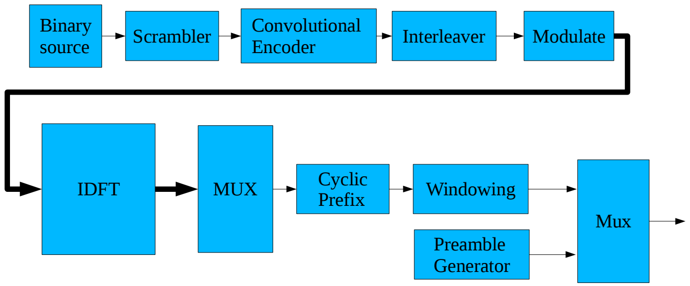
- One of 5 different Air interface standards
  - WirelessMAN-SC
  - WirelessMAN-SCa
  - WirelessMAN-OFDM
  - WirelessMAN-OFDMA
  - WirelessHUMAN

802.16 WirelessMAN-OFDM

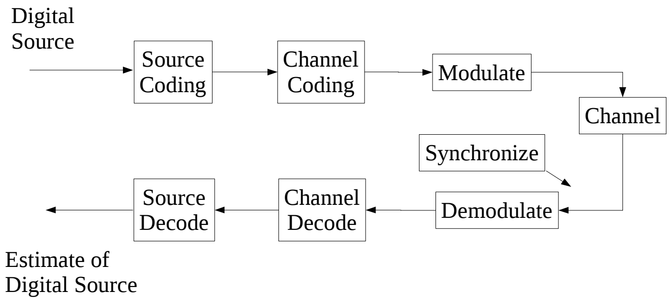
- Different options in standard
- 200 subcarriers used out of 256 available

802.11a & HiperLAN/2 Transmitter Details

- Excluding interpolation, A/D, and RF circuits

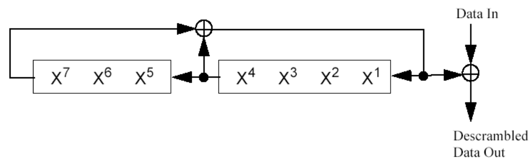


Components of a digital communication system



Scrambler

- Used to reduce probability of long sequences of 1 or 0.
- Pseudorandom sequences allows more efficient synchronisation at the reciever



802.11a vs HiperLAN/2 Physical Layer

HiperLAN/2

- Additional preamble
- Additional coding rate 9/16
- Possible to use 400 ns guard interval

802.11a

- Different initialization of the scrambler

Modulation details

- Three variables
  - Amplitude
  - Phase
  - Frequency
- Fixed subcarrier frequencies => Frequency modulation not possible
- Previously seen basic idea in BPSK, QAM etc.

Coherent and non-coherent modulation

- Coherent modulation
  - requires a phase lock between transmitter and reciever RF carrier waves.
  - Gives higher performance
  - Requires more complex reciever structure
- Non-coherent modulation
  - Simpler reciever structure
  - Can not use QAM, PSK, ASK