E225C – Lecture 16
OFDM Introduction

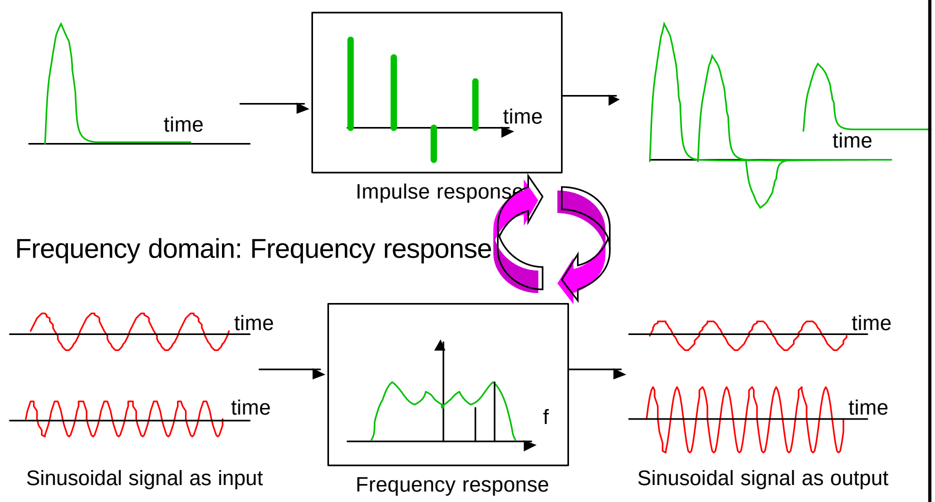
EE225C

Introduction to OFDM

- Basic idea
  - » Using a large number of parallel narrow-band sub-carriers instead of a single wide-band carrier to transport information
- Advantages
  - » Very easy and efficient in dealing with multi-path
  - » Robust again narrow-band interference
- Disadvantages
  - » Sensitive to frequency offset and phase noise
  - » Peak-to-average problem reduces the power efficiency of RF amplifier at the transmitter
- Adopted for various standards
  - – DSL, 802.11a, DAB, DVB

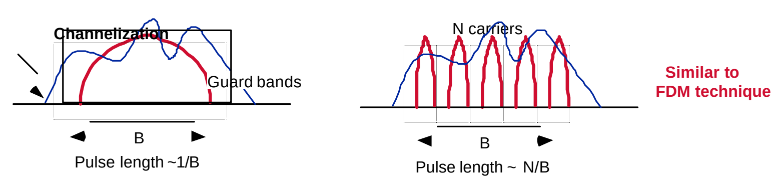
Multipath can be described in two domains: time and frequency

Time domain: Impulse response



Modulation techniques: monocarrier vs. multicarrier

Channel



– Data are transmited over **only one carrier**

– Data are shared among **several carriers** and simultaneously transmitted

Drawbacks

- **Selective Fading**
- **Very short pulses**
- **ISI is compartively long**
- **EQs are then very long**
- **Poor spectral efficiency because of band guards**

Advantages

- **Flat Fading per carrier**
- **N long pulses**
- **ISI is comparatively short**
- **N short EQs needed**
- **Poor spectral efficiency because of band guards**

Furthermore

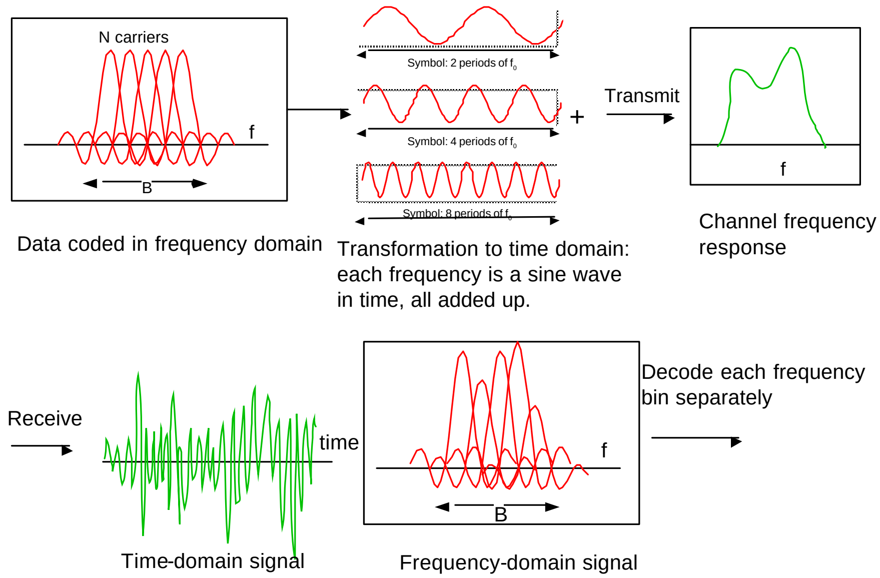
- It is easy to exploit Frequency diversity
- It allows to deploy 2D coding techniques
- Dynamic signalling

To improve the spectral efficiency:

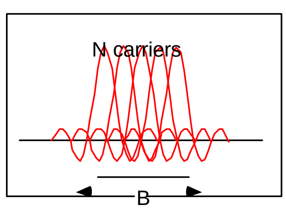
Eliminate band guards between carriers

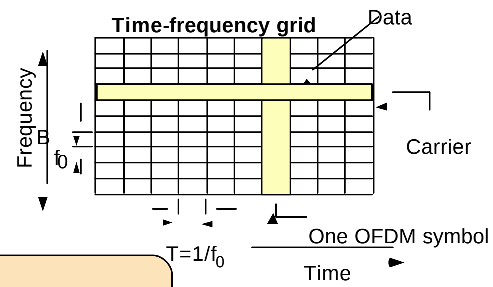
To use orthogonal carriers (allowing overlapping)

Orthogonal Frequency Division Modulation



OFDM uses multiple carriers to modulate the data





Features

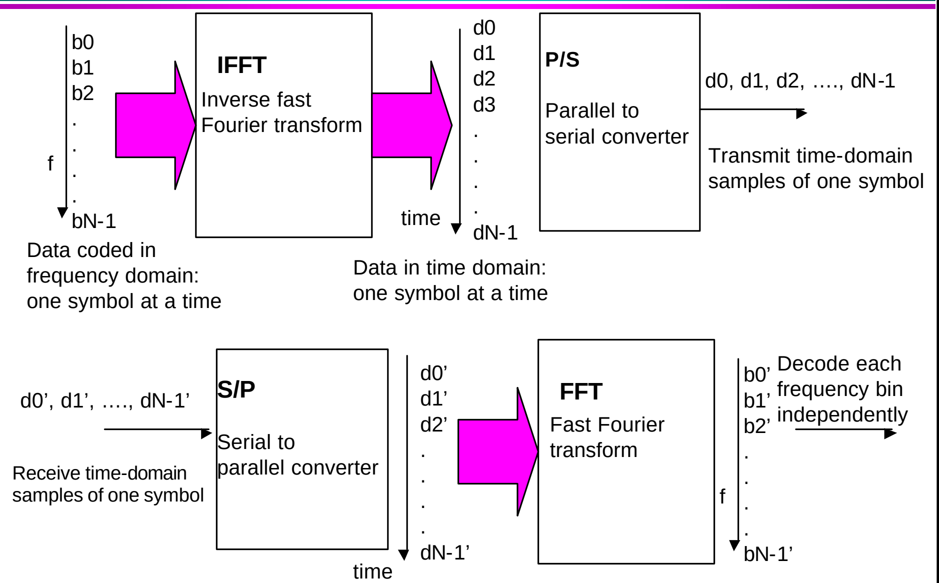
- **No intercarrier guard bands**
- **Controlled overlapping of bands**
- **Maximum spectral efficiency (Nyquist rate)**
- **Easy implementation using IFFTs**
- **Very sensitive to freq. synchronization**

Intercarrier Separation = 1/(symbol duration)

Modulation technique

A user utilizes all carriers to transmit its data as coded quantity at each frequency carrier, which can be quadrature-amplitude modulated (QAM).

OFDM Modulation and Demodulation using FFTs



Loss of orthogonality (by frequency offset)

Transmission pulses $y_k(t) = \exp(jk2pt/T)$ y $y_{k+m}(t) = \exp\left(j2p(k+m)t/T\right)$

Reception pulse with offset d $y^{d}_{k+m}(t) = \exp\left(j2p(k+m+d)/T\right)$ *con* $|d| \le 1/2$

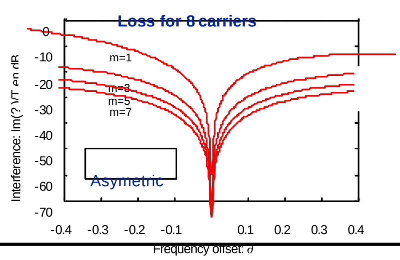
Interference between channels k and k+m

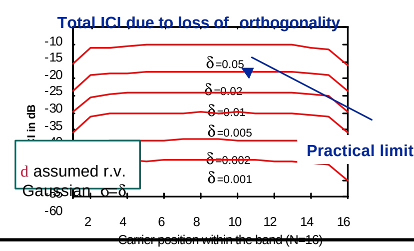
$$I_m(d) = \int_0^T \exp\left(jk2pt/T\right)\exp\left(-j(k+m+d)2pt/T\right)dt = \frac{T(1-\exp(-j2pd))}{j2p(m+d)}$$

$$|I_m(d)| = \frac{T|\sin pd|}{p|m+d|}$$

Summing up $\forall$ m

$$\sum_m I_m^2(d) \approx (Td)^2 \sum_{m=1}^{N-1} \frac{1}{m^2} \approx (Td)^2 \frac{23}{14} \quad \text{for} \quad N >> 1 \; (N > 5 \text{ Is enough})$$





Loss of orthogonality (time)

Let us assume a misadjustment t

$$X_i = c_0\int_{-T/2}^{-T/2+t} y_k(t)\,y_l^*(t-t)\,dt + c_1\int_{-T/2+t}^{T/2} y_k(t)\,y_l^*(t-t)\,dt$$

2 consecutive symbols

Then if m=k-l

$$|X_l| = \begin{cases} \left|2T\dfrac{\text{sen}\, m\pi \frac{t}{T}}{m\pi}\right|, & c_0 \neq c_1 \\ 0, & c_0 = c_1 \end{cases}$$

Or approximately, when τ<<T

$$\frac{|X_l|}{T} \approx \frac{2m\pi \frac{t}{T}}{m\pi} = 2\frac{t}{T}$$

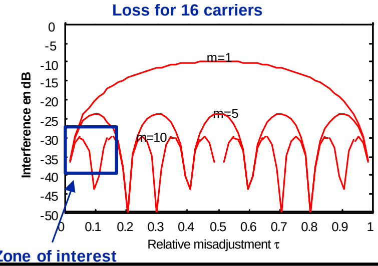
independent on m

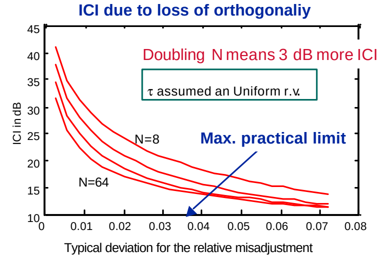
In average, the interfering power in any carrier is

$$E\left[\frac{|X_l|^2}{T^2}\right] = 4\left(\frac{t}{T}\right)^2\frac{1}{2} + 0\,\frac{1}{2} = 2\left(\frac{t}{T}\right)^2$$

$$ICI \approx 20\log\left(\sqrt{2}\,\frac{t}{T}\right),\quad t \ll T$$

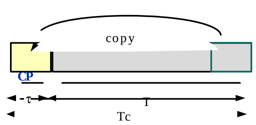
Per carrier





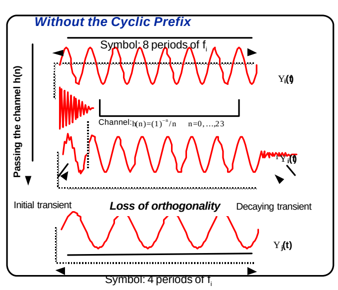
Including a "cyclic prefix"

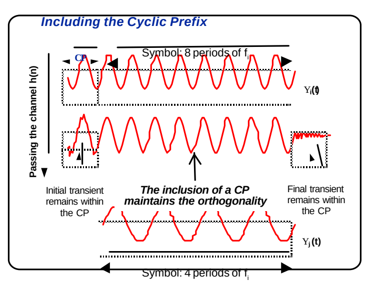
To combat the time dispersion: including 'special' time guards in the symbol transitions



Furthermore it converts **Linear conv. = Cyclic conv.**

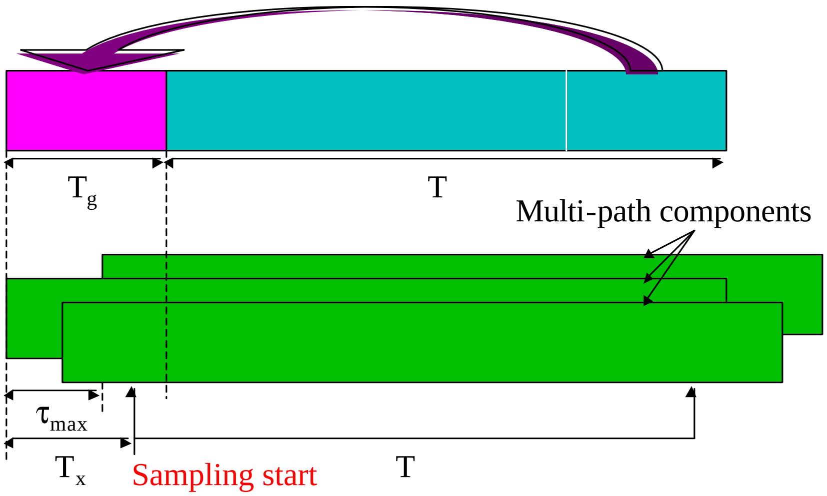
(Method: overlap-save)



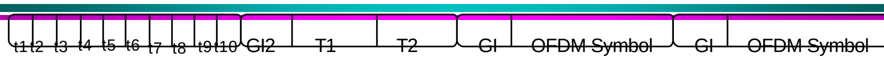


CP functions:
- It **acomodates** the decaying transient of the previous symbol
- It **avoids** the initial transient reachs the current symbol

Cyclic Prefix



802.11a System Specification



Short training sequence:
AGC and frequency offset

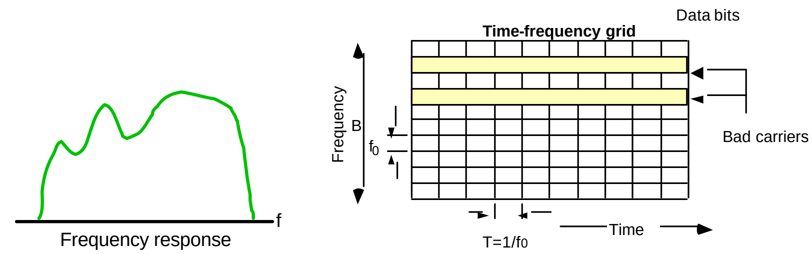
Long training sequence:
Channel estimation

- Sampling (chip) rate: 20MHz
- Chip duration: 50ns
- Number of FFT points: 64
- FFT symbol period: 3.2µs
- Cyclic prefix period: 16 chips or 0.8µs
  - » Typical maximum indoor delay spread < 400ns
  - » OFDM frame length: 80 chips or 4µs
  - » FFT symbol length / OFDM frame length = 4/5
- Modulation scheme
  - » QPSK: 2bits/sample
  - » 16QAM: 4bits/sample
  - » 64QAM: 6bits/sample
- Coding: rate ½ convolutional code with constraint length 7

Frequency diversity using coding

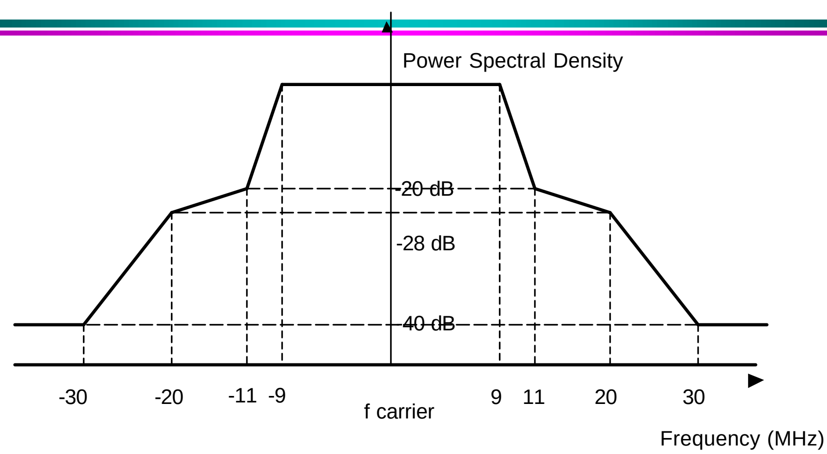
Random errors: primarily introduced by thermal and circuit noise.

Channel-selected errors: introduced by magnitude distortion in channel frequency response.



Errors are no longer random. Interleaving is often used to scramble the data bits so that standard error correcting codes can be applied.

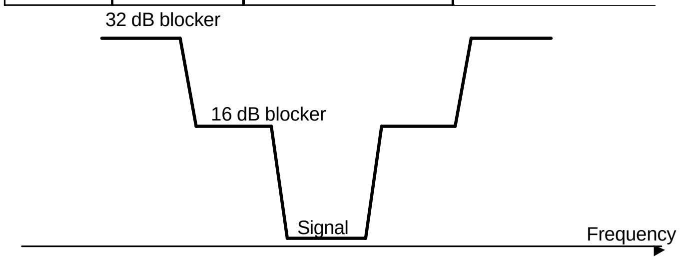
Spectrum Mask



- Requires extremely linear power amplifier design.

Adjacent Channel and Alternate Channel Rejection

Date rate	Minimum Sensibility	Adjacent Channel Rejection	Alternate Channel rejection
6 Mbps	-82 dBm	16 dB	32 dB
12Mbps	-79 dBm	13 dB	29 dB
24Mbps	-74 dBm	8 dB	24 dB
36Mbps	-70 dBm	4 dB	20 dB
54Mbps	-65 dBm	0 dB	15 dB



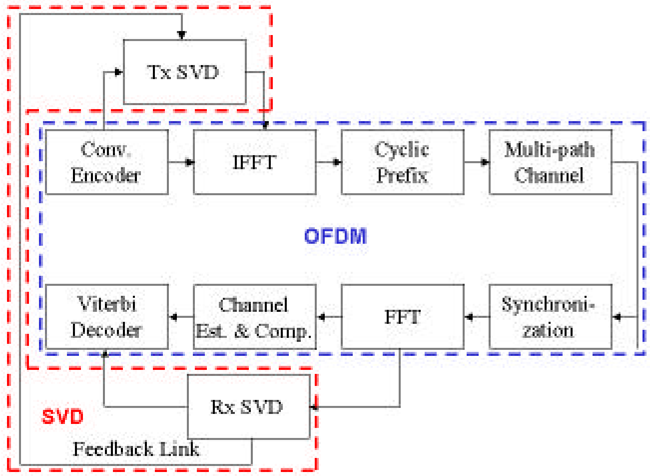
- Requires joint design of the anti-aliasing filter and ADC.

OFDM Receiver Design

Yun Chiu, Dejan Markovic, Haiyun Tang, Ning Zhang

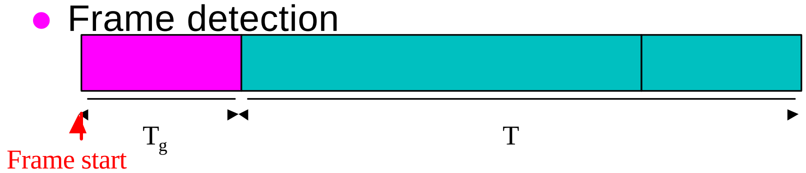
EE225C Final Project Report, 12 December 2000

OFDM System Block Diagram



Synchronization

- Frame detection

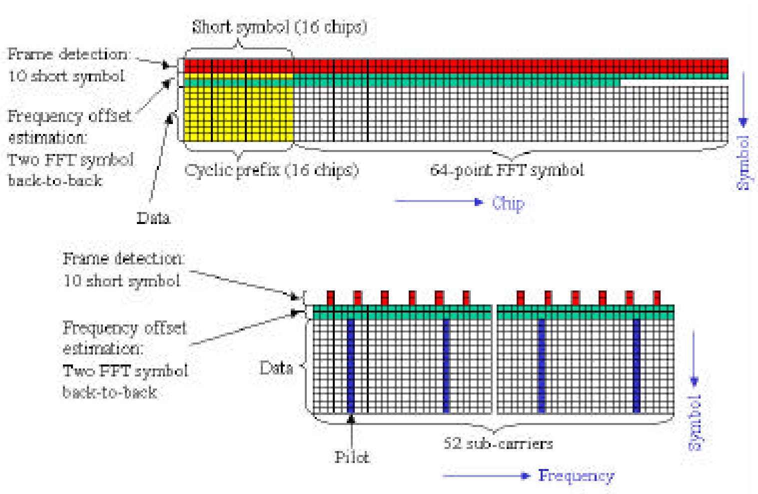


- Frequency offset compensation

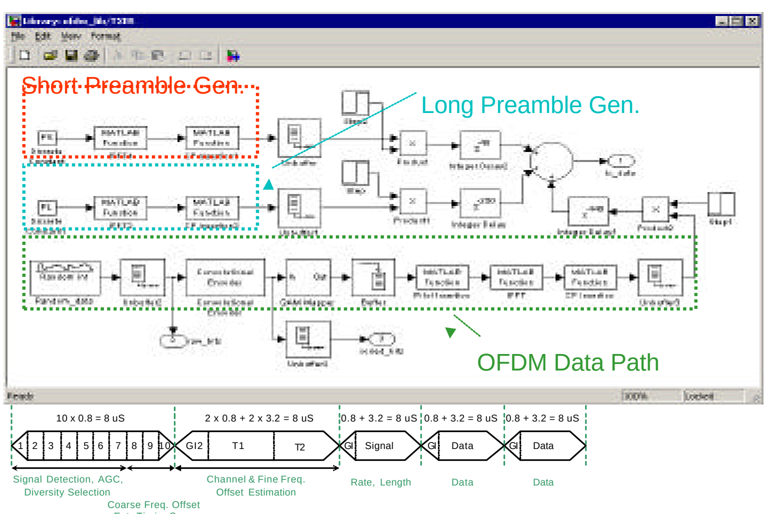
$$e^{j2\pi \Delta f_c t}$$

- Sampling error
  - » Usually less 100ppm and can be ignored
    - – 100ppm = off 1% of a sample every 100 samples

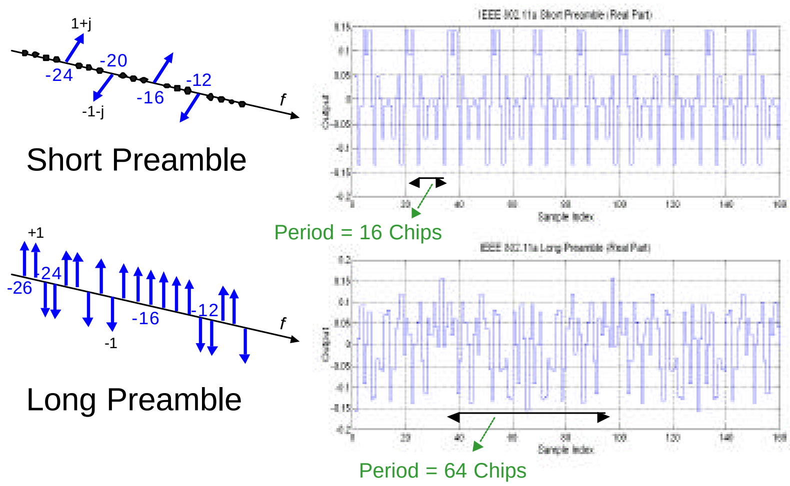
System Pilot Structure



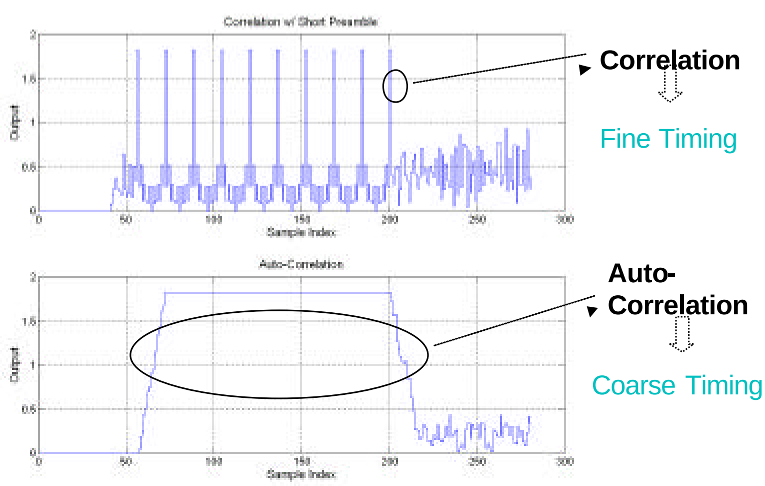
IEEE 802.11a OFDM Txer



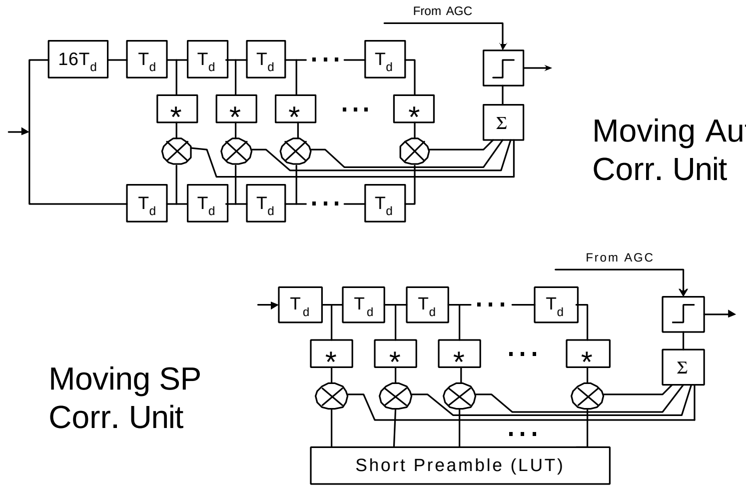
Short & Long Preambles



Correlation of Short Preamble



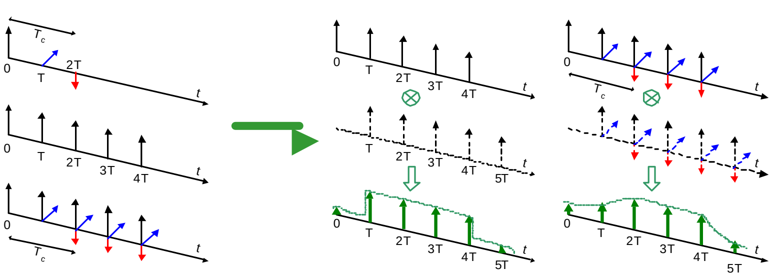
Synchronization



Moving Auto-Corr. Unit

Moving SP Corr. Unit

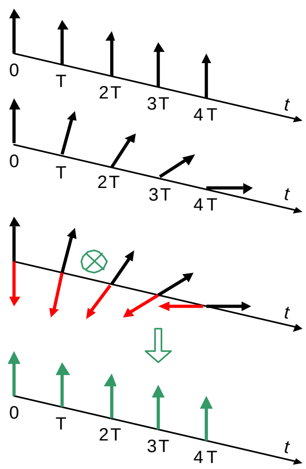
Impairments: Multi-Path Channel

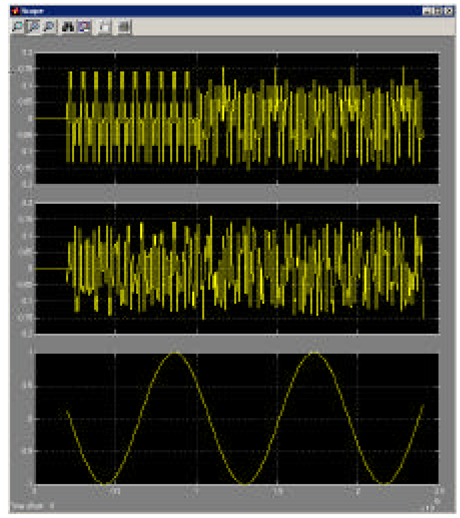


Ch. Impulse Response

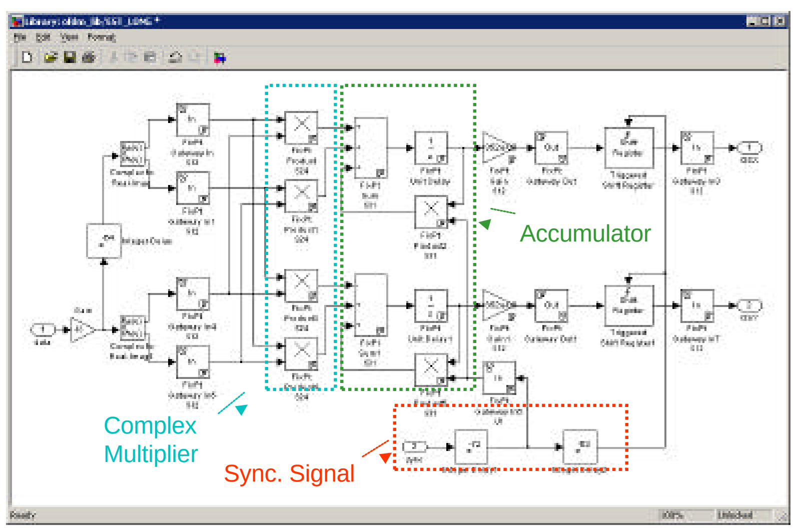
Auto-Correlation w/ Multi-Path Channel Response.

Impairments: Frequency Offset

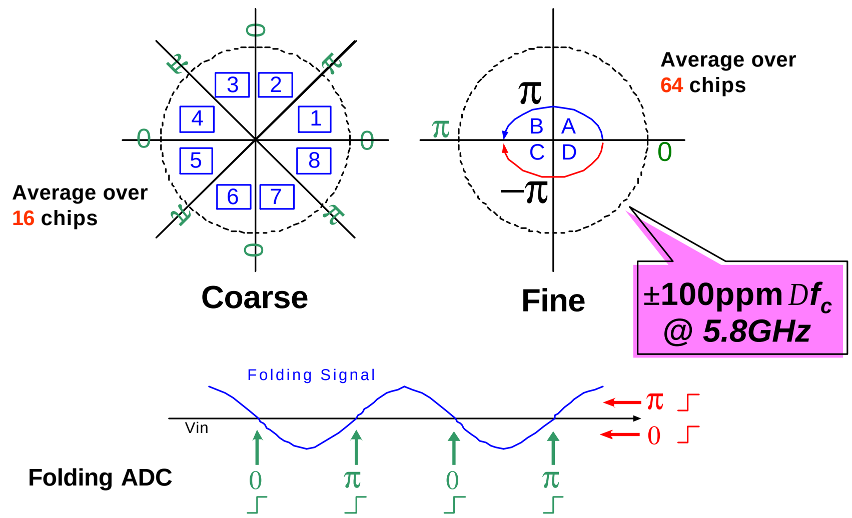




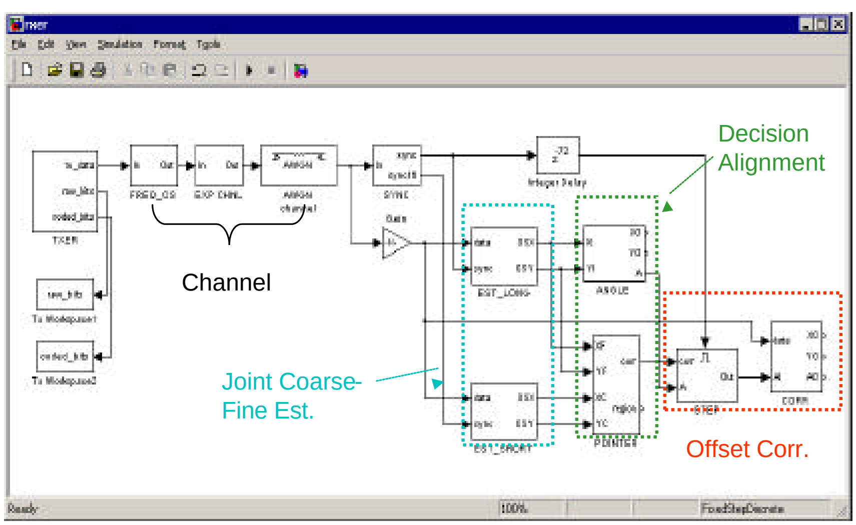
Fine Frequency Offset Est.



Coarse-Fine Joint Estimation & Decision Alignment Error Correction



Frequency Offset Compensation



Performance Summary

Parameters	*Metrics*
Number of sub-carriers	**48 data +4 pilot**
OFDM symbol freq.	**4 ms**
Modulation Scheme	**BPSK up to 64-QAM**
Sampling clock freq.	**20 MHz**
Sync. Frame Start Accuracy	**£ 8 chips (CP = 16 chips)**
Freq. Offset Est. Range	**± 5p = ± 100ppm @ 5.8 GHz**
Freq. Offset Est. Accuracy	**1% (@ 15dB SNR)**
Critical path delay	**12.7 ns**
Silicon area	**397,080 mm^2**
Total power consumption	**3.4 mW @ 20 MHz**