OFDM – Orthogonal Frequency Division Multiplexing

Dr. Jean Armstrong
Associate Professor
Department of Electronic Engineering
La Trobe University

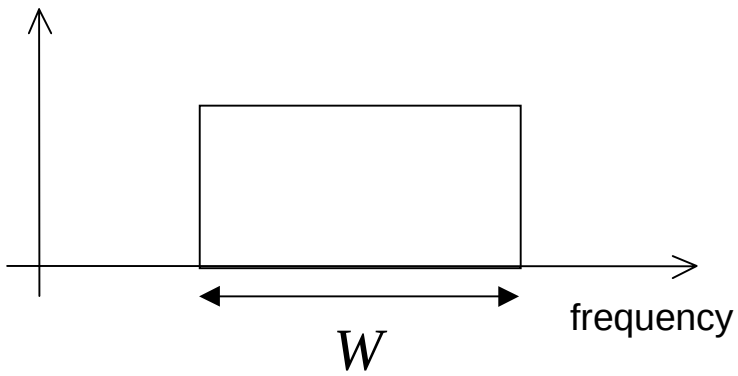
Overview

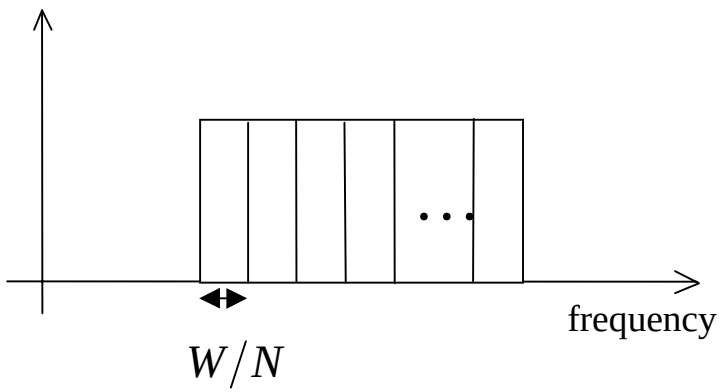
- Introduction
  - applications
  - multicarrier systems
- Why use OFDM?
  - multipath transmission
- How OFDM works
- Applications of OFDM
- Problems with OFDM
- Research in OFDM

Applications of OFDM

- Digital Television
  - European and Australian standard
- Wireless Local Area Networks (LANs)
  - Hiperlan 2
- ADSL (asymmetric digital subscriber loop)
  - High speed data transmitted along existing telephone lines
- Future mobile telephony?

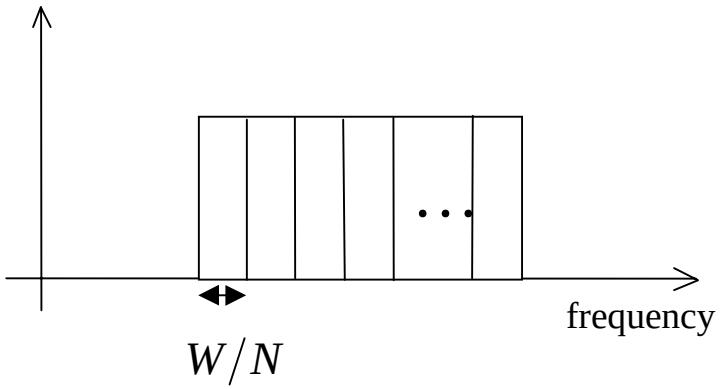
Multicarrier systems

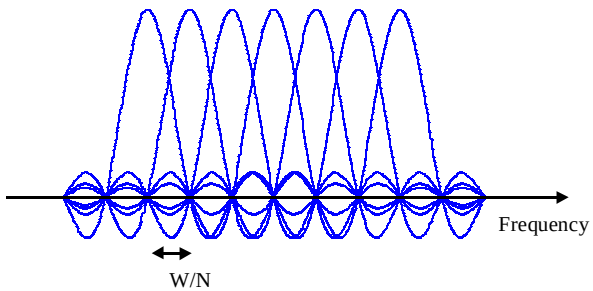




- Single carrier system
  - signal representing each bit uses all of the available spectrum
- Multicarrier system
  - available spectrum divided into many narrow bands
  - data is divided into parallel data streams each transmitted on a separate band

What is OFDM?





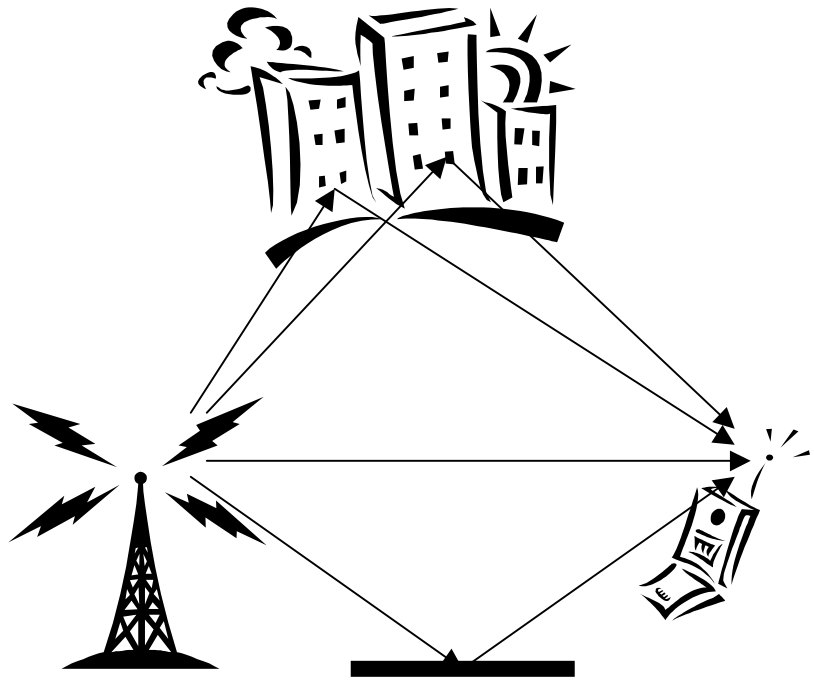
- OFDM is a multicarrier system
  - uses discrete Fourier Transform/Fast Fourier Transform (DFT/FFT)
  - sin(x)/x spectra for subcarriers
- Available bandwidth is divided into very many narrow bands
  - ~2000-8000 for digital TV
  - ~48 for Hiperlan 2
- Data is transmitted in parallel on these bands

Why is OFDM so popular for new broadband systems?

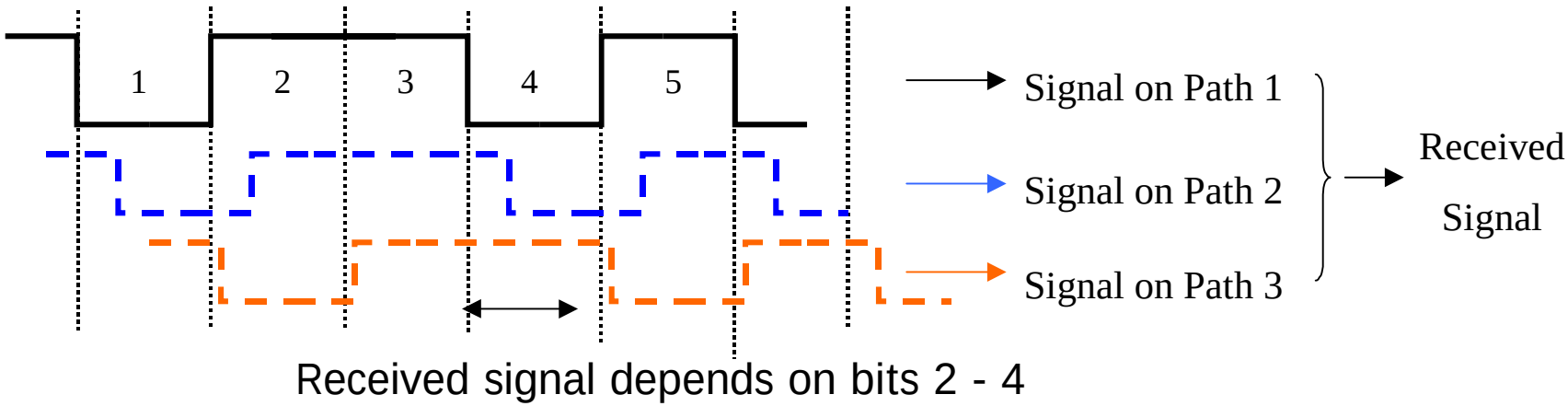
- Most broadband systems are subject to multipath transmission
- Conventional solution to multipath is an equalizer in the receiver
  - high data rates - equalizers too complicated
- With OFDM there is a simple way of dealing with multipath
  - relatively simple DSP algorithms

What is Multipath?

- More than one transmission path between transmitter and receiver
- Received signal is the sum of many versions of the transmitted signal with varying delay and attenuation

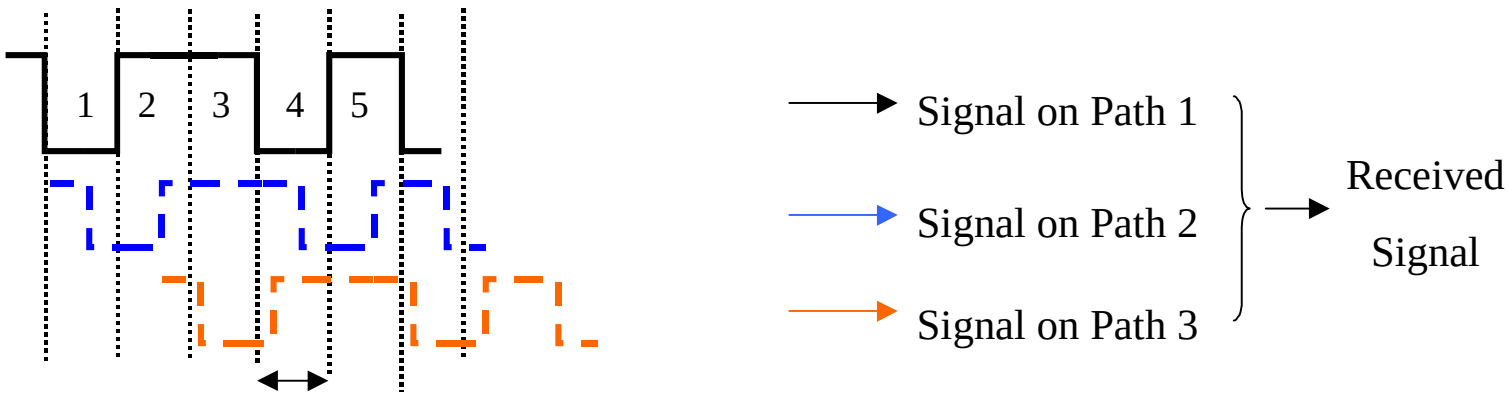


Effect of Multipath on Received Baseband Signal



- Received signal at any time depends on a number of transmitted bits
  - Intersymbol Interference (ISI)
- Need equalizer to recover data

ISI gets worse as data rate increases



Received signal depends on bits 1 - 4

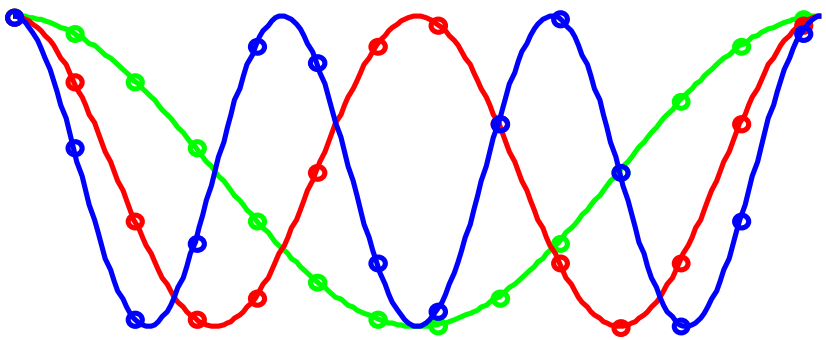
- ISI covers more symbol periods
- Equalizer becomes too complicated

How does OFDM solve the multipath problem?

- Data is transmitted in parallel
  - longer symbol period
  - e.g. for *N* parallel streams, symbol period is *N* times as long
- Cyclic prefix
  - trick to avoid residual ISI

How are signals transmitted in parallel without interference?

First three subcarriers

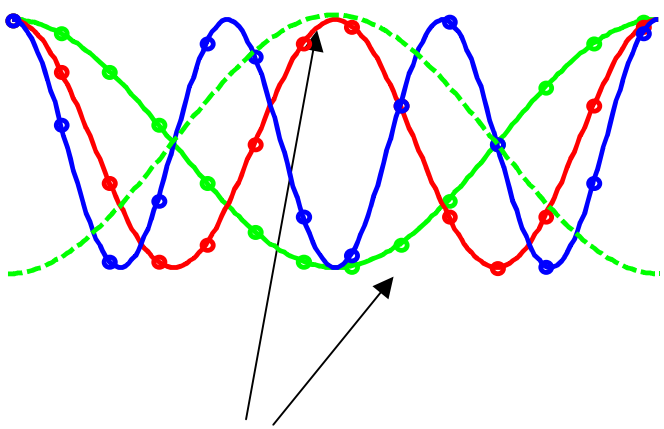


Symbol period

$$\int_0^T \sin\frac{2\pi kt}{T}\sin\frac{-2\pi lt}{T}\,dt = 0, \quad k \neq l$$

- Each subcarrier has a different frequency
- Frequencies chosen so that an integral number of cycles in a symbol period
- Signals are mathematically orthogonal

How is data carried on the subcarriers?



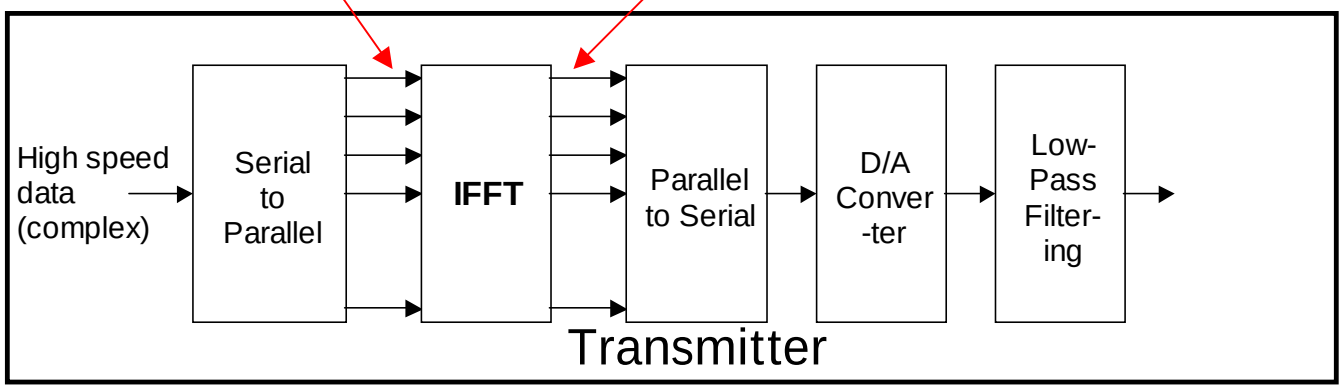
Two possible subcarrier values

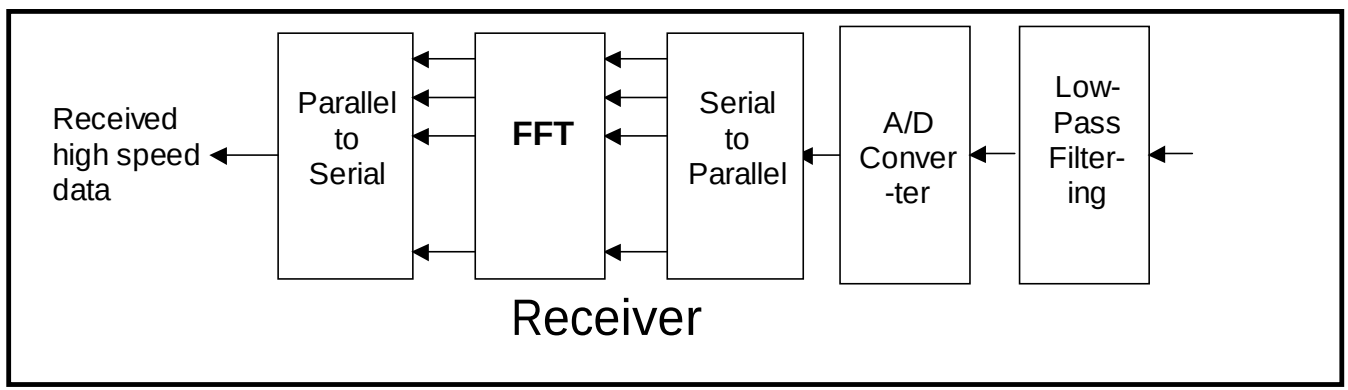
- Data is carried by varying the phase or amplitude of each subcarrier
- QPSK, 4-QAM, 16-QAM, 64-QAM

Baseband OFDM system

Discrete frequency domain
Each input controls signal at one frequency

Discrete Time Domain
Samples of modulated and multiplexed signals





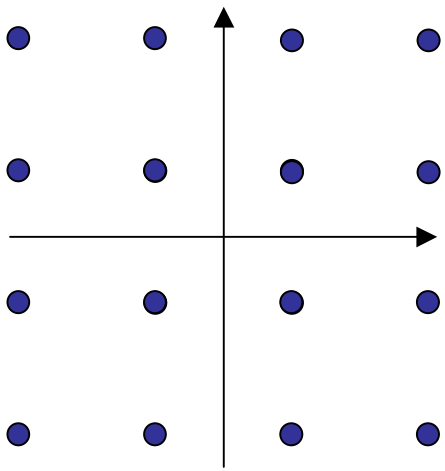
How are OFDM signals generated?

Typical IFFT Output Samples

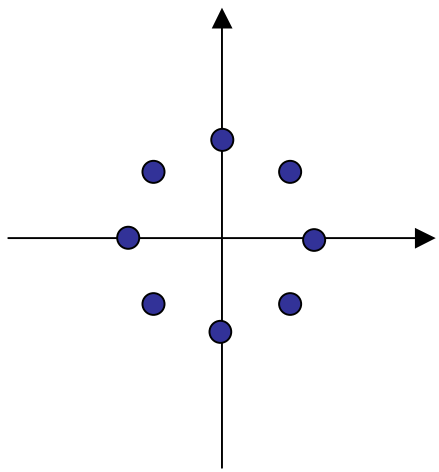
Signal values at the output of the IFFT are the sum of many samples of many sinusoids - looks random

- Parallel data streams are used as inputs to an IFFT
- IFFT output is sum of signal samples
- IFFT does modulation and multiplexing in one step
- Filtering and D/A of samples results in baseband signal

Modulation



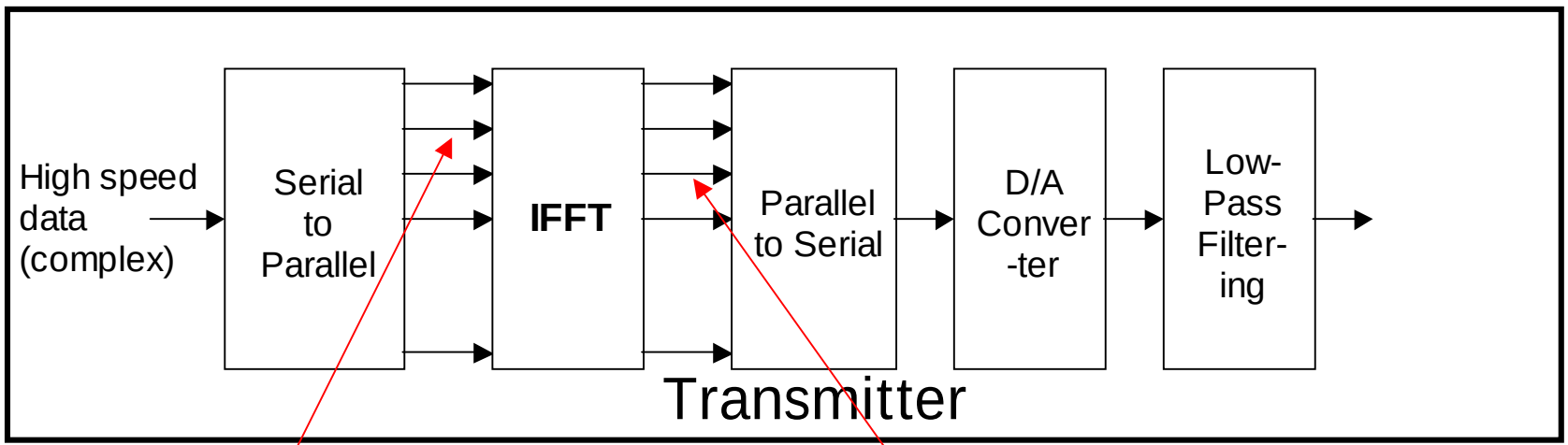
16-QAM

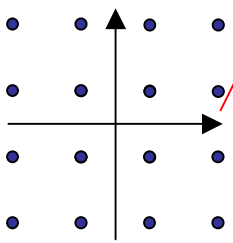


8-PSK

- Varying the complex numbers at the IFFT input results in modulation of the subcarriers

Signals at Input and Output of Transmitter IFFT

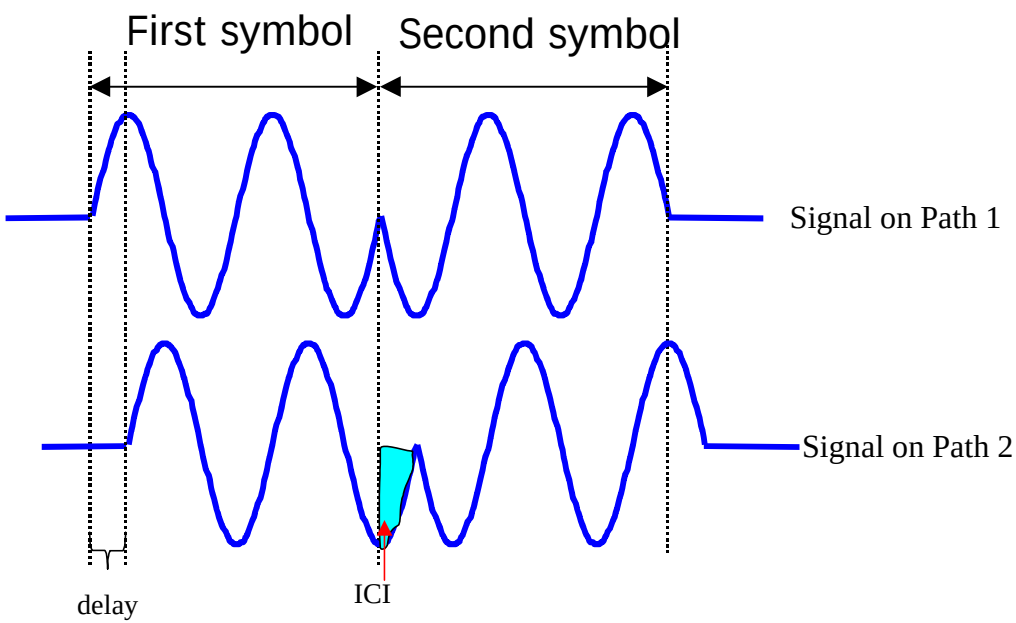




Complex value representing data is input to IFFT

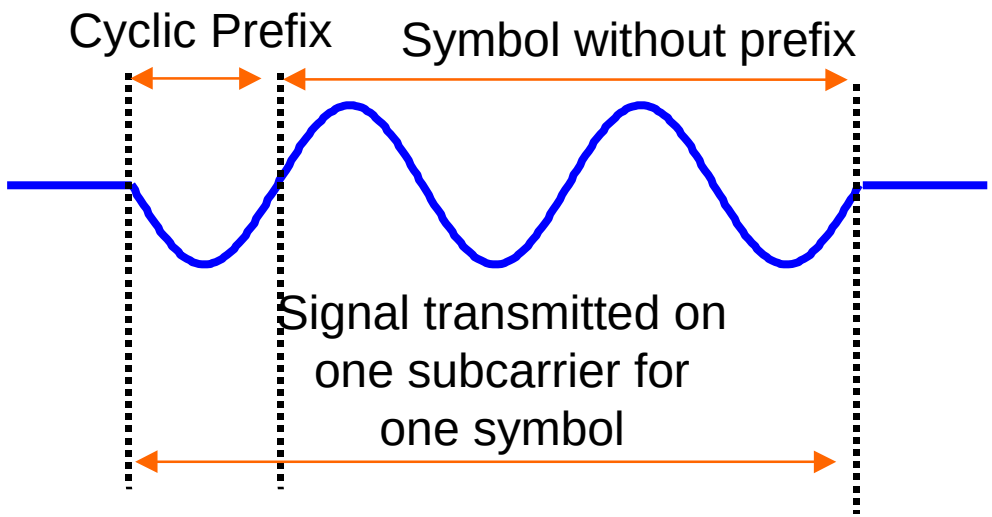
IFFT output gives samples of modulated multiplexed signal

OFDM in a multipath environment - effect on one subcarrier



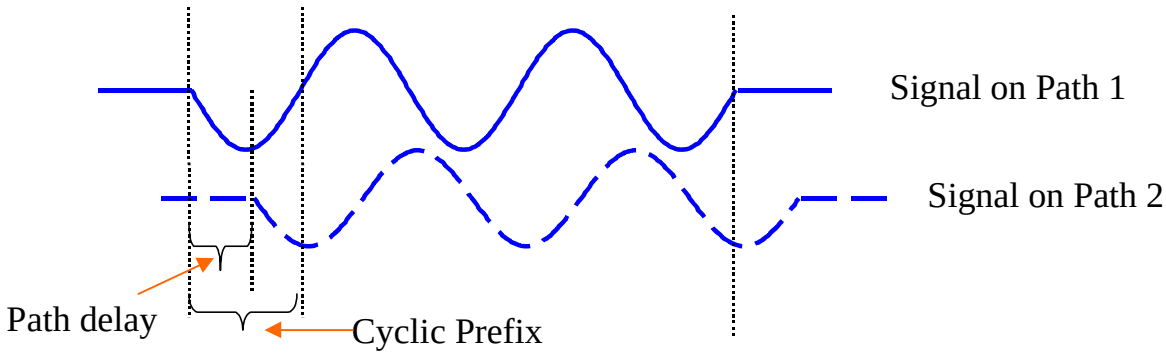
- Received signal in one symbol period is not a sinusoid
- Causes intercarrier interference (ICI)

Cyclic Prefix



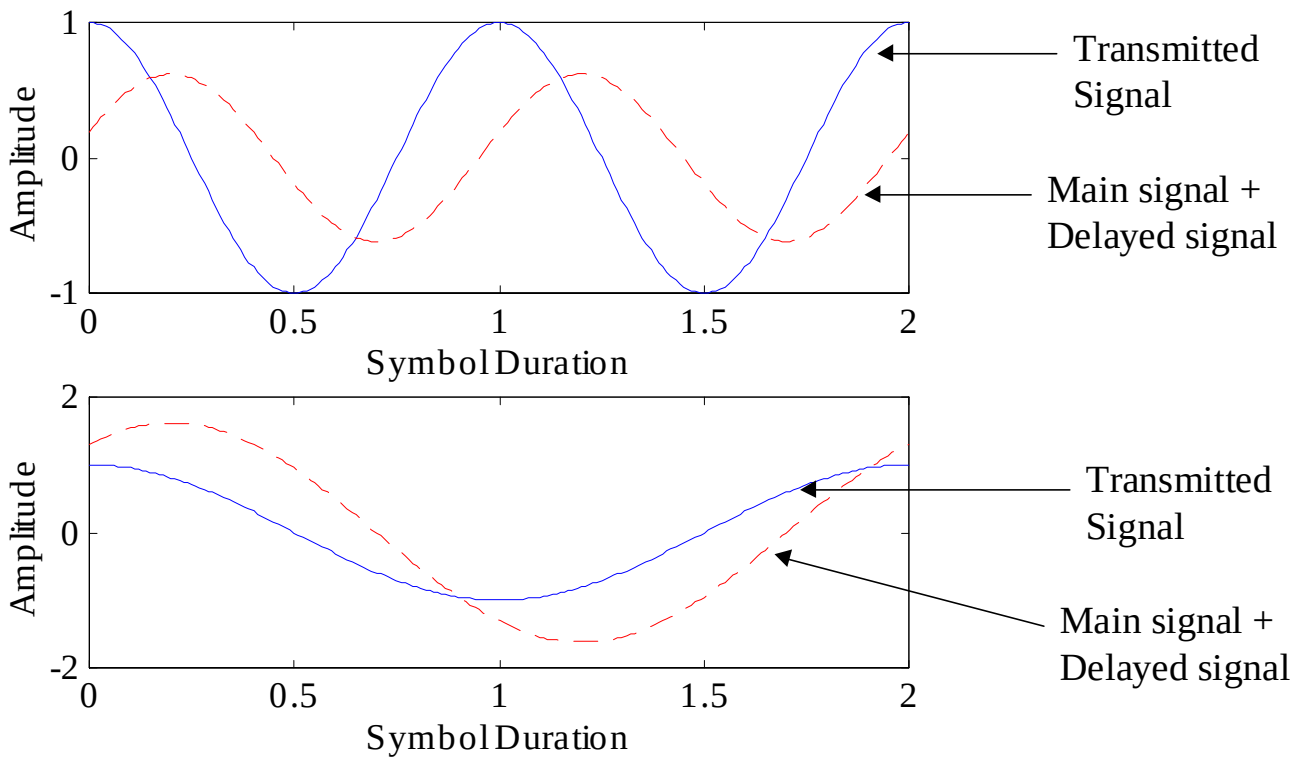
- Each symbol is cyclically extended
- Some loss in efficiency as cyclic prefix carries no new information

Effect of multipath on symbol with cyclic prefix

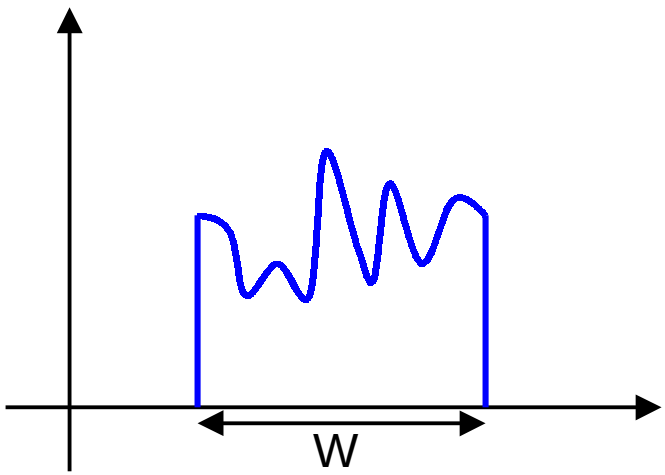


- If multipath delay is less than the cyclic prefix
  - no intersymbol or intercarrier interference
  - amplitude may increase or decrease

Frequency selective fading

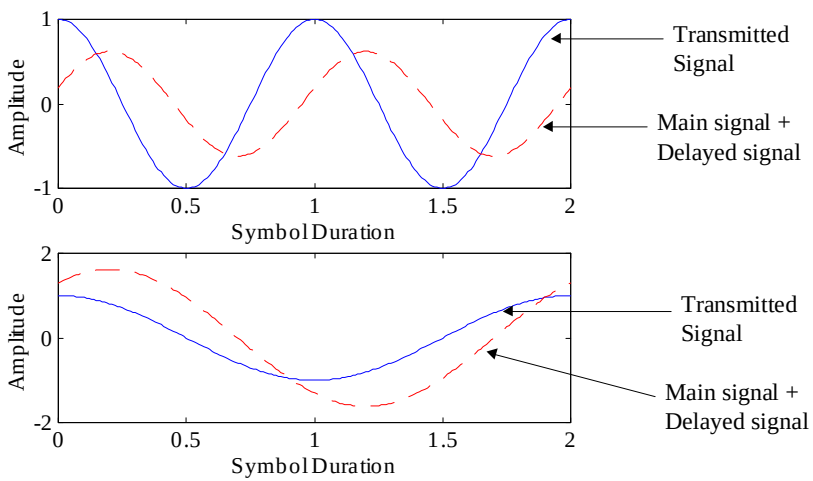


Spectrum of Received Signal



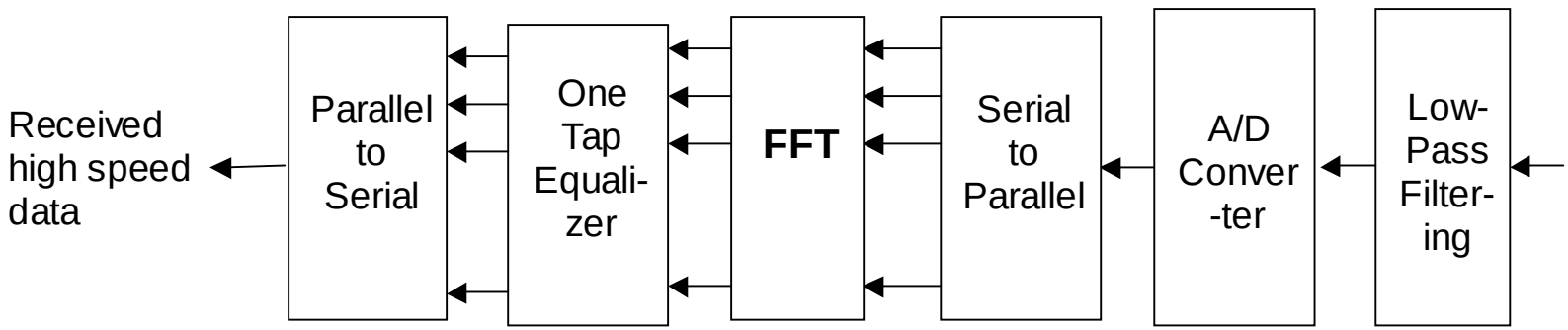
- Multipath fading causes some frequencies to be attenuated
- Fading is approximately constant over narrow band
- This is corrected in the receiver

Amplitude and phase change



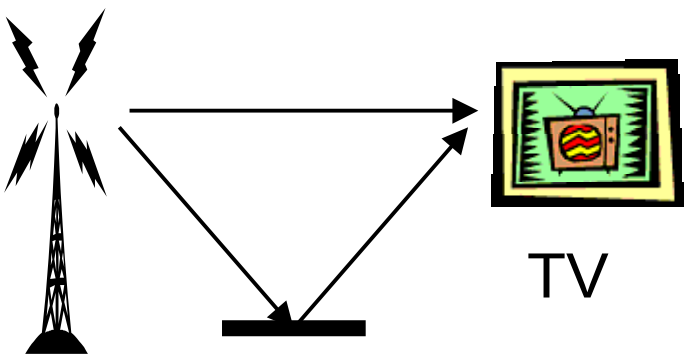
- Multipath delay causes change in amplitude and phase of each subcarrier
- Change depends on subcarrier frequency
- Corrected in receiver by one complex multiplication per subcarrier

Multipath fading corrected by ‘single tap equalizer’



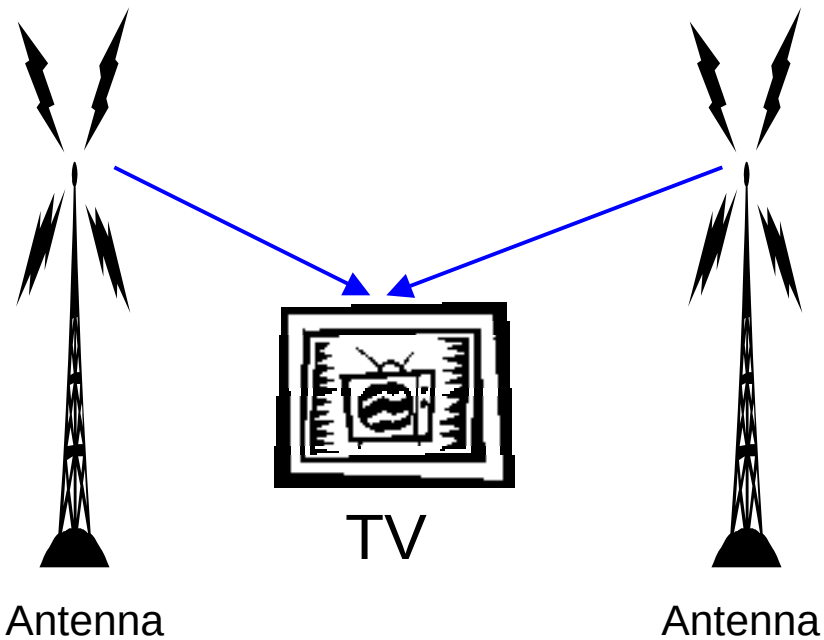
- Change in phase and amplitude corrected by complex multiplication
- Receiver structure suited to DSP implementation

Digital Video Broadcasting (DVB)



- OFDM is used in the Australian digital television system
- 2048 point IFFT
  - 1705 subcarriers used
- Flexible standard
  - variable error coding
  - variable cyclic prefix
  - variable constellation
    - 4QAM, 16QAM, 64QAM
- Broadcast system
  - mode determined by broadcaster

DVB - single frequency network

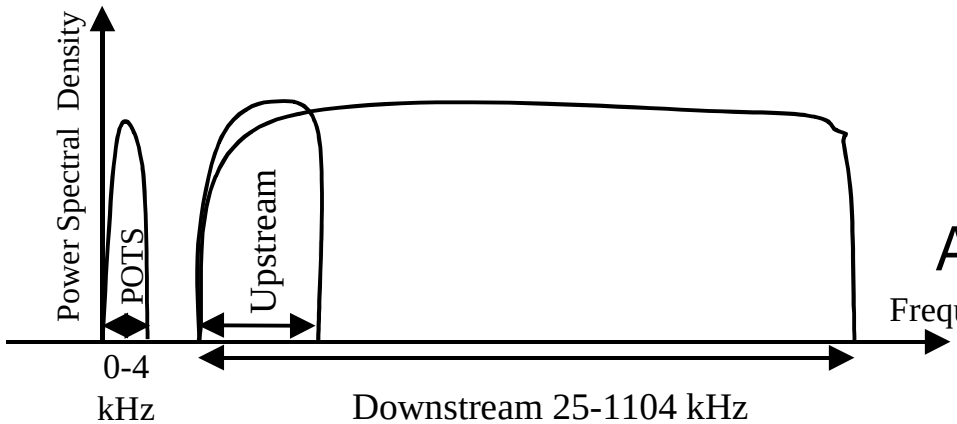


- DVB designed to allow the same frequency to be used for the same channel throughout a region
- Single Frequency Network
- More than one received signal
  - like extreme multipath
- Reason for large number of subcarriers
  - 8000 subcarrier option allows greater distance between transmitters

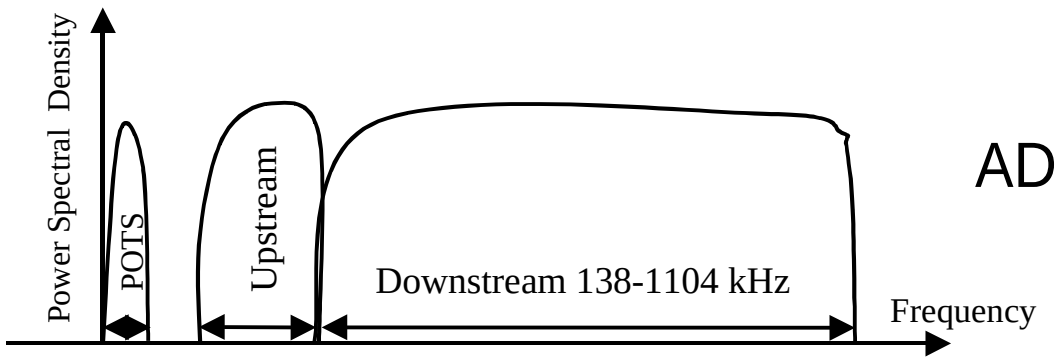
OFDM in ADSL

- OFDM used in ADSL is usually called ‘Discrete Multitone’ (DMT)
- Two way transmission
  - transmission can be tailored to the particular channel
- Baseband system
  - only real (not complex signal can be transmitted)

Frequencies used for ADSL

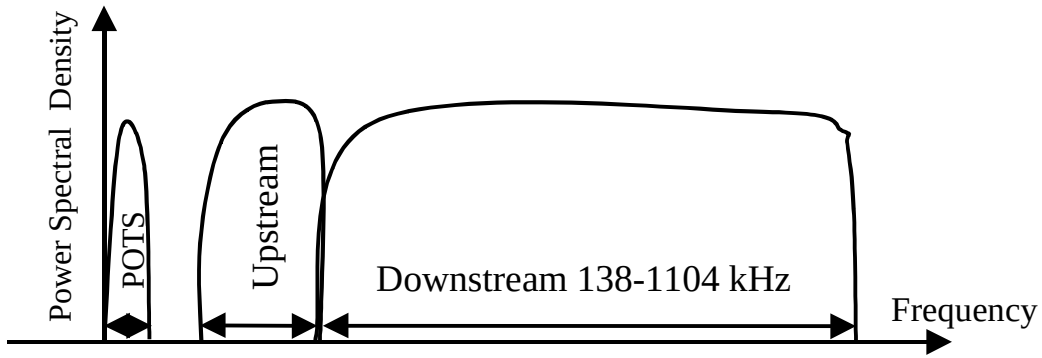


ADSL with Echo Cancelling (EC)



ADSL with Frequency Division Duplexing (FDD)

OFDM/DMT in ADSL



- 256 subcarriers
- Test signals transmitted
  - received signal and noise level of each tone measured
- Large constellations used on good tones

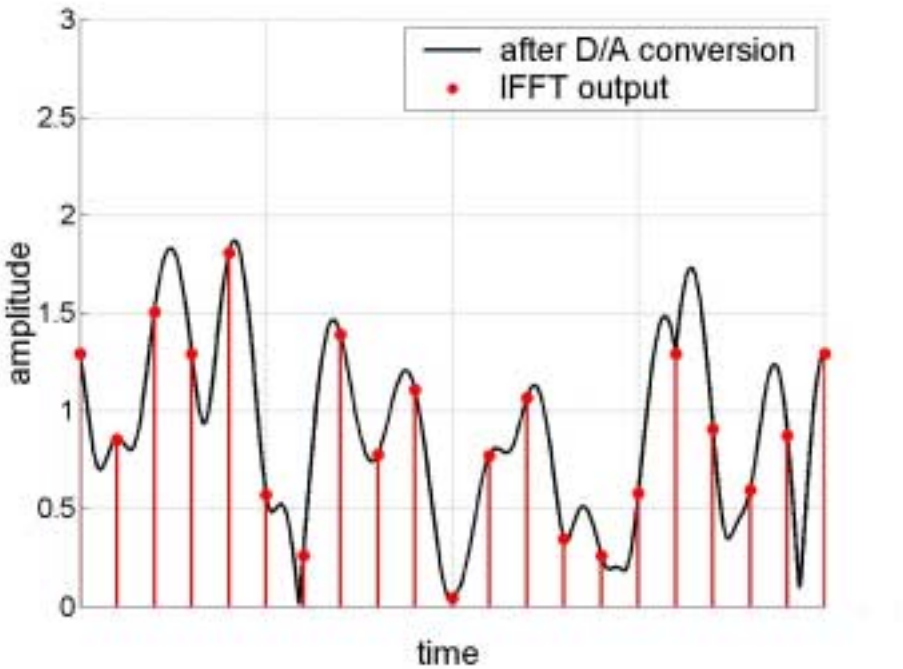
Hiperlan-2 - Wireless LAN

- 64 point FFT, 52 subcarriers used
- Different modes
  - signal constellation, error coding, cyclic prefix
- Two way channel
  - feedback be used to determine transmission mode

OFDM Problems

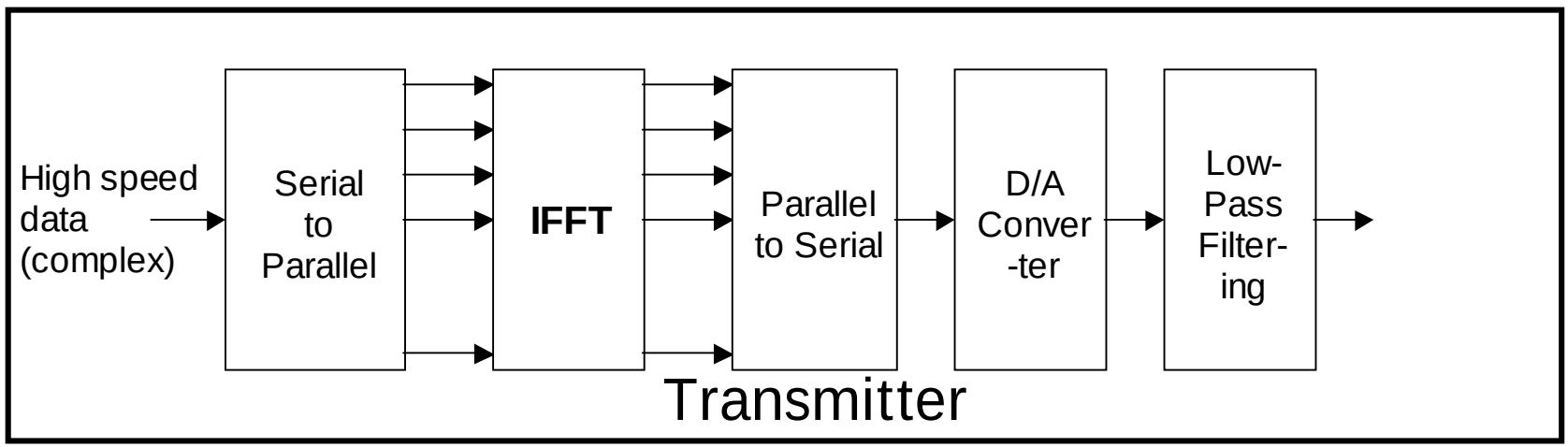
- High peak-to-average power ratio
  - peak signals power much greater than average signal power
  - need very linear amplifiers with large dynamic range
- Very sensitive to frequency errors
  - tight specifications for local oscillators
  - Doppler limitation

High peak-to-average power



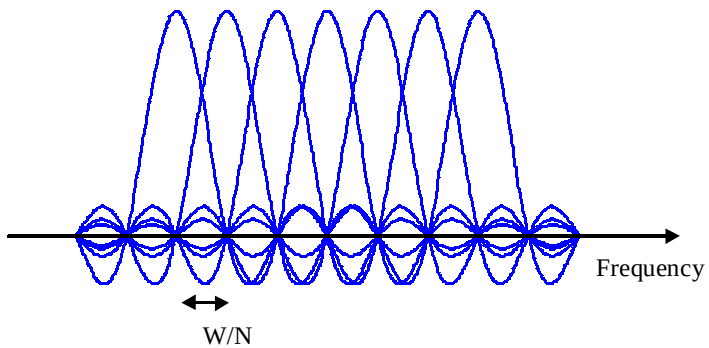
- OFDM signal is sum of many separate sinusoids
- In worst case may all add constructively
- High peaks occur rarely

Solutions to peak-to-average power



- Coding to avoid the peaks - Monash
- Clip the peaks - La Trobe
- Predistort the signal to compensate for the amplifier nonlinearity - Victoria University

Frequency Sensitivity

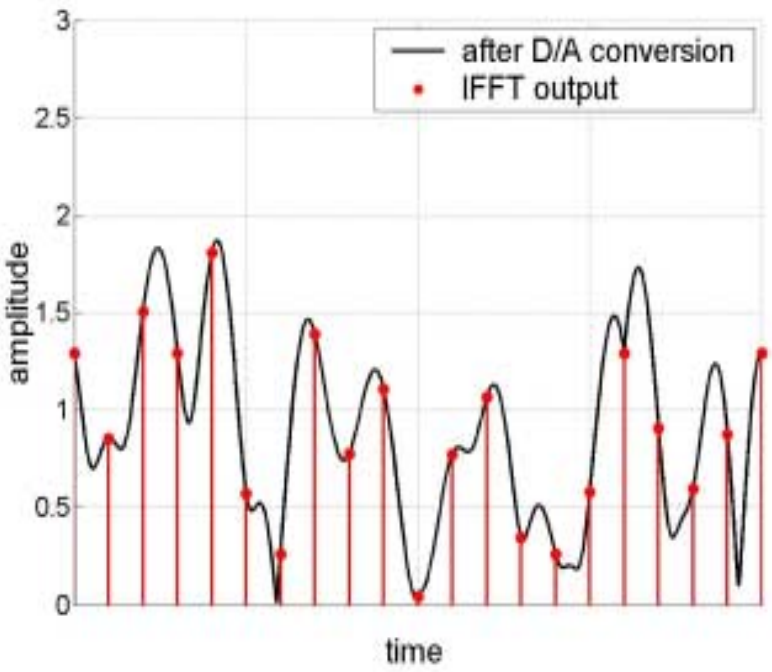


- Individual subcarriers have sin(x)/x spectrum
- Large sidelobes result in sensitivity to frequency offset
- Subcarriers no longer orthogonal
- Tight specifications on local oscillators

Research at La Trobe University

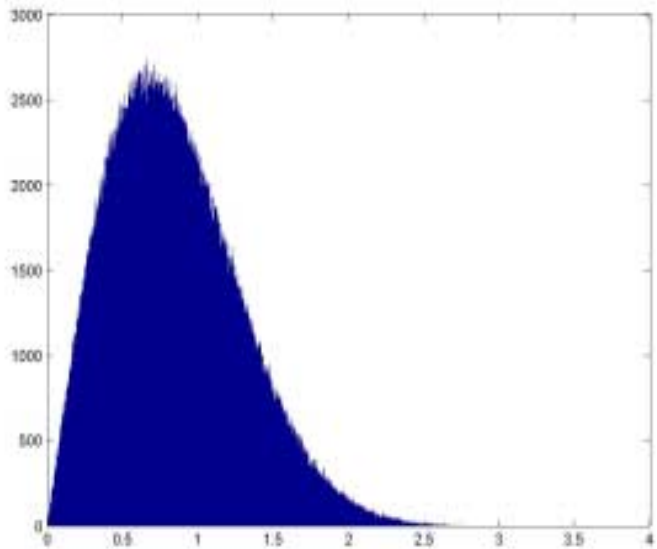
- Peak-to-average power reduction
  - clipping
  - effect on signal constellation
  - clipping noise added at transmitter
- Alternative modulation schemes based on OFDM
  - polynomial cancellation coded OFDM (PCC-OFDM)

Peak-to-Average power of OFDM

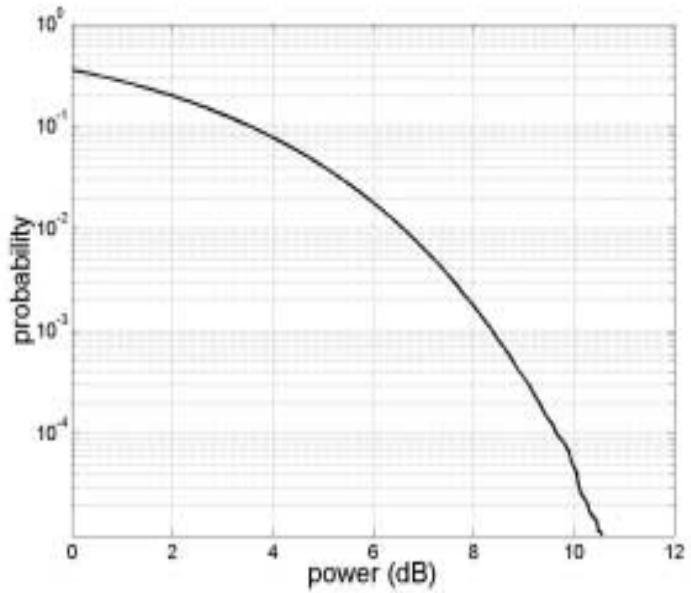


- High PAPR
- Linear amplifiers with large dynamic range required
- Peaks after D/A conversion may occur between Inverse Fast Fourier Transform (IFFT) output values

Amplitude distribution in OFDM



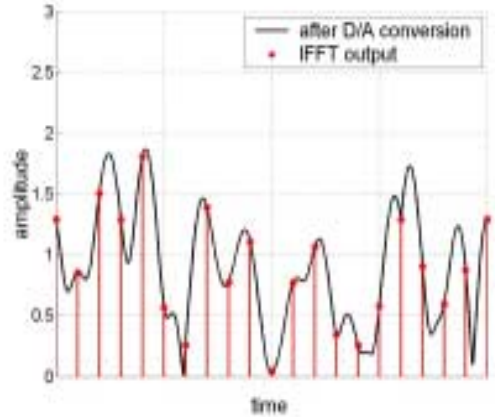
Histogram of signal amplitude



Probability amplitude exceeds given power

- Power >8.3dB above average for 0.1% of time

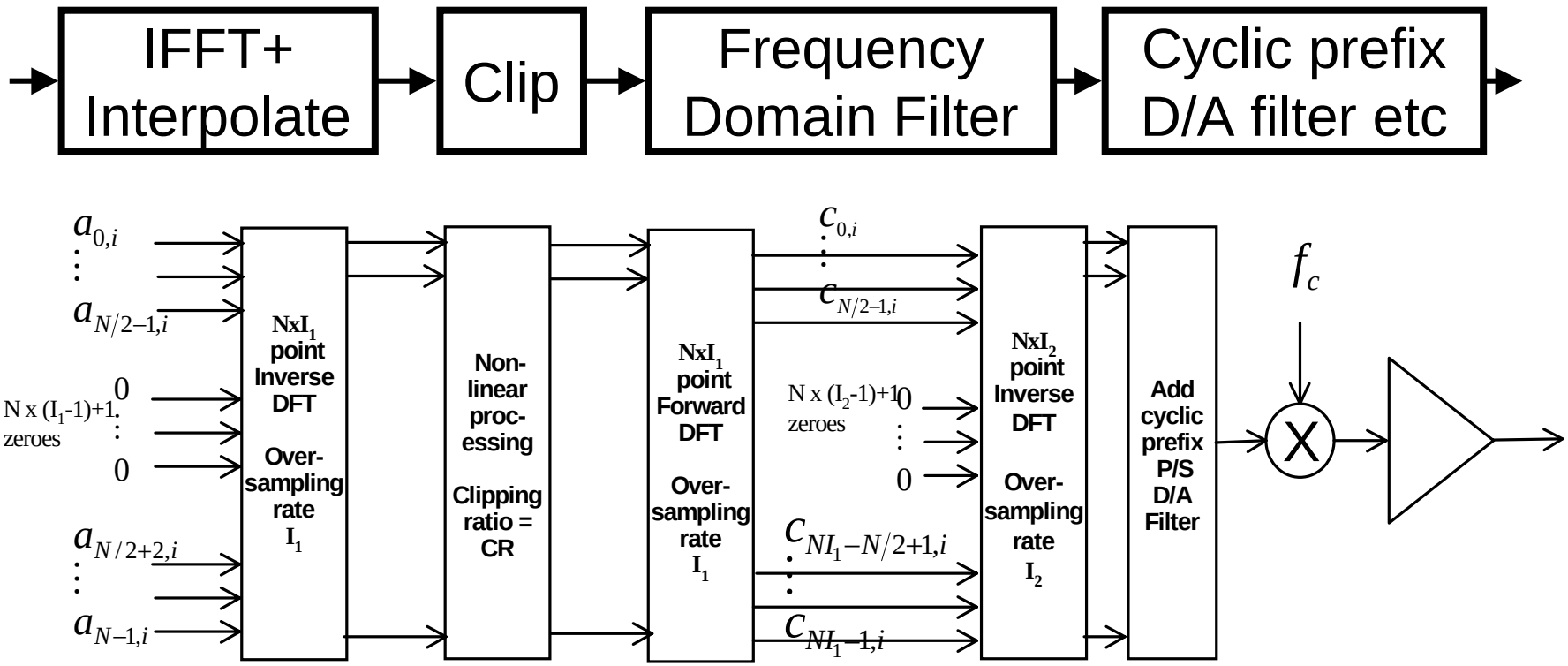
Previous clipping techniques



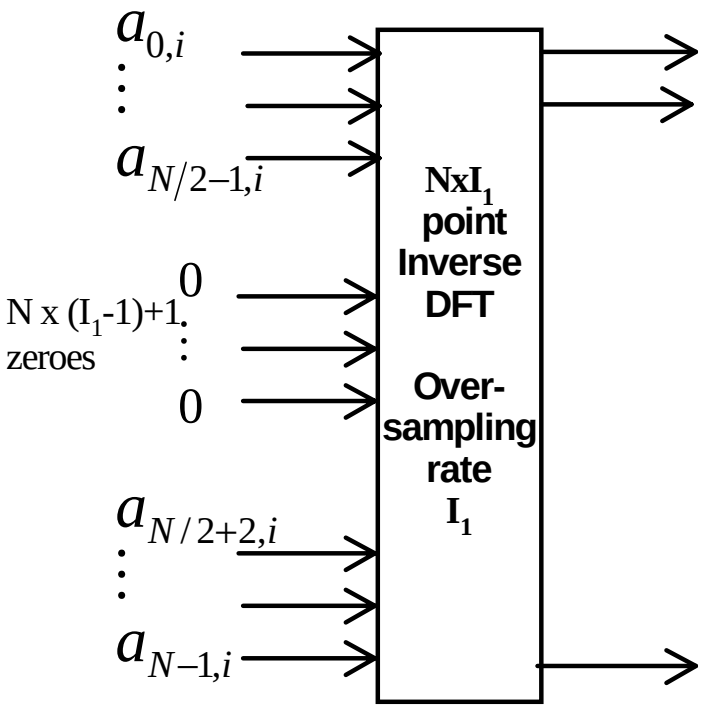
- Clip at IFFT output
  - may miss peaks
- Clip after interpolation
  - non-linearity causes out-of-band power
- Clip after interpolation+filter to remove out-of-band power
  - complicated filters, long impulse response, cause Intersymbol Interference (ISI)

New Peak Reduction Technique

Transmitter block diagram

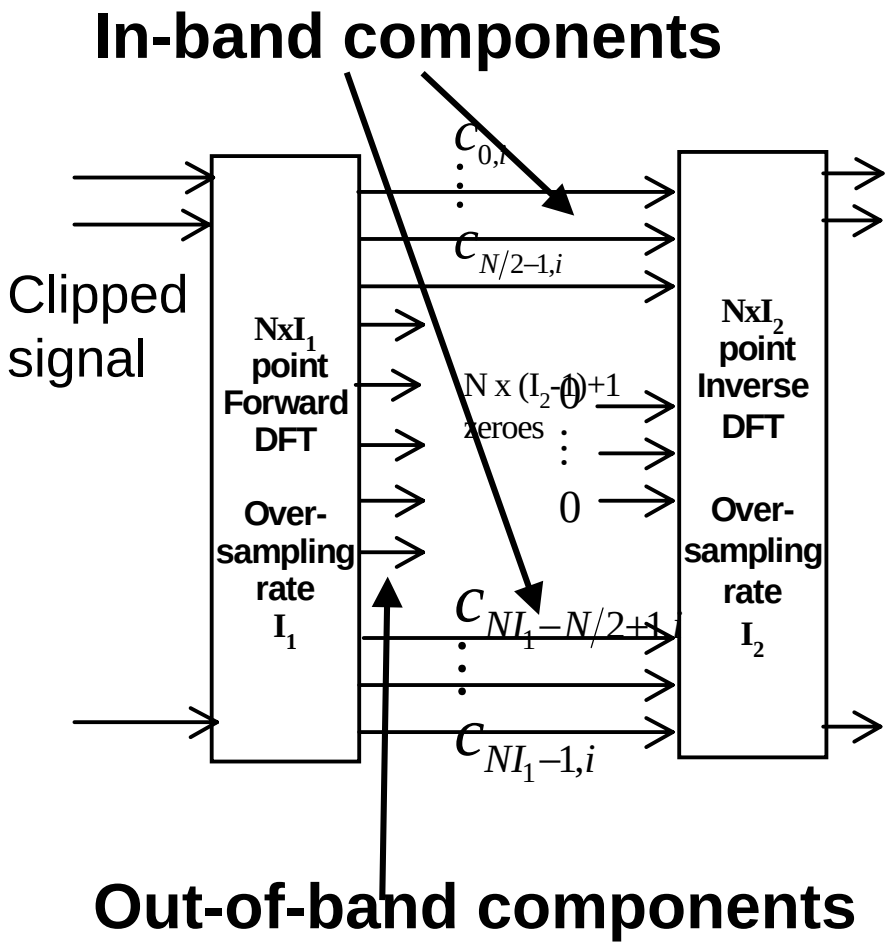


Trigonometric Interpolation usingoversize IFFT



- Oversize IFFT
- Zeros on middle inputs
- trigonometric interpolation of output

Frequency Domain filtering

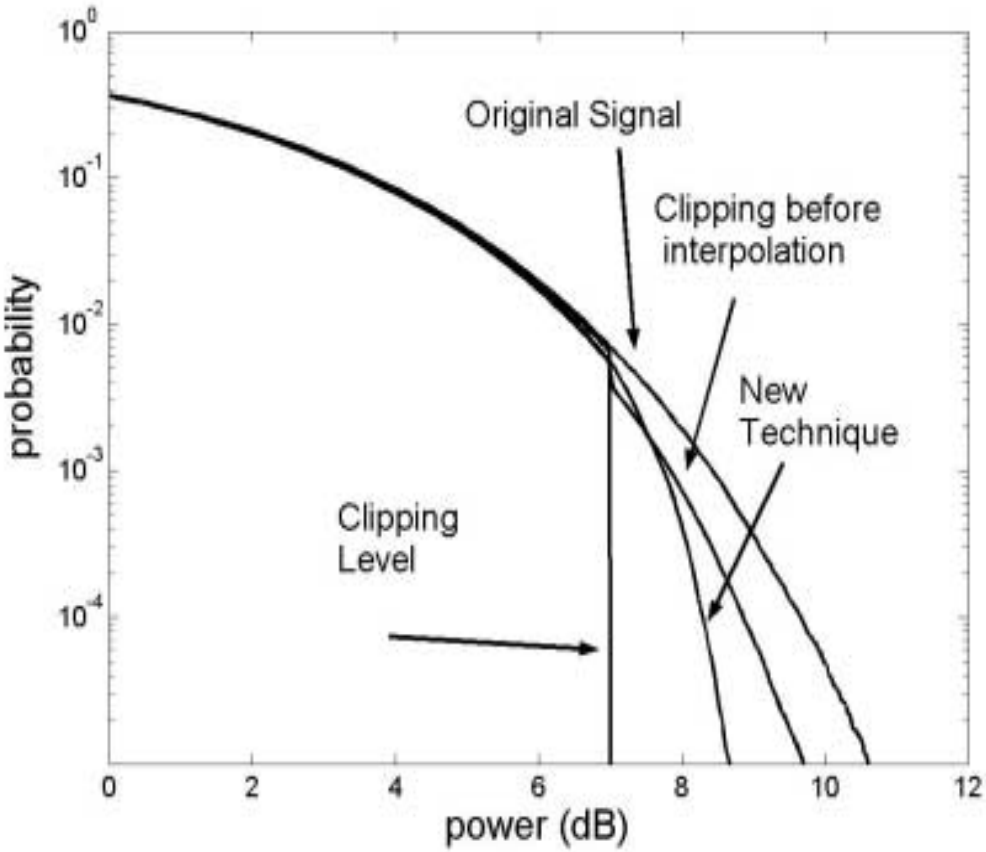


- In-band components are passed to inverse DFT
- Out-of-band components are nulled
- Operates on blocks - time variant filter
- Filter does not distort wanted OFDM signal

Performance

- PAPR reduction
- Out-of-band power
  - with ideal amplifier with limited dynamic range
  - with non-linear amplifier
- In-band distortion

PAPR Reduction

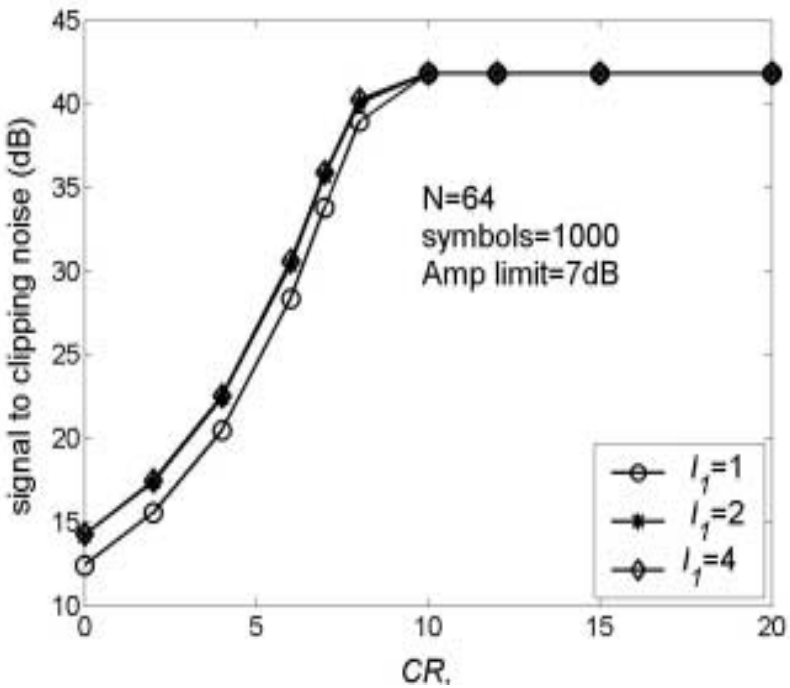


- PAPR is reduced
- Filtering causes some peak regrowth
- Better performance than clipping before interpolation
  - note logarithmic scales

Out-of-band power

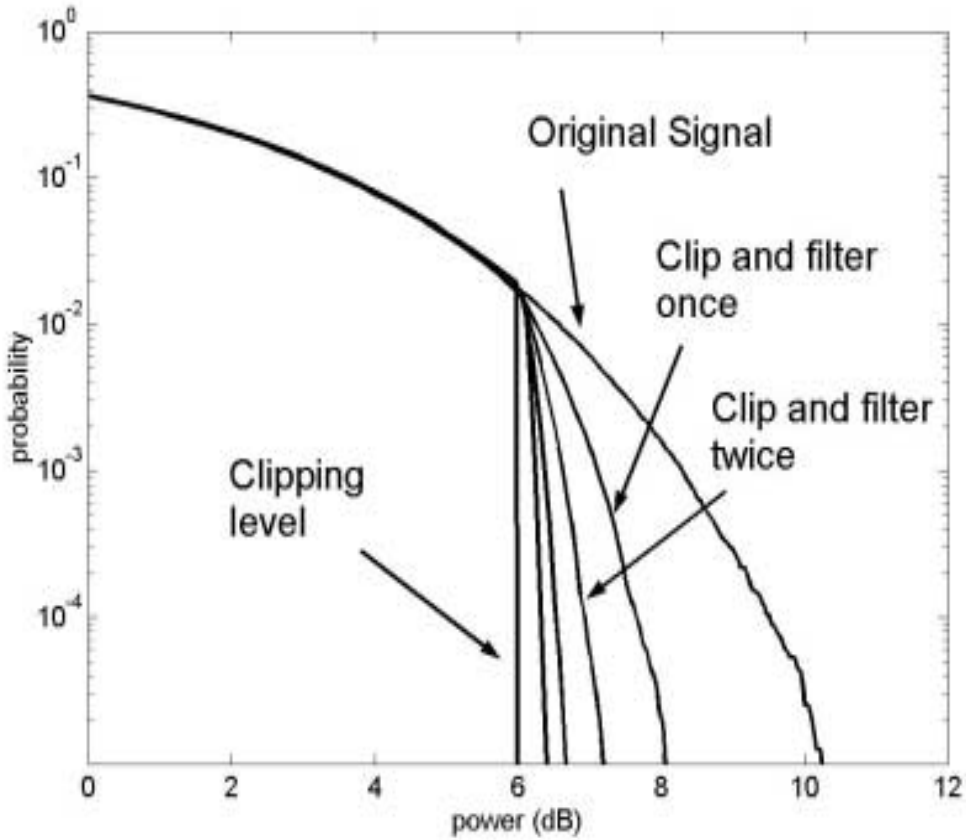
- No increase in out-of-band power after clipping and filtering
  - in systems with unused band-edge subcarriers these subcarriers nulled by filter
- Amplification will result in out-of-band power
  - signal outside dynamic range of amplifier
  - amplifier non-linearities

Signal to clipping noise ratio



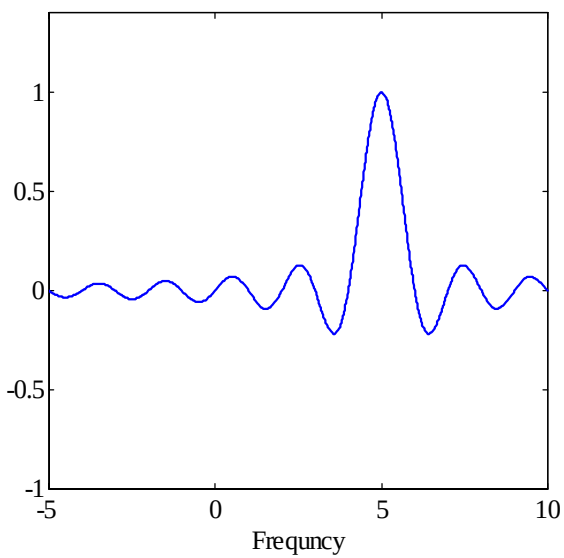
- Even extreme clipping gives moderate signal to clipping noise ratio
- Main effect of clipping is shrinking of constellation
- Clipping noise is added at transmitter so fades along with signal

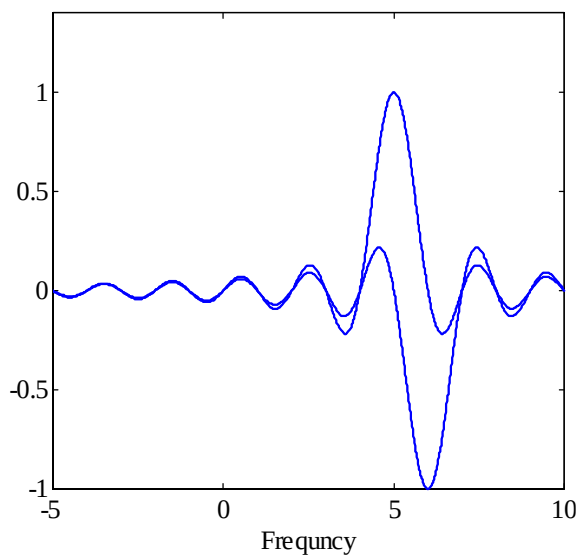
Repeated clipping and filtering

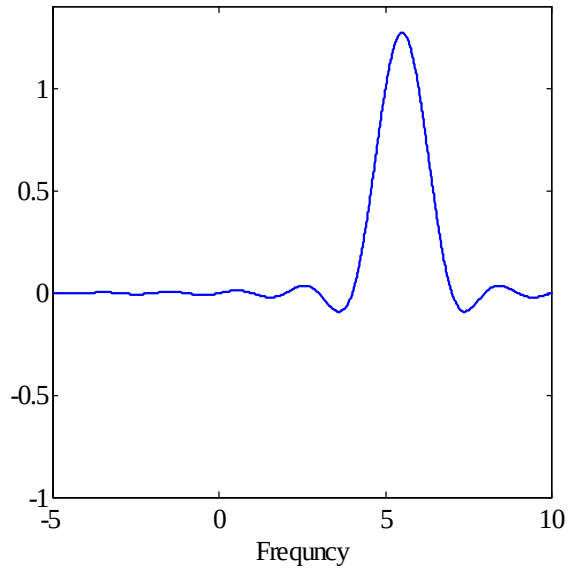


- Peak regrowth can be reduced by repeatedly clipping and filtering

PCC-OFDM - solution to frequency sensitivity

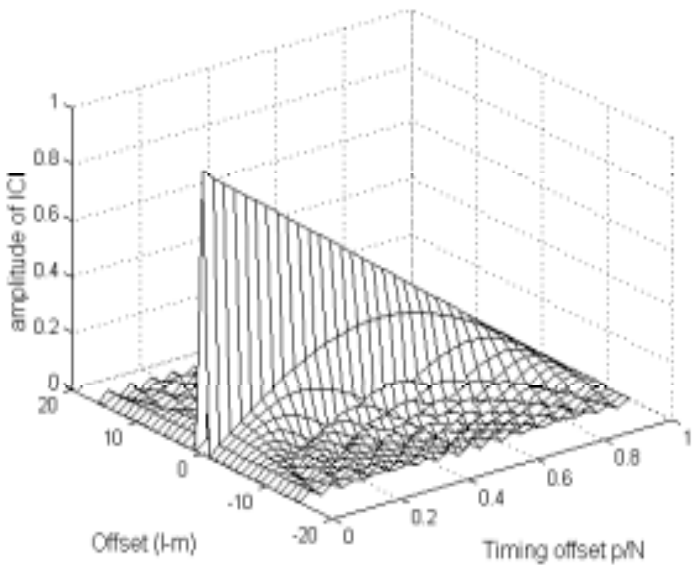




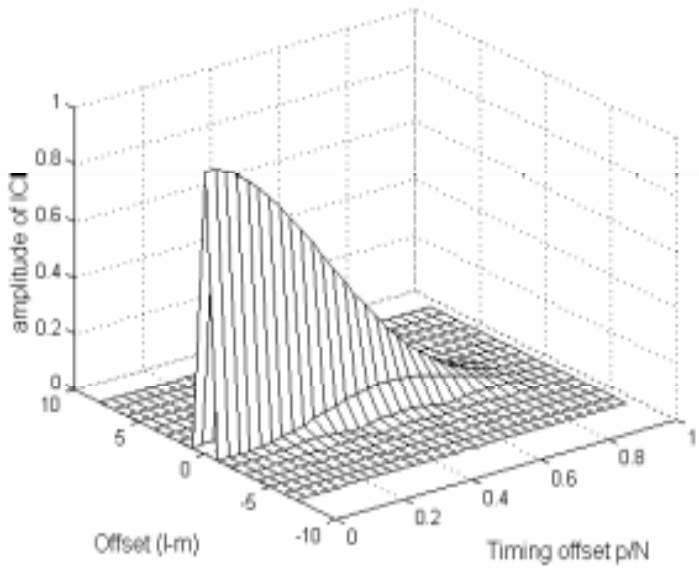


- By coding the subcarriers in pairs frequency sensitivity can be reduced
- Would have been a better basis for DVB

ISI/ICI of OFDM and PCC-OFDM



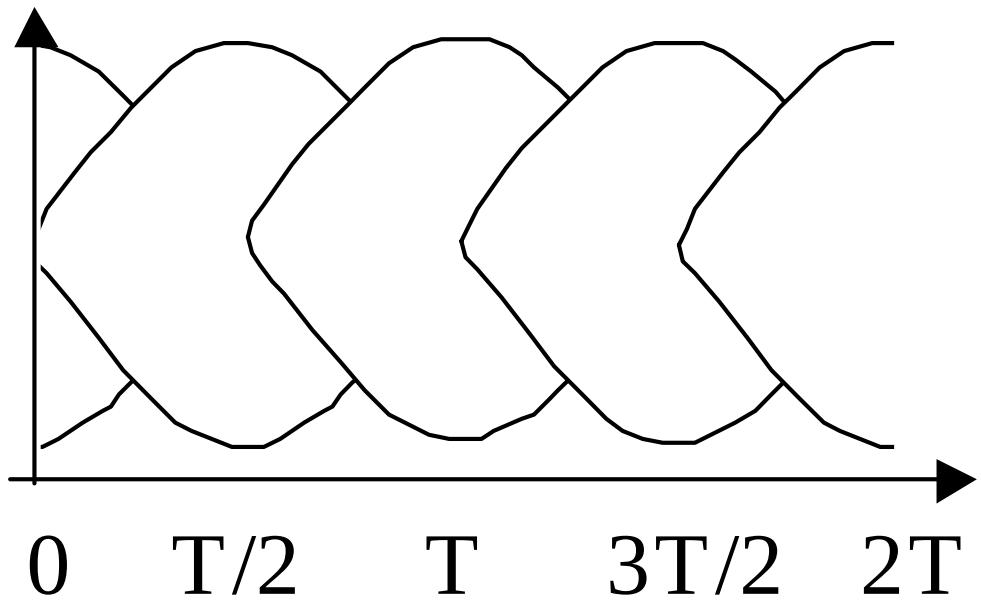
OFDM



PCC-OFDM

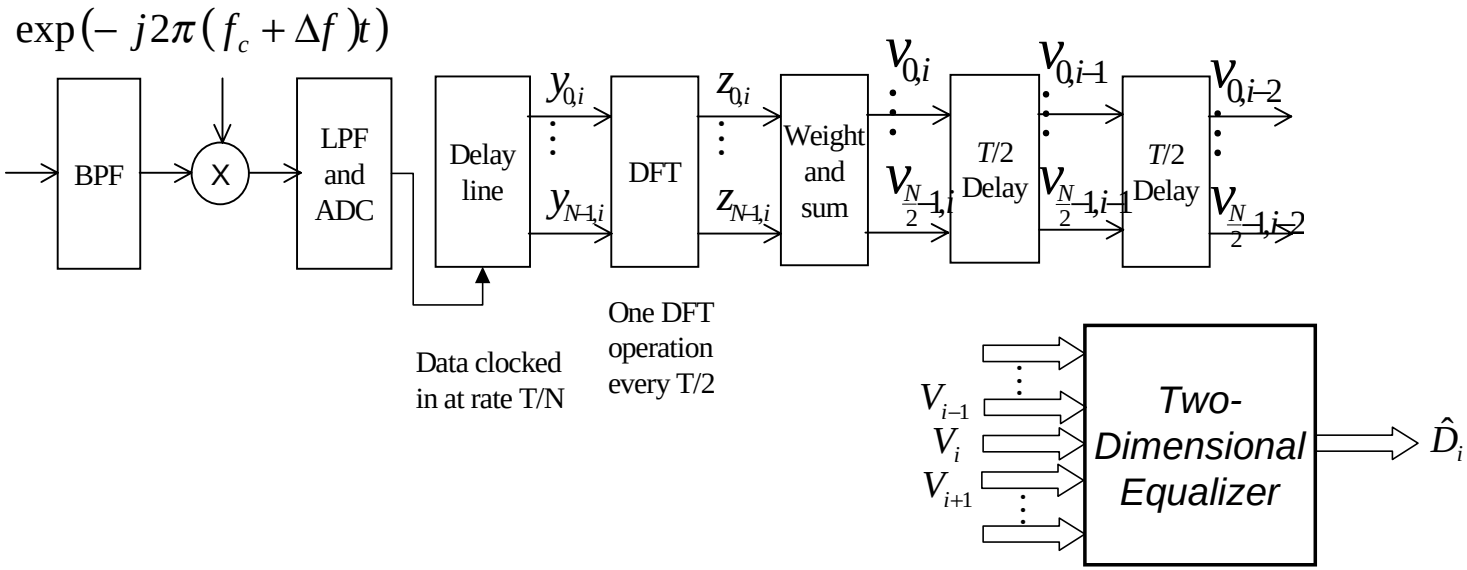
- Concentration of subchannels in time and frequency domain reduce ICI and ISI

PCC with overlapping symbol periods



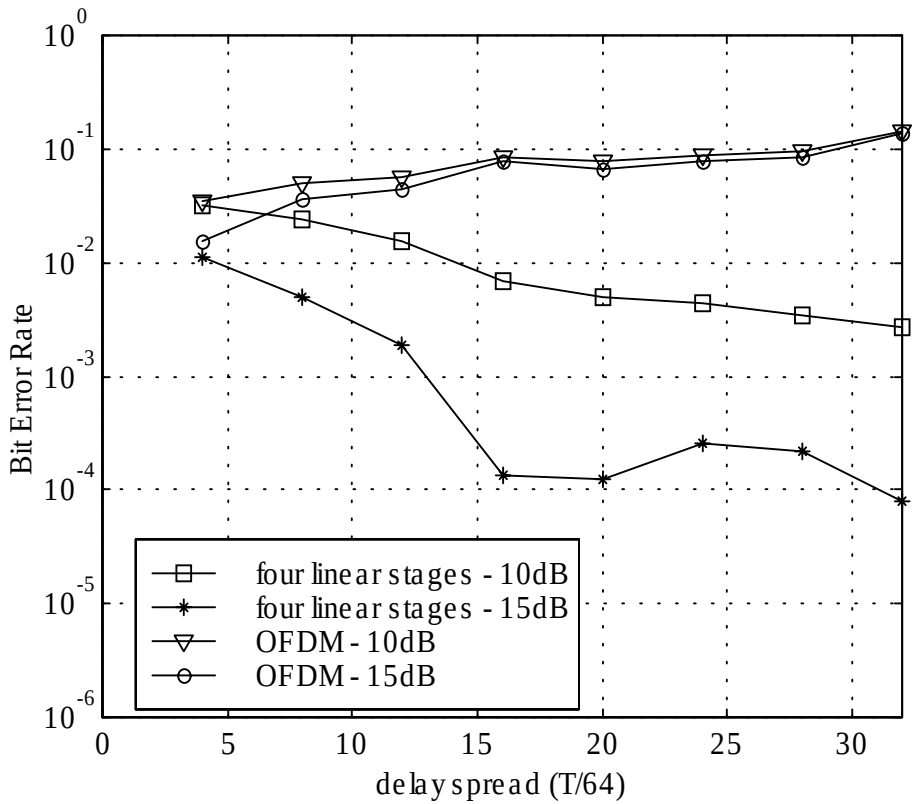
- Symbols are overlapped
  - ISI is deliberately introduced
  - equalizer required in receiver to recover data

PCC-OFDM receiver structure



- Requires two dimensional equalizer
- Properties of PCC-OFDM mean that only a few terms along the diagonal are significant

Performance in a multipath channel



- PCC-OFDM outperforms OFDM
- Advantages increase as delay spread increases
- tolerance to delay spread depends on equalizer length, not length of cyclic prefix

N=64, OFDM cyclic prefix length =6T/64

Conclusions

- OFDM is used in many applications
  - solution to multipath
  - good digital signal processing algorithms
- Any questions?

Baseband OFDM system