# EE382V:
# System-on-a-Chip (SoC) Design

## Lecture 4 – DRM Overview

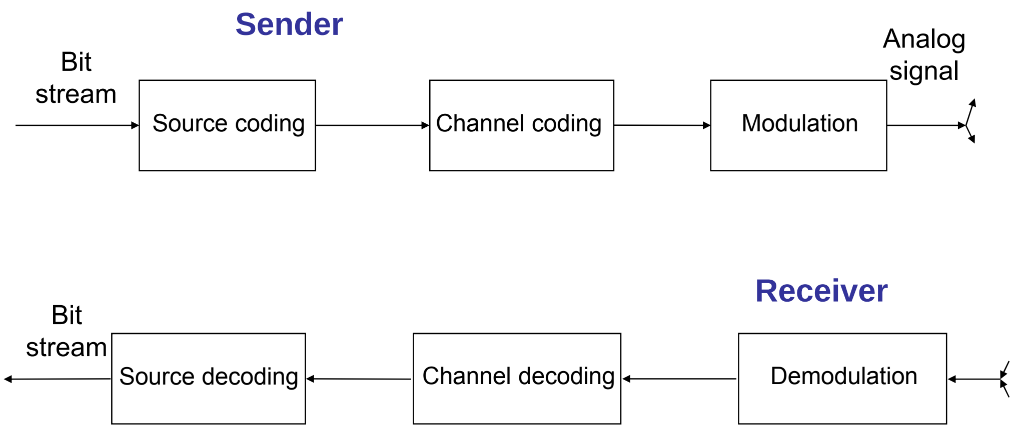
*Sources:*
*Dr. Saf Asghar, Austin,*
*Prof. Y. Richard Yang, Yale*
*Sriram Sambamurthy, UT*
*Chip Fleming, Spectrum Applications*

Andreas Gerstlauer
Electrical and Computer Engineering
University of Texas at Austin
`gerstl@ece.utexas.edu`

## Lecture 4: Outline

- **Introduction to OFDM**
  - Wireless transmission
  - Modulation
  - Coding
  - OFDM basics
- **DRM Tutorial**
  - Overview
  - Channel estimation
  - Synchronization

## Overview of Wireless Transmission



**Sender**

Bit stream

Source coding

Channel coding

Modulation

Analog signal

**Receiver**

Bit stream

Source decoding

Channel decoding

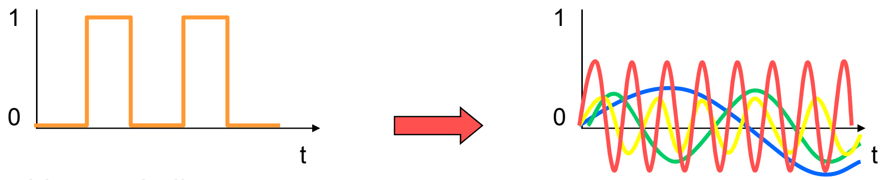
Demodulation

- ➢ **Why not send signals digitally?**

## Fourier Transform

- **Every signal can be decomposed as a collection of harmonics**

$$g(t) = \frac{1}{2}c + \sum_{n=1}^{\infty} a_n \sin(2\pi nft) + \sum_{n=1}^{\infty} b_n \cos(2\pi nft)$$

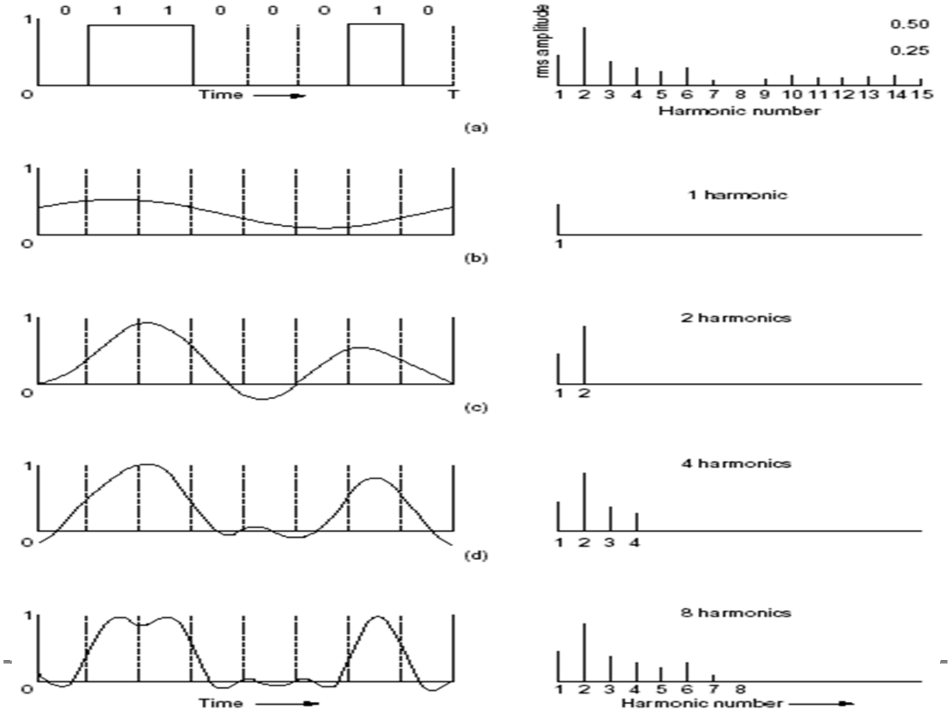


ideal periodical digital signal

decomposition

- ➢ **The more harmonics used, the smaller the approximation error**

## Fourier Transform (2)



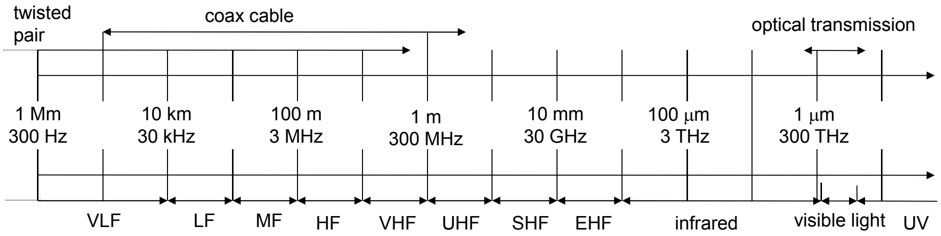
## Shannon Channel Capacity

- **Spectrum and bandwidth**
  - The maximum number of bits that can be transmitted per second by a physical channel is:

$$\boxed{W \log_2 (1 + \frac{S}{N})}$$

  - where W is the bandwidth of the channel, and S/N is the signal noise ratio, assuming Gaussian noise

# Frequencies for Communication



VLF = Very Low Frequency
LF = Low Frequency
MF = Medium Frequency
HF = High Frequency
VHF = Very High Frequency

UHF = Ultra High Frequency
SHF = Super High Frequency
EHF = Extra High Frequency
UV = Ultraviolet Light

- **Frequency and wave length: $\lambda = c/f$**
  - Wave length $\lambda$, speed of light $c \cong 3 \times 10^8$m/s, frequency $f$

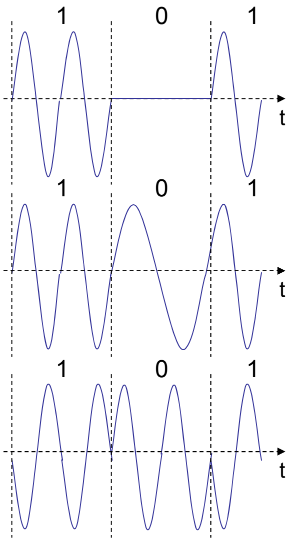
# Frequencies and Regulations

- **ITU-R holds auctions for new frequencies, manages frequency bands worldwide (WRC, World Radio Conferences)**

| | Europe | USA | Japan |
|---|---|---|---|
| **Cellular Phones** | **GSM** 450 - 457, 479 - 486/460 - 467,489 - 496, 890 - 915/935 - 960,<br>1710 - 1785/1805 - 1880<br>**UMTS** (FDD) 1920 - 1980, 2110 - 2190<br>**UMTS** (TDD) 1900 - 1920, 2020 - 2025 | **AMPS**, **TDMA**, **CDMA**<br>824 - 849,<br>869 - 894<br>**TDMA**, **CDMA**, **GSM**<br>1850 - 1910,<br>1930 - 1990 | **PDC**<br>810 - 826,<br>940 - 956,<br>1429 - 1465,<br>1477 - 1513 |
| **Cordless Phones** | **CT1+** 885 - 887, 930 - 932<br>**CT2**<br>864 - 868<br>**DECT**<br>1880 - 1900 | **PACS** 1850 - 1910, 1930 - 1990<br>**PACS - UB** 1910 - 1930 | **PHS**<br>1895 - 1918<br>**JCT**<br>254 - 380 |
| **Wireless LANs** | **IEEE 802.11**<br>2400 - 2483<br>**HIPERLAN 2**<br>5150 - 5350, 5470 - 5725 | 902 - 928<br>**IEEE 802.11**<br>2400 - 2483<br>5150 - 5350, 5725 - 5825 | **IEEE 802.11**<br>2471 - 2497<br>5150 - 5250 |
| **Others** | **RF - Control**<br>27, 128, 418, 433, 868 | **RF - Control**<br>315, 915 | **RF - Control**<br>426, 868 |

## Digital Modulation

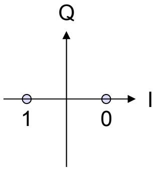
- **Amplitude shift keying (ASK)**
- **Frequency shift keying (FSK)**
- **Phase shift keying (PSK)**



➢ **Bandwidth requirements and resistance to interference?**

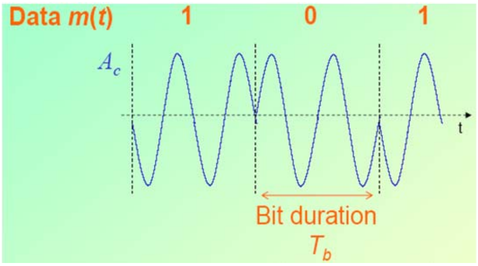
## Phase Shift Keying: BPSK

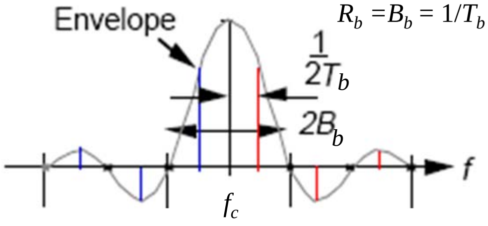
- **BPSK (Binary Phase Shift Keying)**
  - Bit value 0: sine wave
  - Bit value 1: inverted sine wave
  - Very simple PSK
- **Properties**
  - Low spectral efficiency
  - Robust, used e.g. in satellite systems



$f_c$ : freq. of carrier

$R_b = B_b = 1/T_b$

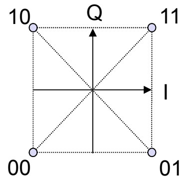




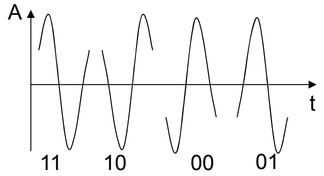
Spectral density of BPSK

## Phase Shift Keying: QPSK

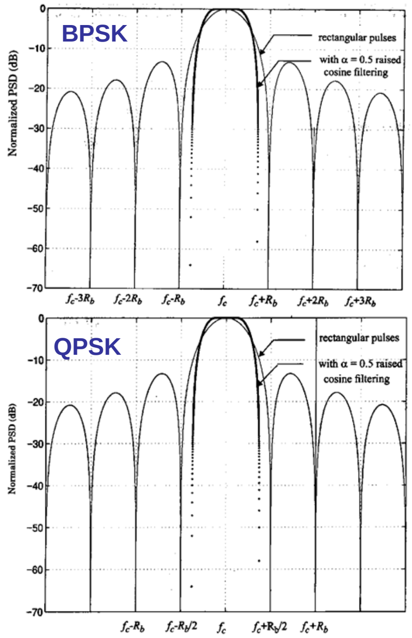
- **QPSK (Quadrature Phase Shift Keying)**
  - 2 bits coded as one *symbol*
  - Symbol determines shift of sine wave
  - Often also transmission of relative, not absolute phase shift
    - DQPSK - Differential QPSK

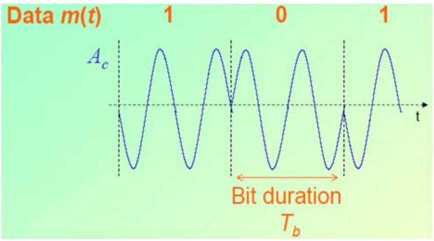


- **Properties**
  - Less bandwidth compared to BPSK



## Power Spectral Density (PSD)

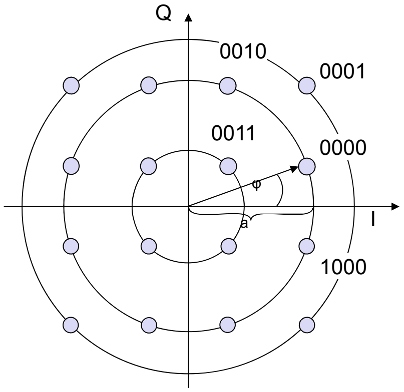




$f_c$: modulation frequency
$R_b$: frequency of data

## Quadrature Amplitude Modulation

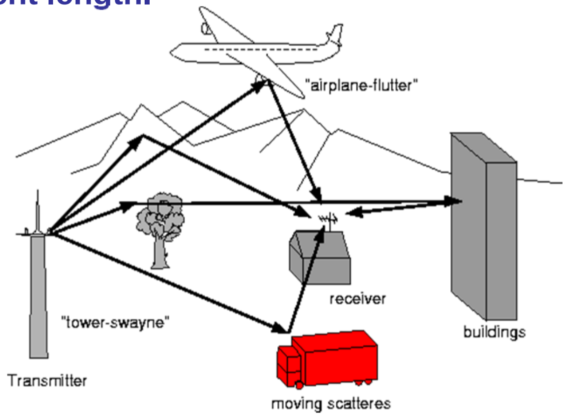
- **Quadrature Amplitude Modulation (QAM)**
  - Combines amplitude and phase modulation
  - It is possible to code *n* bits using one symbol
    - $2^n$ discrete levels
  - Bit error rate increases with *n*



- **Example**
  - 16-QAM (4 bits = 1 symbol)
  - Symbols 0011 and 0001 have the same phase *φ*, but different amplitude *a*
  - 0000 and 1000 have same amplitude but different phase

## Multipath Propagation

- **Transmitted signal arrives at the receiver in various paths of different length.**



➢ **Interference**
  - Inter-symbol interference (ISI) due to delay spread
  - Multiple versions of the same symbol interfere w/ each other

# Inter Symbol Interference (ISI)

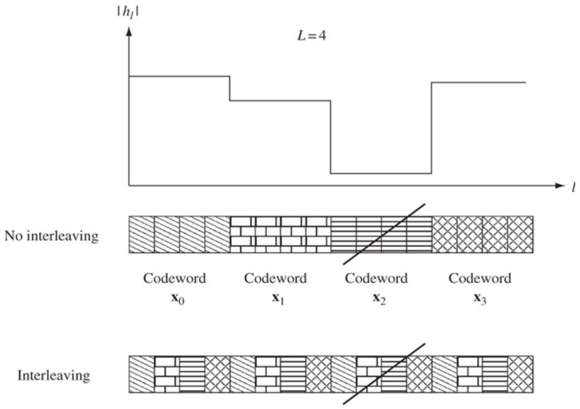
- **Delay spread**
  - Channel delay spread can cause ISI
  - Power delay profile conveys the multipath delay spread effects of the channel
  - RMS delay spread quantifies the severity of the ISI phenomenon
  - The ratio of RMS delay spread to the data symbol period determines the severity of the ISI
- **Reduced symbol rate**
  - Long symbols with guard time at symbol transitions
  - Delay spread related to frequency-selectivity of fading
  - Flat fading occurs when the symbol period is large compared to the delay spread

# Interference Channels

- **Multipath interference**
  - Fading due to constructive and destructive addition of multipath signals
  - Communication over a flat fading channel has poor performance due to significant probability that channel is in a *deep fade*
  - Reliability is increased by providing more resolvable signal paths that fade *independently*
- **Diversity can be provided across**
  - *Time*, *space* and *frequency*
  - How to exploit the added diversity in an *efficient* manner?

## Space and Time Diversity

- **Space diversity through Multiple-Input, Multiple-Output (MIMO) antenna systems**
- **Time diversity can be obtained by interleaving and *coding* over symbols across different coherent time periods**



Coding alone is not sufficient!

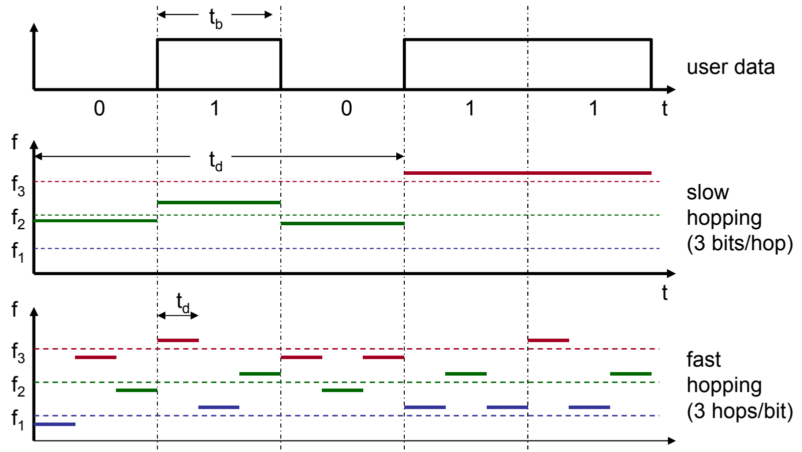
## Frequency Diversity

- **FHSS (Frequency Hopping Spread Spectrum)**
  - Discrete changes of carrier frequency
    - Sequence of frequency changes determined via pseudo random number sequence
    - Used in 802.11, GSM, etc.
  - Co-inventor: Hedy Lamarr
    - Patent# 2,292,387 issued on August 11, 1942
    - Intended to make radio-guided torpedoes harder for enemies to detect or jam
    - Used a piano roll to change between 88 frequencies

http://en.wikipedia.org/wiki/Hedy_Lamarr

# Frequency Hopping Spread Spectrum

- **Two versions**
  - Slow hopping: several user bits per frequency
  - Fast hopping: several frequencies per user bit



$t_b$: bit period $t_d$: dwell time

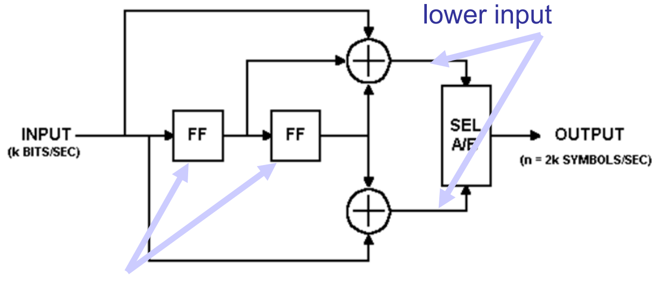
# Lecture 3: Outline

- **Introduction to OFDM**
  - ✓ Wireless transmission
  - ✓ Modulation
  - Coding
  - OFDM basics
- **DRM Tutorial**
  - Overview
  - Channel estimation
  - Synchronization

# Interleaving and Coding

- **Interleaving**
  - Spread the errors out in the bit-stream that is presented to the error correction decoder
  - Errors are not concentrated to one part of the bit stream
- **Channel coding**
  - Convolutional encoding and decoding + additional error correcting codes like Reed Solomon are used
    - – Forward error correction (no re-transmission is necessary)
    - – Decoding is performed using *Viterbi* decoder
  - ➢ First homework will include an exercise on convolutional encoding and decoding

# Convolution Encoder



Output upper input followed by lower input

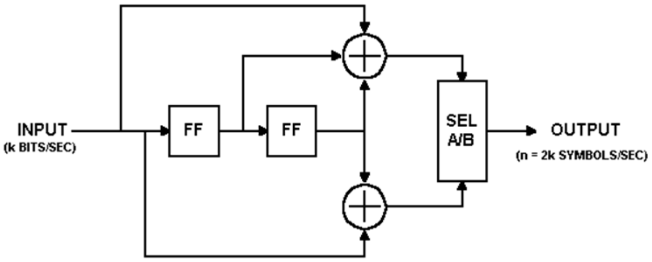
Flip flop
(stores one bit)

$k = 15$, $n = 30$, $r = ½$, $K = 3$, $m = 2$

- **Terminology**

| | |
|---|---|
| • *k* | number of message symbols |
| • *n* | number of codeword symbols |
| • *r* | rate = *k*/*n* |
| • *m* | number of encoding cycles an input symbol is stored |
| • *K* | number of input symbols used to compute each output symbol (decoding time exponentially dependent on *K*) |

## Encoding Example



- Both flip-flops set to 0 initially
- Input: 0 1 0 1 1 1 0 0 1 0 1 0 0 0 1
- Output: 00 11 10 00 01 10 01 11 11 10 00 10 11 00 11
- Flush encoder by clocking *m* = 2 times with 0 inputs.

## State Transition and Output Tables

| | Next State, if | |
|---|---|---|
| Current State | Input = 0: | Input = 1: |
| **00** | **00** | **10** |
| **01** | **00** | **10** |
| **10** | **01** | **11** |
| **11** | **01** | **11** |

**State transition table**

| | Output Symbols, if | |
|---|---|---|
| Current State | Input = 0: | Input = 1: |
| **00** | **00** | **11** |
| **01** | **11** | **00** |
| **10** | **10** | **01** |
| **11** | **01** | **10** |

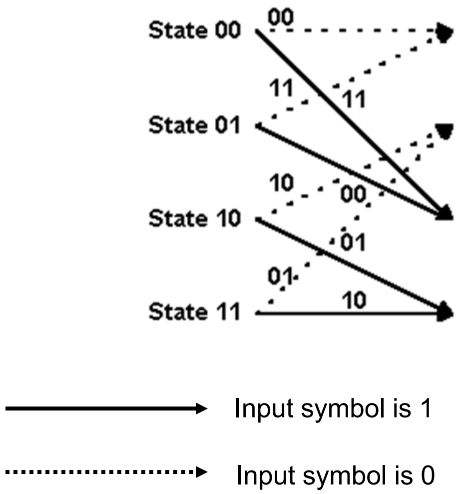
**Output table**

**$2^{K-1}$ rows, $2^k$ columns**

# State Transitions

| | Next State, if | |
|---|---|---|
| Current State | Input = 0: | Input = 1: |
| **00** | **00** | **10** |
| **01** | **00** | **10** |
| **10** | **01** | **11** |
| **11** | **01** | **11** |

| | Output Symbols, if | |
|---|---|---|
| Current State | Input = 0: | Input = 1: |
| **00** | **00** | **11** |
| **01** | **11** | **00** |
| **10** | **10** | **01** |
| **11** | **01** | **10** |

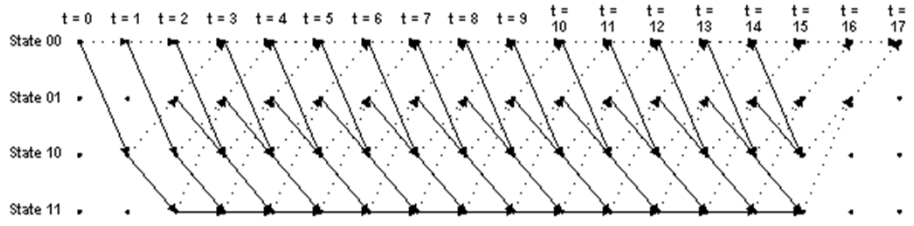


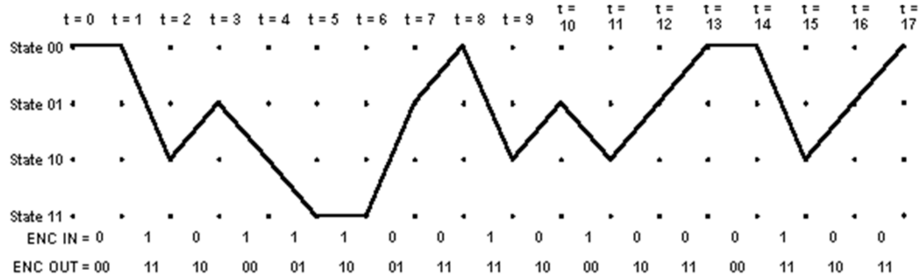
Input symbol is 1

Input symbol is 0

Arcs labeled with output symbols

# Trellis





## Viterbi Decoding

- **Decoding trellis-coded modulation in modems**
  - Highly parallelizable convolutional decoding algorithm
  - Most common forward error correction (FEC) technique used in space communications ($r = ½$, $K = 7$)
  - Usually implemented as serial concatenated block and convolutional coding – first Reed-Solomon, then convolutional
  - ➢ *Turbo codes* are a new parallel-concatenated convolutional coding technique

## Lecture 3: Outline

- **Introduction to OFDM**
  - ✓ Wireless transmission
  - ✓ Modulation
  - ✓ Coding
  - OFDM basics
- **DRM Tutorial**
  - Overview
  - Channel estimation
  - Synchronization

## OFDM

- **A solution for multi-path ISI channels**
  - Convert high-rate stream into several low-rate streams
  - Parallel streams are modulated onto orthogonal carriers
    - Frequency diversity across symbols
    - Data symbols modulated on these carriers without mutual interference
    - Overlap of the modulated carriers in the frequency domain (unlike FDM)
  - Interleaving and coding to address flat fading carriers
- ➢ **Orthogonal Frequency Division Multiplexing (OFDM)**
  - High bit-rate wireless applications
  - Without a high complexity receiver
    - (De)modulation using efficient (I)FFTs
  - OFDM is part of WLAN, DVB, and BWA standards
    - IEEE 802.11a standard
  - 4G wireless standards (LTE)

## OFDM Mathematics

$$s(t) = \sum_{k=0}^{N-1} X_k e^{j2\pi f_k t} \qquad t \equiv [0, T_{os}]$$

Orthogonality condition:

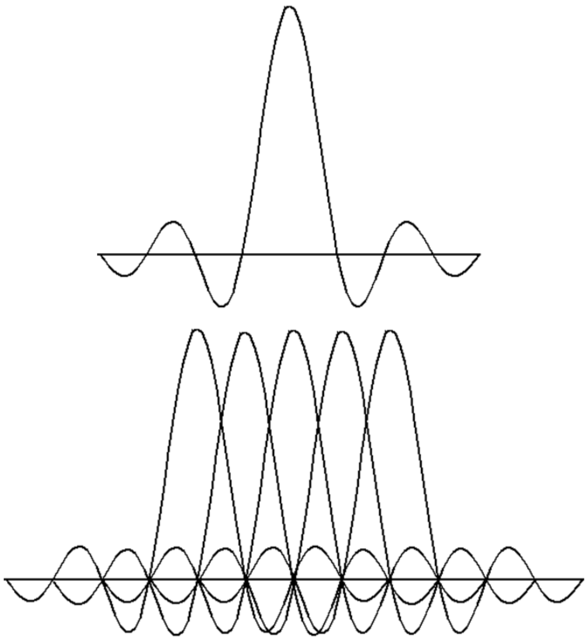
$$\int_0^{T_{os}} g_1(t).g_2^*(t)dt = 0$$

In our case:

$$\int_0^{T_{os}} e^{j2\pi f_p t}.e^{-j2\pi f_q t} dt = 0$$

For $p \neq q$ where $f_k = k/T_{os}$

## Transmitted Spectrum



## OFDM Basics

- **Terminology**
  - Orthogonal carriers referred to as subcarriers $\{f_i, i=0,....N-1\}$
  - OFDM symbol period $\{T_{os} = N \times T_s\}$
  - Subcarrier spacing $D_f = 1/T_{os}$
- **Implementation**
  - Take $N$ symbols and use one symbol for each subcarrier
  - Straightforward implementation can be expensive if we use one oscillator for each subcarrier
  - Key observation: consider data as coefficients in the frequency domain, use inverse Fourier transform to generate time-domain sequence

# OFDM Example

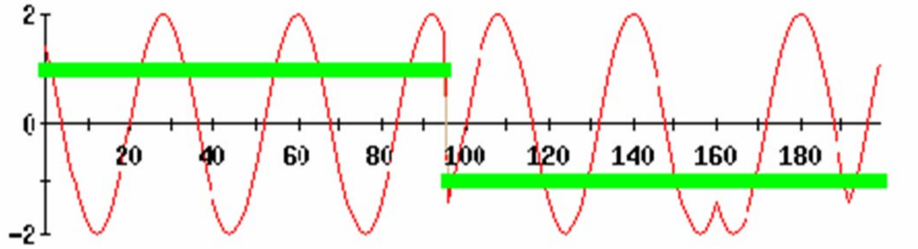
- **24 bits of data to be transmitted**
  - 1 1 -1 -1 1 1 1 -1 1 -1 -1 -1 -1 1 -1 -1 -1 1 1 -1 -1 -1 1 1

- **4 subcarriers, each modulated using BPSK**

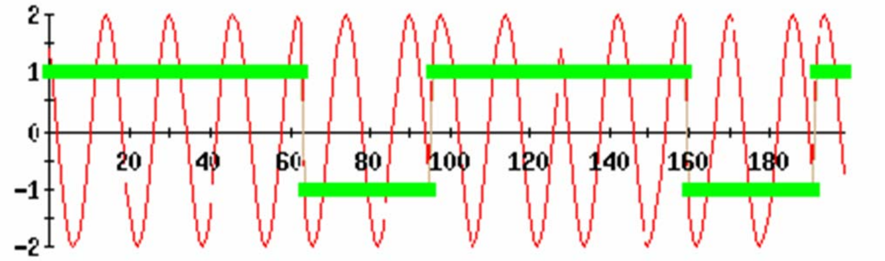
| ***c1*** | ***c2*** | ***c3*** | ***c4*** |
|---|---|---|---|
| 1 | 1 | -1 | -1 |
| 1 | 1 | 1 | -1 |
| 1 | -1 | -1 | -1 |
| -1 | 1 | -1 | -1 |
| -1 | 1 | 1 | -1 |
| -1 | -1 | 1 | 1 |

# OFDM Example (cont'd)

- **Sub-carrier 1 and the bits it is modulating (1st column)**

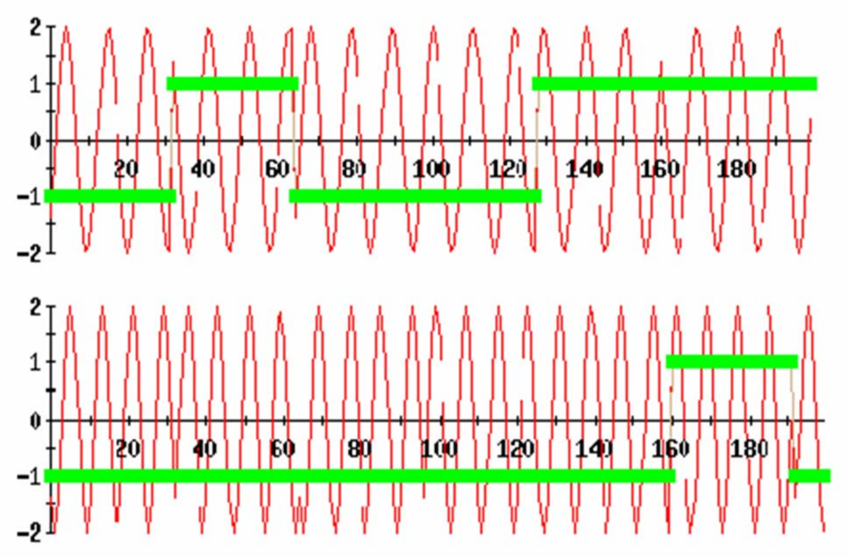


- **Sub-carrier 2 and the bits it is modulating (2nd column)**

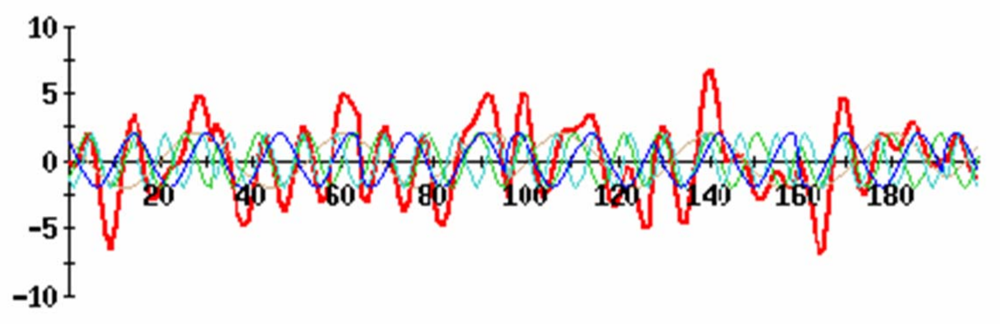


## OFDM Example (cont'd)

- Sub-carrier 3 and 4 (3rd and 4th column)



## Generated OFDM Signal

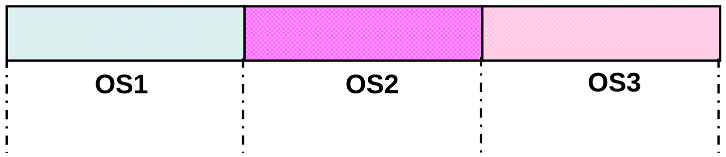


## OFDM and FFT

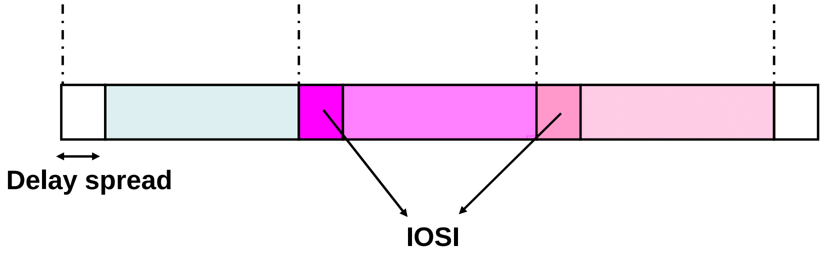
- **Fast Fourier Transform (FFT)**
  - Samples of the multicarrier signal can be obtained using the inverse FFT (IFFT) of the data symbols - a key issue
  - FFT used at the receiver to obtain the data symbols
  - No need for 'N' oscillators, filters, etc.
  - Popularity of OFDM is due to the use of IFFT/FFT which have efficient implementations
- **Interpretation of FFT and IFFT**
  - IFFT at the transmitter & FFT at the receiver
  - Data symbols modulate the spectrum and the time domain symbols are obtained using the IFFT
  - Time domain symbols are then sent on the channel
  - FFT at the receiver to obtain the data

## Interference Between OFDM Symbols

- **Transmitted signal**



- **Due to delay spread ISI occurs**



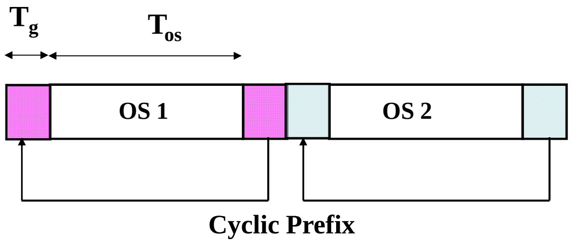
- **Solution could be guard interval between OFDM symbols**

# Cyclic Prefix

- **Inter-OFDM symbol interference (IOSI)**
  - Zeros used in the guard time can alleviate interference between OFDM symbols
  - Orthogonality of carriers is lost when multipath channels are involved

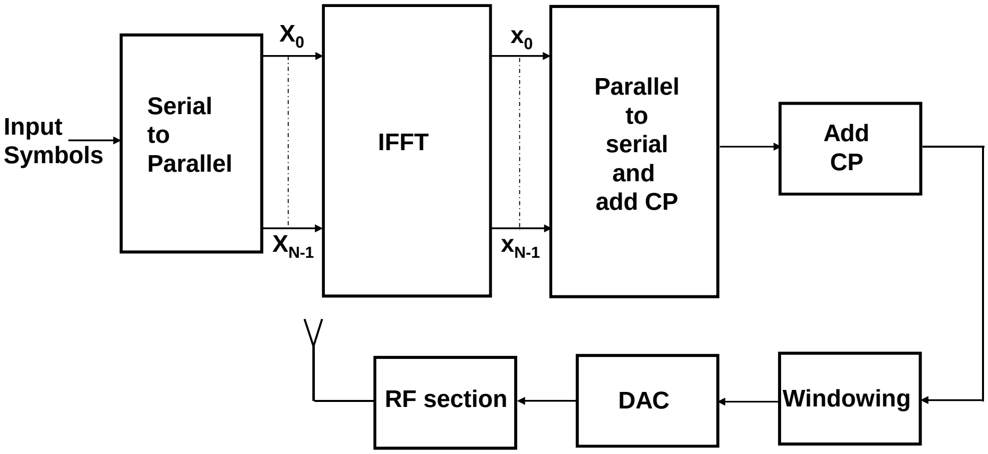
➢ **Cyclic prefix can restore the orthogonality**
  - Convert a linear convolution channel into a circular convolution channel
  - This restores the orthogonality at the receiver
  - Energy is wasted in the cyclic prefix samples

# Cyclic Prefix Illustration



| | |
|---|---|
| **OS1,OS2** | **OFDM Symbols** |
| **$T_g$** | **Guard Time Interval** |
| **$T_s$** | **Data Symbol Period** |
| **$T_{os}$** | **OFDM Symbol Period - $N * T_s$** |

# OFDM Transmitter



Input Symbols

Serial to Parallel

$X_0$

$X_{N-1}$

IFFT

$x_0$

$x_{N-1}$

Parallel to serial and add CP

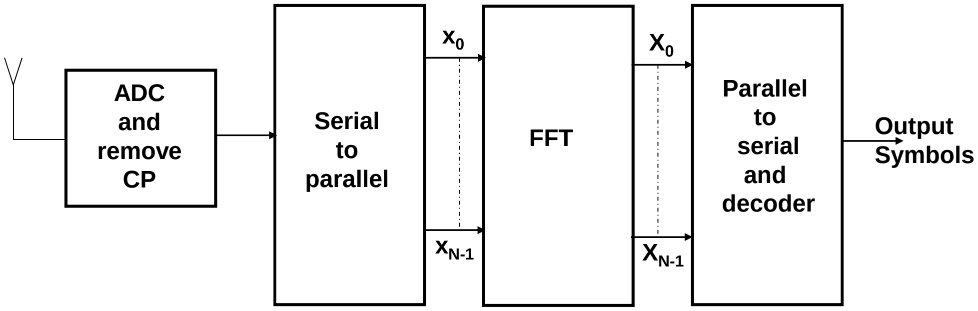
Add CP

Windowing

DAC

RF section

# OFDM Receiver



ADC and remove CP

Serial to parallel

$x_0$

$x_{N-1}$

FFT

$X_0$

$X_{N-1}$

Parallel to serial and decoder

Output Symbols

## Synchronization

- **Timing and frequency offset can influence performance**
  - Inter-symbol interference (ISI)
  - Inter-carrier interference (ICI)

- **Timing influences demodulation window**
  - Shift of demodulation window leads to ISI
- **Frequency influences orthogonality of subcarriers**
  - Loss of orthogonality leads to ICI

- ➢ **Timing and frequency synchronization**
  - Acquisition followed by tracking

## References and Sources

- http://www.ert.rwth-aachen.de/Projekte/Theo/OFDM/www_ofdm.html
- http://www.wave-report.com/tutorials/OFDM.htm
- http://www.radio-electronics.com/info/rf-technology-design/ofdm/ofdm-basics-tutorial.php
- http://eesof.tm.agilent.com/docs/adsdoc2005A/dgwlan/dgwlan013.html
- http://bwrc.eecs.berkeley.edu/Classes/EE225C/Lectures/Lec16_ofdm.pdf
- http://cnx.org/content/m11762/latest/
- http://drm.sourceforge.net/
- http://www.intel.com/technology/itj/2003/volume07issue03/art05_air/vol7iss3_art05.pdf
- http://ieeexplore.ieee.org/Xplore/login.jsp?url=/iel5/35/27889/01244928.pdf
- http://www.ece.rochester.edu/research/wcng/papers/theses/goldsmith_MSthesis.pdf
- http://developer.intel.com/technology/itj/2004/volume08issue03/art03_scalableofdma/vol8_art03.pdf
- http://www.complextoreal.com/chapters/ofdm2.pdf

## Lecture 3: Outline

- ✓ **Introduction to OFDM**
  - ✓ Wireless transmission
  - ✓ Modulation
  - ✓ Coding
  - ✓ OFDM basics

- **DRM Tutorial**
  - Overview
  - Channel estimation
  - Synchronization

## DRM Motivation

- **DRM has a small bandwidth of less than 20 kHz**
  - Easy to handle with current PC sound cards
- **Real-time software implementation possible**
  - Open-source Dream reference implementation
  - Infeasible for embedded, low-power implementations
  - ➢ Custom SoC design

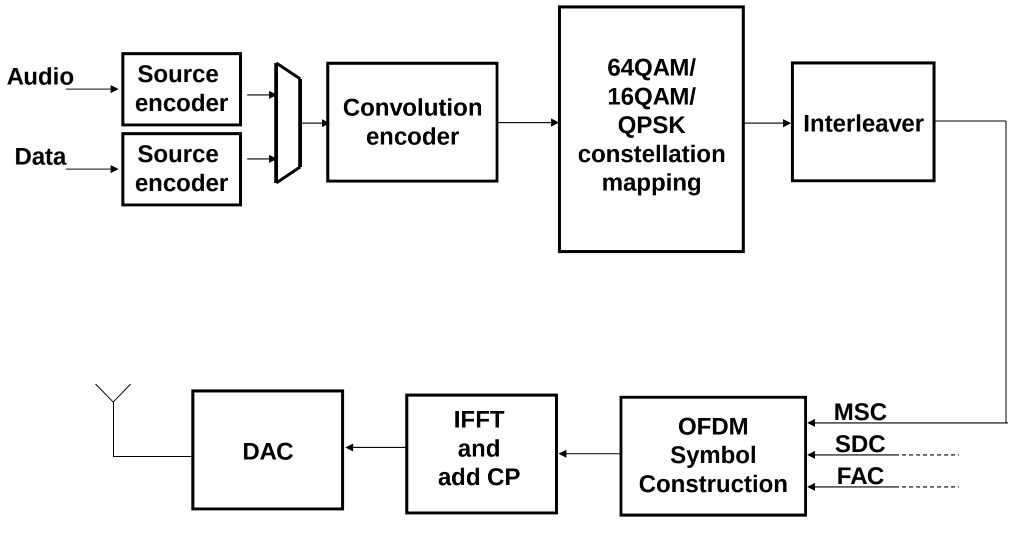
- **OFDM**
  - High data rate in multipath environments
  - Need for synchronization
    - – Vulnerable to frequency offsets (causes ICI)
    - – Timing critical if delay spread is in the range of the guard interval (ISI)

# DRM OFDM Rates/Modes

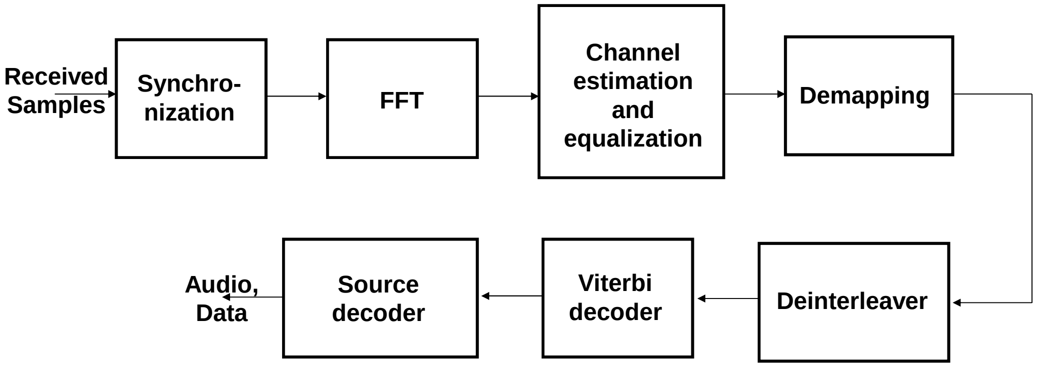
| Mode | Carrier spacing (Hz) | Number of carriers per bandwidth | | | | | | OFDM length (ms) | Guard interval (ms) | Symbol length (ms) | Symbols per frame |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 4.5 kHz | 5 kHz | 9 kHz | 10 kHz | 18 kHz | 20 kHz | | | | |
| A | 41 2/3 | | | 204 | 228 | 412 | 460 | 24 | 2.66 (1/9) | 26.66 | 15 |
| B | 46 7/8 | | | 182 | 206 | 366 | 410 | 21.33 | 5.33 (1/4) | 26.66 | 15 |
| C | 68 2/11 | | | - | 138 | - | 280 | 14.66 | 5.33 (4/11) | 20.00 | 20 |
| D | 107 1/7 | | | - | 88 | - | 178 | 9.33 | 7.33 (11/14) | 16.66 | 24 |

- **Multi-level coding (MLC) scheme**
  - 64-QAM, 16-QAM or 4-QAM (QPSK) modulation
  - 1/2 rate convolution encoder with size K=7
    - Puncturing for variable number of bits within an OFDM symbol
  - Interleaving of cells in OFDM symbols, frames, superframes
    - Main service channel (MSC) with 4 audio or data streams
    - Fast access and service description channels (FAC, SDC)
- **MPEG4 AAC (w/ SBR), CELP or HVCX audio source coding**

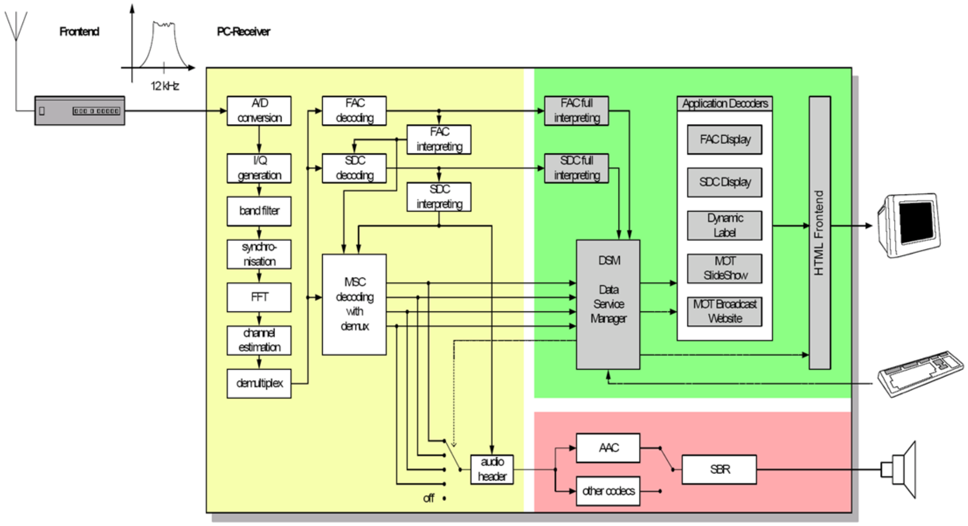
# DRM Transmitter



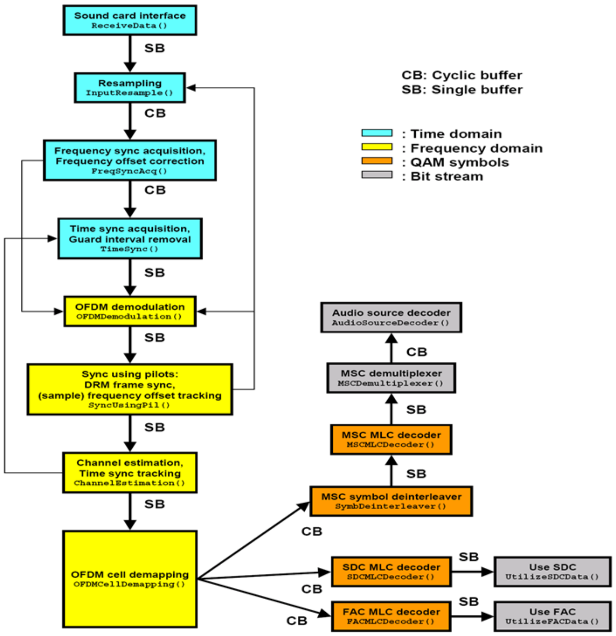
## DRM Receiver



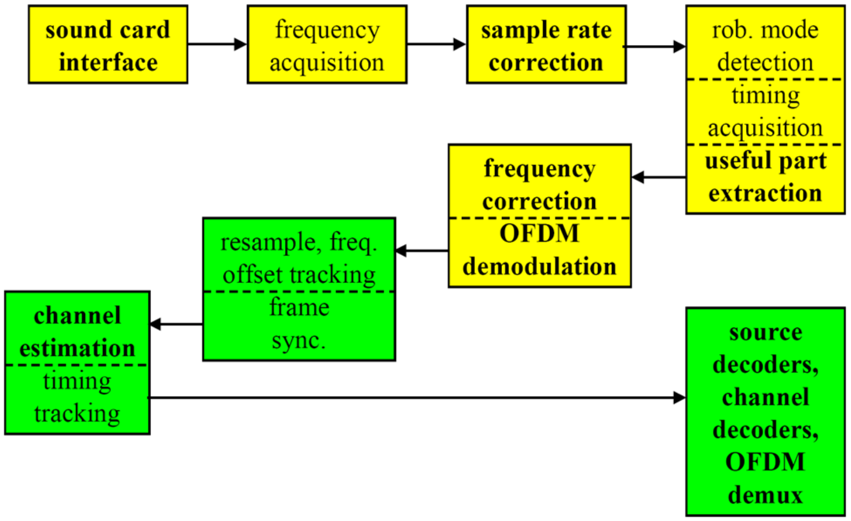
## PC-Based DRM Architecture



## Dream DRM Software Architecture



## Dream Software Overview



**sound card interface**

frequency acquisition

**sample rate correction**

rob. mode detection

timing acquisition

**useful part extraction**

**frequency correction**

**OFDM demodulation**

resample, freq. offset tracking

frame sync.

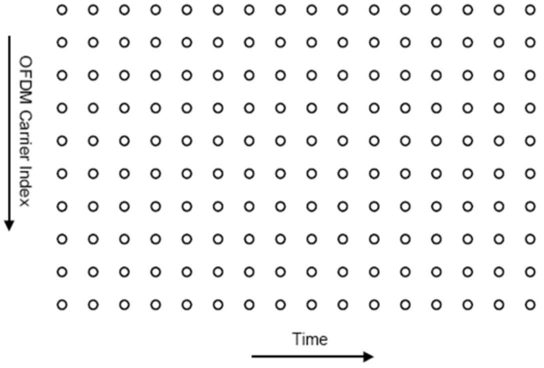
**channel estimation**

timing tracking

**source decoders, channel decoders, OFDM demux**

*Source: A. Kurpiers, V. Fischer, Darmstadt Univ.*

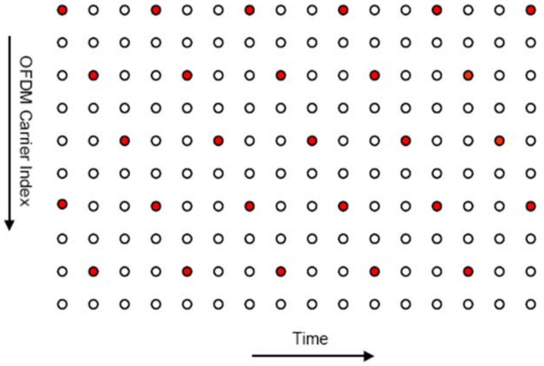
# Channel Estimation



On every OFDM carrier the channel transfer function $H_{k,l}$ has to be estimated

Source: A. Kurpiers, V. Fischer, Darmstadt Univ.

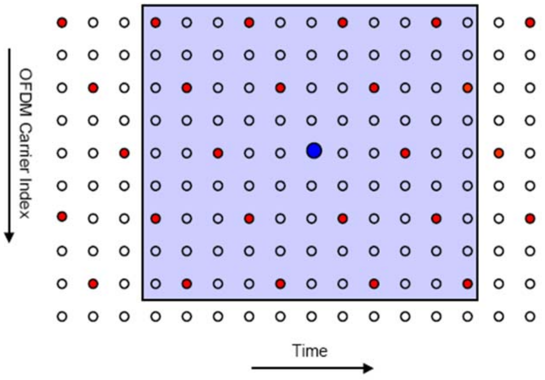
# Channel Estimation



Scattered pilots allow for easy channel estimation

Source: A. Kurpiers, V. Fischer, Darmstadt Univ.

## Channel Estimation

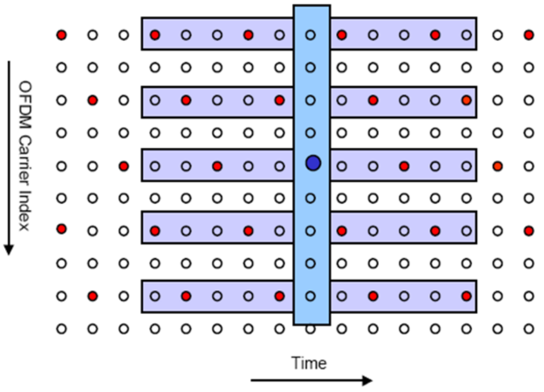


**two dimensional Wiener Interpolator is optimal**

**but too complex**

*Source: A. Kurpiers, V. Fischer, Darmstadt Univ.*

## Channel Estimation



**Wiener Interpolator can be separated into two 1D filters**

*Source: A. Kurpiers, V. Fischer, Darmstadt Univ.*

## Channel Estimation: Wiener Interpolation

- **MMSE solution:** $\hat{\mathbf{h}} = \mathbf{R}_{h\hat{p}}\mathbf{R}_{\hat{p}\hat{p}}^{-1}\hat{\mathbf{p}}$ $\quad \mathbf{R}_{\hat{p}\hat{p}} = \mathbf{R}_{pp} + \frac{1}{\mathrm{SNR}}\mathbf{I}$

  $\mathbf{R}_{h\hat{p}}$ : Cross-covariance matrix between $\mathbf{h}$ and the noisy pilot estimates $\hat{\mathbf{p}}$

  $\mathbf{R}_{\hat{p}\hat{p}}$ : Auto-covariance matrix of the pilot estimates
- **Doppler profile of a typical shortwave channel:** $|H(f)| = \frac{1}{\sqrt{2\pi\sigma_{\mathrm{d}}^2}} e^{-\frac{f^2}{2\sigma_{\mathrm{d}}^2}}$

  **Resulting correlation function:** $r_{f_d}(\Delta k) = e^{-2(\sigma_{\mathrm{d}}\,\pi\, NT\Delta k)^2}$
- **Assuming uniform delay power spectrum with the length of the guard-interval:**

  $$r_\tau(\Delta l) = \mathrm{sinc}\left(\Delta l \frac{N_{\mathrm{G}}}{N}\right)$$

  $N_{\mathrm{G}}$ : Length of guard-interval

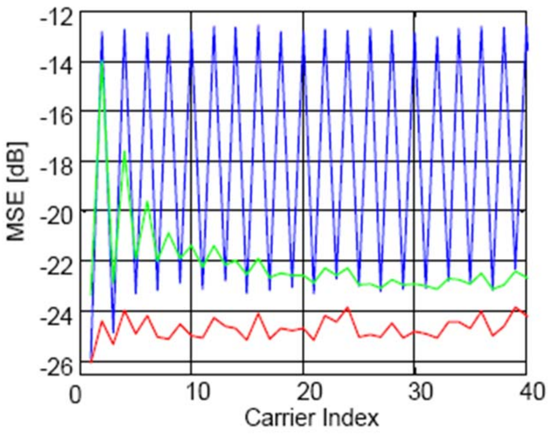
  $N$ : Length of useful part

*Source: A. Kurpiers, V. Fischer, Darmstadt Univ.*

## Channel Estimation

The following parameters were used in this simulation:
*Robustness mode B, 10 kHz bandwidth, 20 dB SNR, channel No. 3 (US Consortium)*
The mean squared error (MSE) between the estimated channel and an ideal channel estimation is plotted.

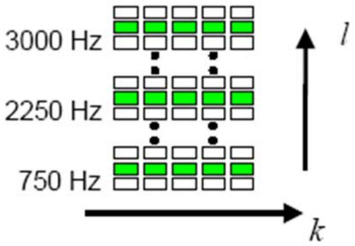
- **Blue line**: Linear interpolation
- **Green line**: Windowed DFT algorithm
- **Red line**: Wiener interpolation (using all pilot carriers for each interpolated cell



*Source: A. Kurpiers, V. Fischer, Darmstadt Univ.*

## Frequency Acquisition (1)

- Exploiting the power difference of the three frequency pilot cells and data cells
  - **Pilot cells:** boosted, continuous tones
  - **Data cells:** power spread due to modulation



- FFT- based algorithm
  - Squared norm of FFT calculated over more than one symbol (Estimation of PSD)
  - Correlation with known frequency pilot positions
- **Effects of a large FFT window:**
  - Statistical properties of data cells more distinct, peak detection improved
  - BUT fading channel effects reduce performance

*Source: A. Kurpiers, V. Fischer, Darmstadt Univ.*

## Frequency Acquisition (2)

- Estimation of PSD

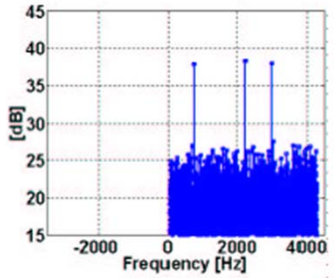
$$R_{m,l} = \left| \sum_{n=0}^{N_{ac}-1} r_{n+l}\, e^{-j\frac{2\pi}{N_{ac}}nm} \right|^2$$

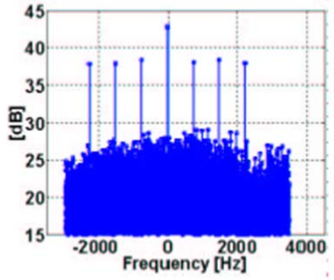
- Correlation with pilot positions

$$\hat{f}_{acq} = \frac{f_s}{N_{ac}} \max_{m} \left\{ \sum_{i=0}^{2} R_{m+p_{f_{ac}}(i),l} \right\}$$

- Placement of FFT window arbitrary

  ➡ No prior timing information needed
- Average error rate < 10% for all channels and robustness modes

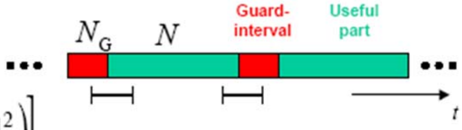




*Source: A. Kurpiers, V. Fischer, Darmstadt Univ.*

## Time Acquisition (1)

- Guard-interval correlation

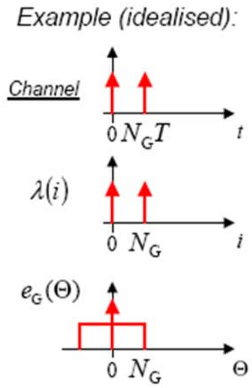


$$\lambda(i)=\sum_{n=i}^{i+N_G-1}\left[\underline{\left|r_n r_{n+N}^{*}\right|}-\left(\left|r_n\right|^2+\left|r_{n+N}\right|^2\right)\right]$$

- Using energy in guard-interval
  - For multipath fading channel

$$e_G(\Theta)=\sum_{m=\Theta}^{\Theta+N_G-1}\lambda(m)$$

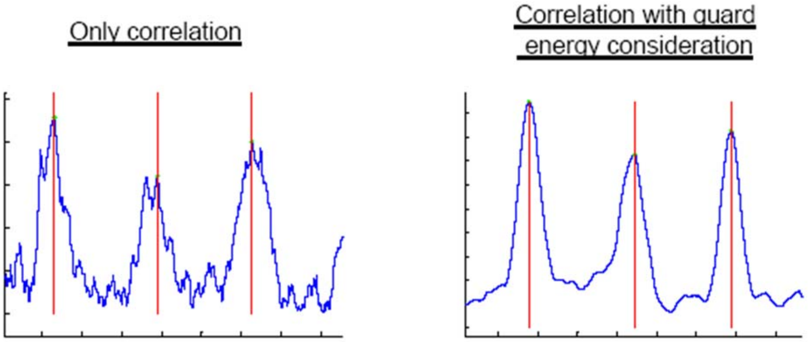
- $\arg\max\{e_G(\Theta)\}$ is the resulting estimated timing position



Source: A. Kurpiers, V. Fischer, Darmstadt Univ.

## Time Acquisition (2)

**Influence of Guard Energy Consideration on a two path fading channel:**



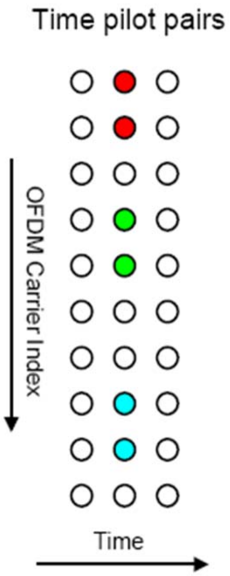
Only correlation

Correlation with guard energy consideration

Robustness modes can be detected by using time difference between peaks (period equals useful part duration $NT$)

Source: A. Kurpiers, V. Fischer, Darmstadt Univ.

## Frame Synchronization



**Assumption:** channel is identical at adjacent pilot positions: $H_{k,p_t(i)} \approx H_{k,p_t(i)+1}$

With this „channel estimate“ we can calculate the squared distance between received and pilot cells:

$$\gamma(k) = \sum_{i=0}^{L_T-1} \left| z_{k,p_t(i)} \frac{c_{k,p_t(i)+1}}{c_{k,p_t(i)}} e^{-j\frac{2\pi}{N}\frac{N_G}{2}} - z_{k,p_t(i)+1} \right|^2$$

This yields a minimum at the beginning of the frame

*Source: A. Kurpiers, V. Fischer, Darmstadt Univ.*

## Frequency Tracking

- **Frequency offset estimation based on phase increment between two successive symbols at the frequency pilot carriers**
  - Frequency offset causes phase shift

$$\hat{\Omega} T_s = \arg\left\{ \sum_{j=0}^{2} z_{l+1,p_f(j)}\left(\hat{f}_{\mathrm{acq}}\right) z^{*}_{l,p_f(j)}\left(\hat{f}_{\mathrm{acq}}\right) \right\}$$

$z_{l,k}$ : Output of the FFT unit for the *l* -th symbol and the *k*-th sub-carrier

$T_s$ : Duration of one symbol

$p_f(j)$ : Positions of frequency pilots

*Source: A. Kurpiers, V. Fischer, Darmstadt Univ.*

## Time Tracking

- Using averaged IFFT-transformation of windowed channel estimation $(\hat{H}_{k,l})$ for estimation of channel impulse response

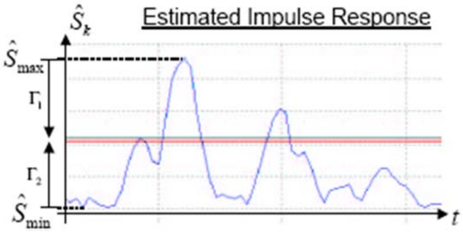
$$\hat{S}_m(k) = \frac{1}{N_{\text{TiTr}}} \sum_{i=0}^{N_{\text{TiTr}}-1} \left| \text{IFFT}\left\{ \hat{H}_{k-i,l} \right\} \right|^2$$

- Afterwards using peak detection for first path estimation

$$-\hat{e} = \frac{1}{2}\min\left\{ m \mid \hat{S}_m(k) > \Gamma, \text{and } \hat{S}_m(k) > \hat{S}_{m+1}(k) \right\}$$

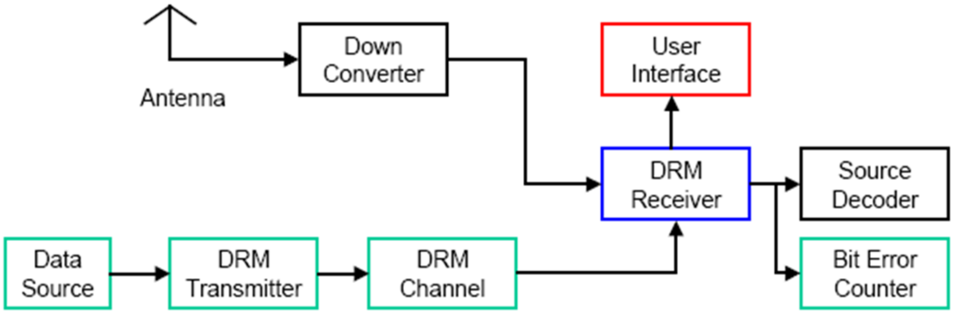
  - Definition of the bound $\Gamma$

$$\Gamma = \max\left\{ \hat{S}_{\max} \times 10^{-\frac{\Gamma_1}{10}}, \hat{S}_{\min} \times 10^{-\frac{\Gamma_2}{10}} \right\}$$



*Source: A. Kurpiers, V. Fischer, Darmstadt Univ.*

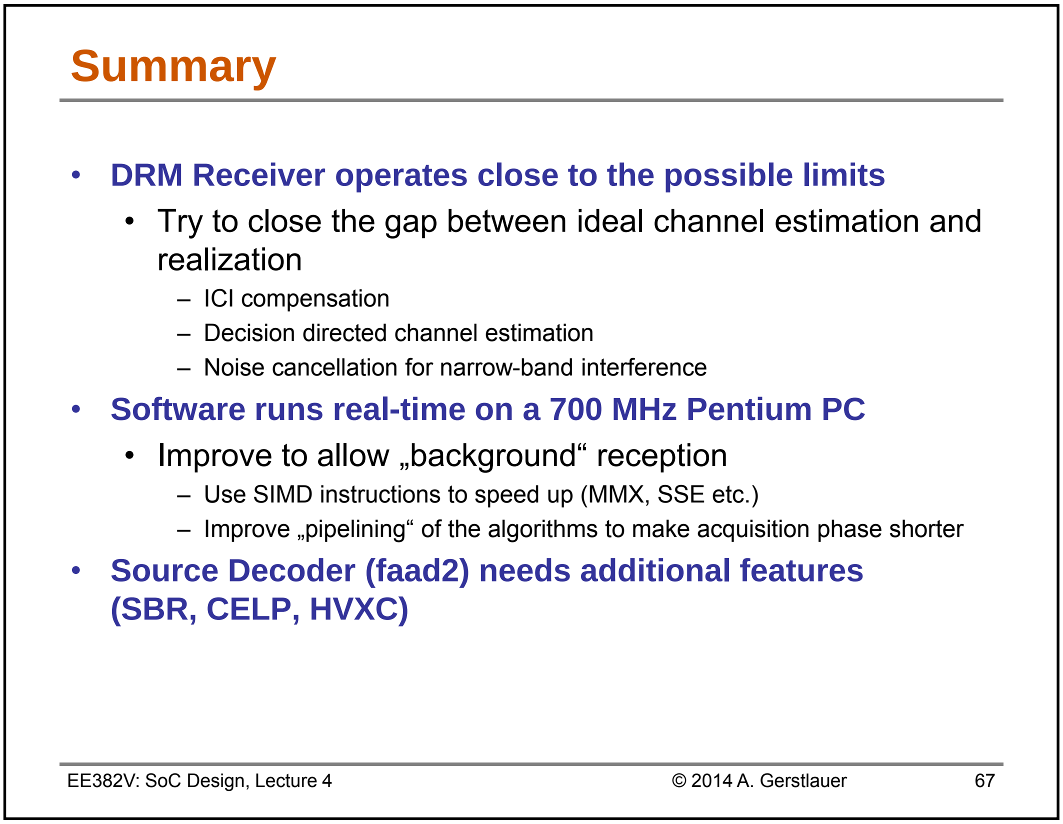
## Dream Software Modules



Software can be used:

- together with Down Converter and Source Decoder to receive real-time DRM radio broadcast
  - Source coding currently limited to plain MPEG4 AAC (no SBR, no CELP/HVXC)
- for BER or Channel Estimation Simulations with build in Data Source, Transmitter and Channel Simulator

*Source: A. Kurpiers, V. Fischer, Darmstadt Univ.*



## Summary

- **DRM Receiver operates close to the possible limits**
  - Try to close the gap between ideal channel estimation and realization
    - ICI compensation
    - Decision directed channel estimation
    - Noise cancellation for narrow-band interference
- **Software runs real-time on a 700 MHz Pentium PC**
  - Improve to allow „background“ reception
    - Use SIMD instructions to speed up (MMX, SSE etc.)
    - Improve „pipelining“ of the algorithms to make acquisition phase shorter
- **Source Decoder (faad2) needs additional features (SBR, CELP, HVXC)**