UESTC4004

Digital Communications

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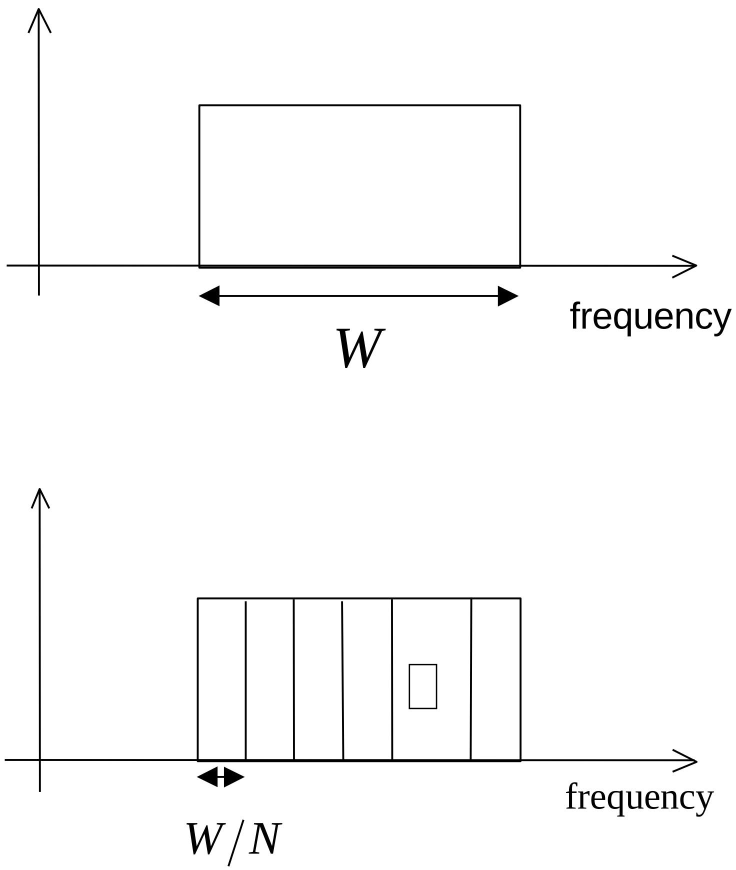
OFDM
Orthogonal Frequency Division Multiplexing

Overview

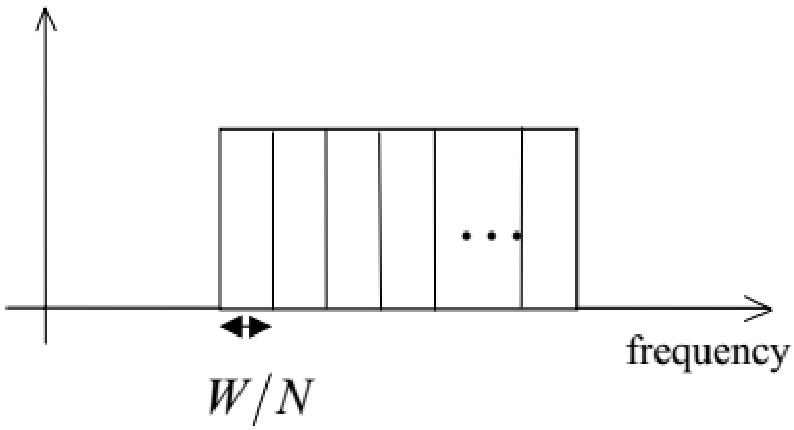
- Introduction
  - Multi-carrier systems
  - OFDM
- Why use OFDM?
  - Multipath transmission
- How OFDM works
- Applications of OFDM
- Problems with OFDM
- Cool trick with OFDM

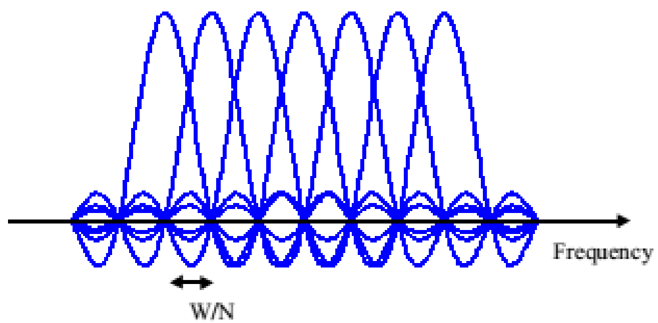
Multicarrier systems



- 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?





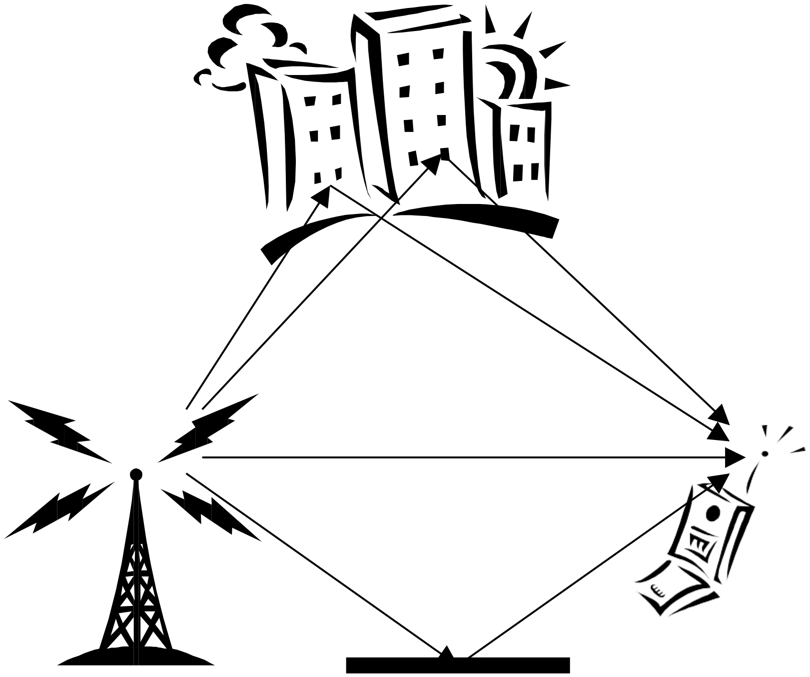
- OFDM is a multicarrier system
  - uses discrete Fourier Transform/Fast Fourier Transform (DFT/FFT)
  - sin(x)/x spectra for subcarriers
- Available bandwidth is divided into very many narrow bands
  - ~2000-8000 for digital TV
  - ~48 for Hiperlan 2
- Data is transmitted in parallel on these bands

Why is OFDM so popular for new broadband systems?

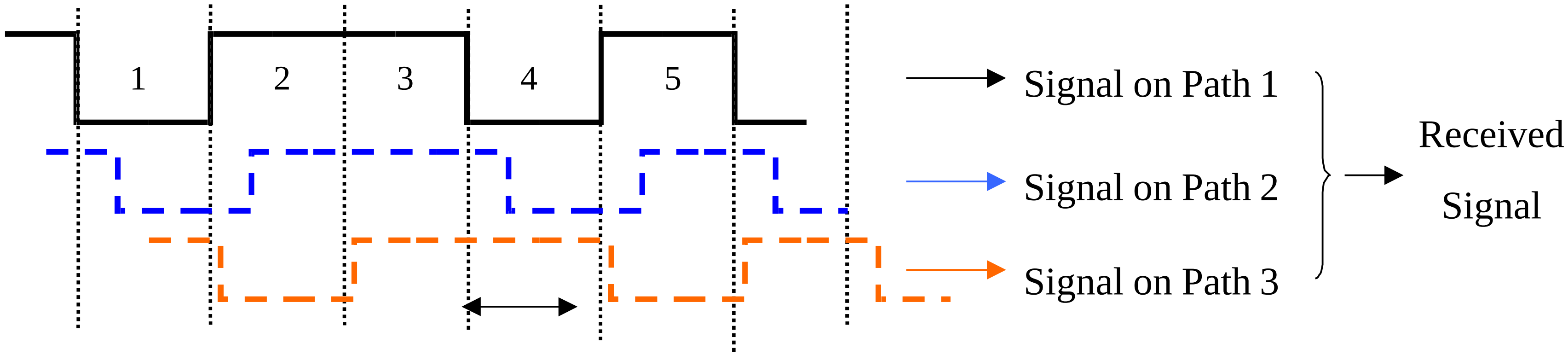
- Most broadband systems are subject to multipath transmission
- Conventional solution to multipath is an equalizer in the receiver
  - high data rates - equalizers too complicated
- With OFDM there is a simple way of dealing with multipath
  - relatively simple DSP algorithms

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



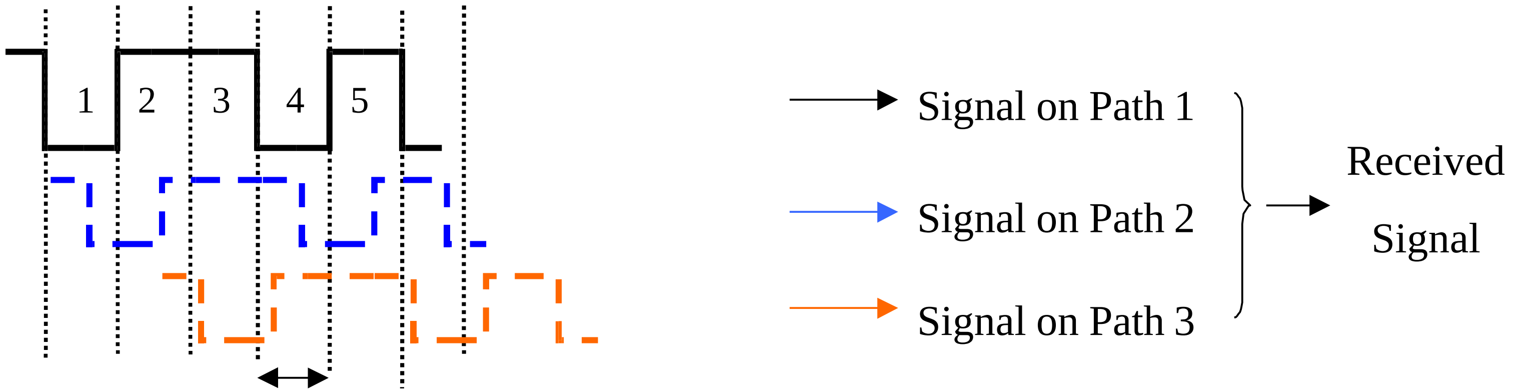
Effect of Multipath on Received Baseband Signal



Received signal depends on bits 2 - 4

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

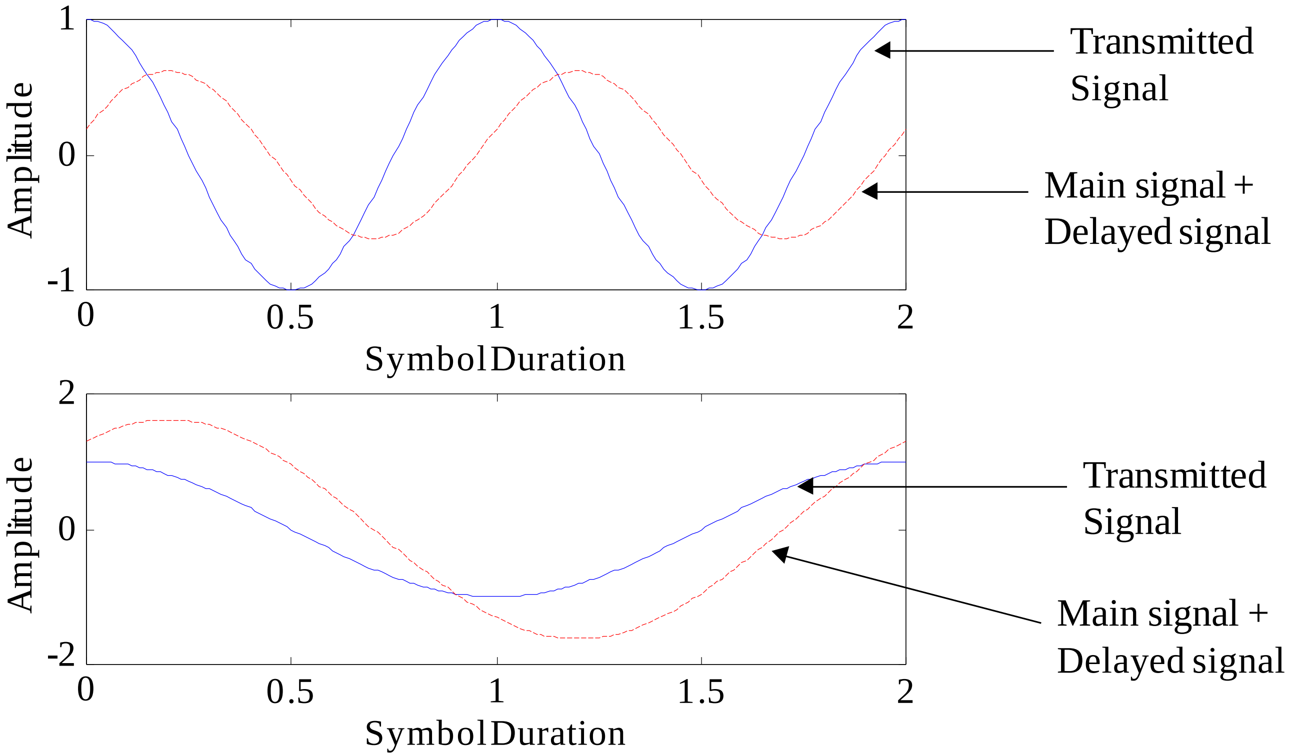
ISI gets worse as data rate increases



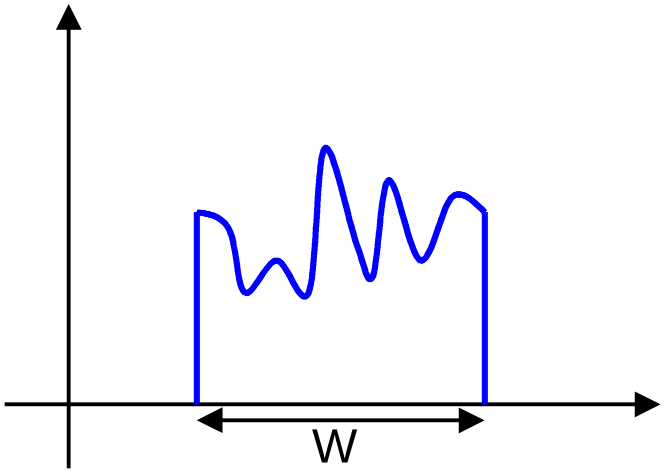
Received signal depends on bits 1 - 4

- ISI covers more symbol periods
- Equalizer becomes too complicated

Multipath Effect

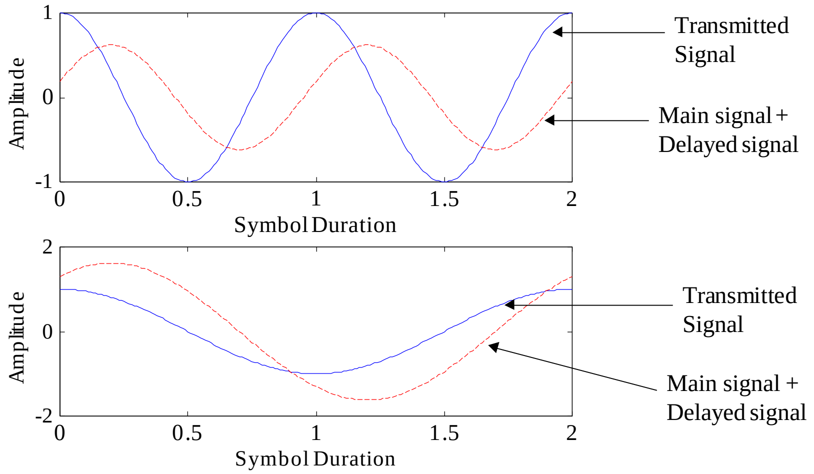


Multipath Effect: Spectrum of Received Signal



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

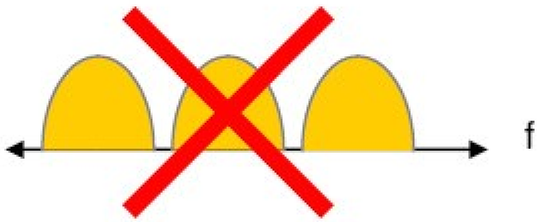
Multipath Effect: Amplitude and phase change



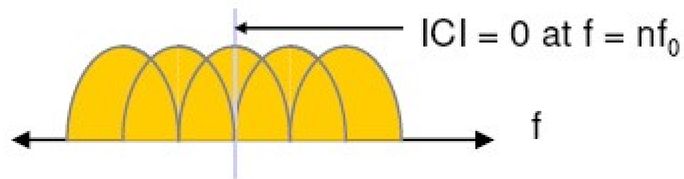
- Multipath delay causes change in amplitude and phase of each subcarrier
- Change depends on subcarrier frequency
- Corrected in receiver by one complex multiplication per subcarrier

OFDM efficiently solves multipath effect.
How?

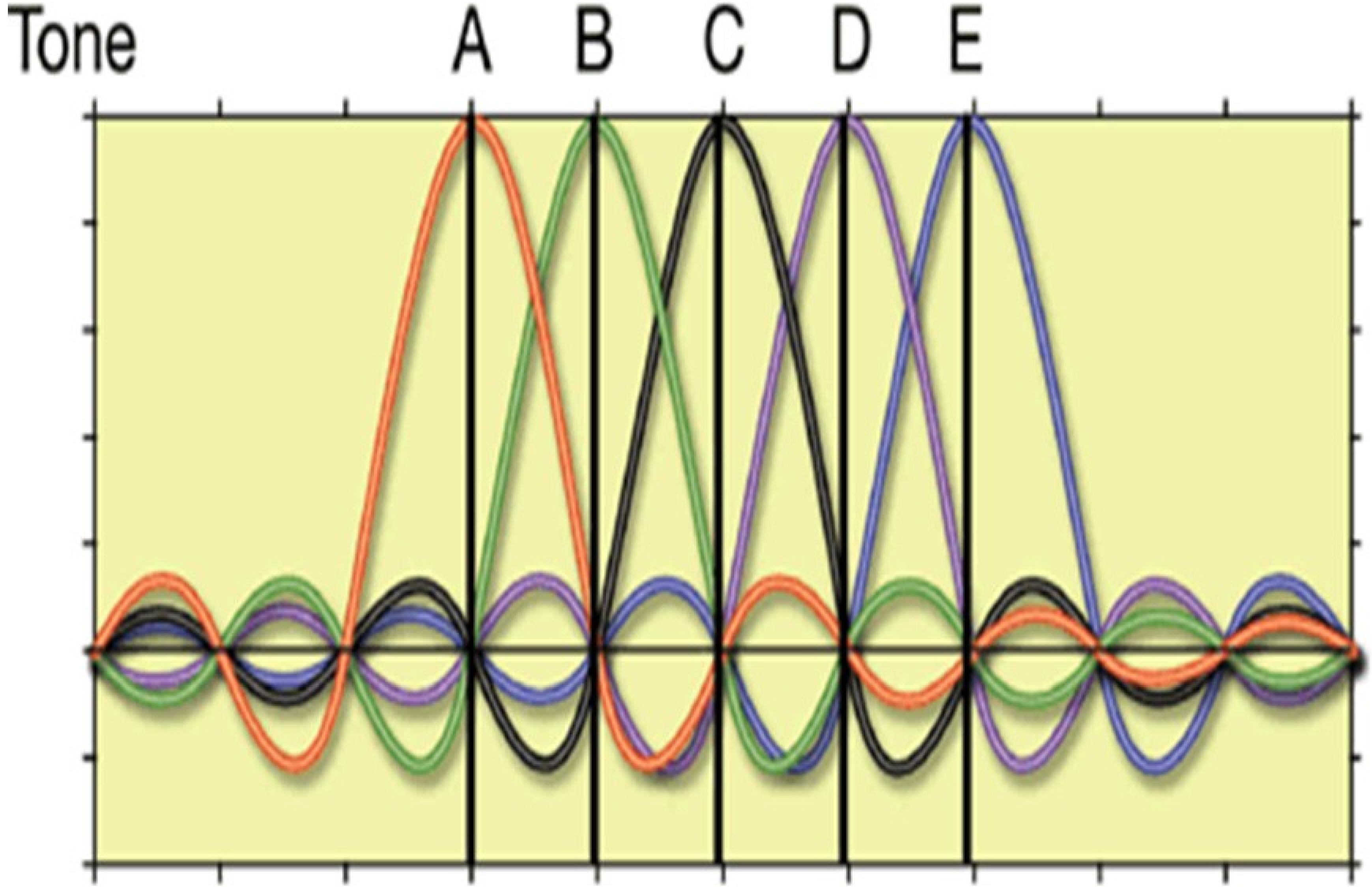
OFDM Spectrum



Some FDM systems achieve orthogonality through zero spectral overlap
⇒ BW inefficient!



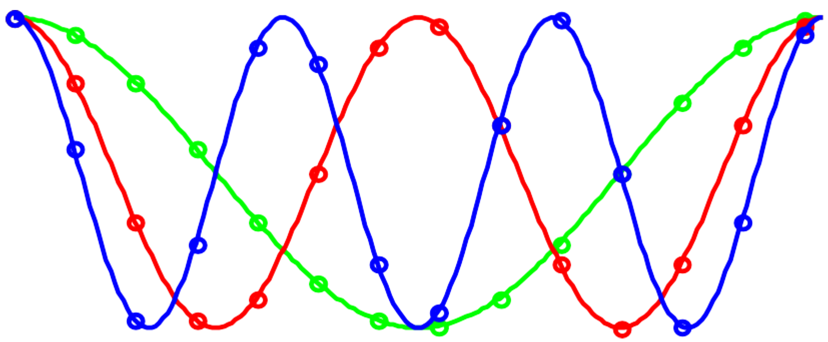
OFDM systems have overlapped spectra with each subcarrier spectrum having a Nyquist “zero ISI pulse shape” (really zero ICI in this case).
⇒ BW efficient!



OFDM Spectrum

How are signals transmitted in parallel without interference?

First three subcarriers

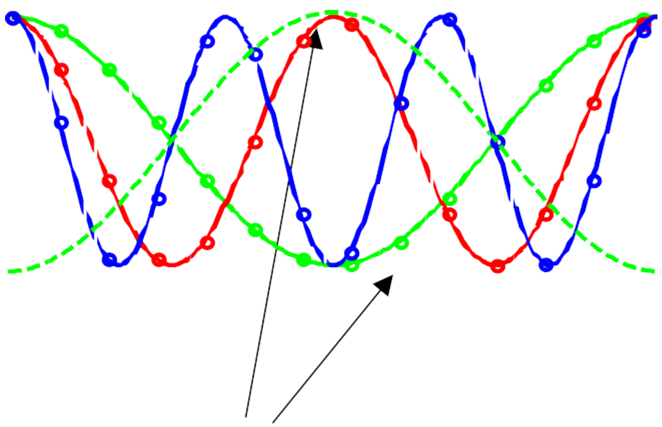


Symbol period

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

- 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?



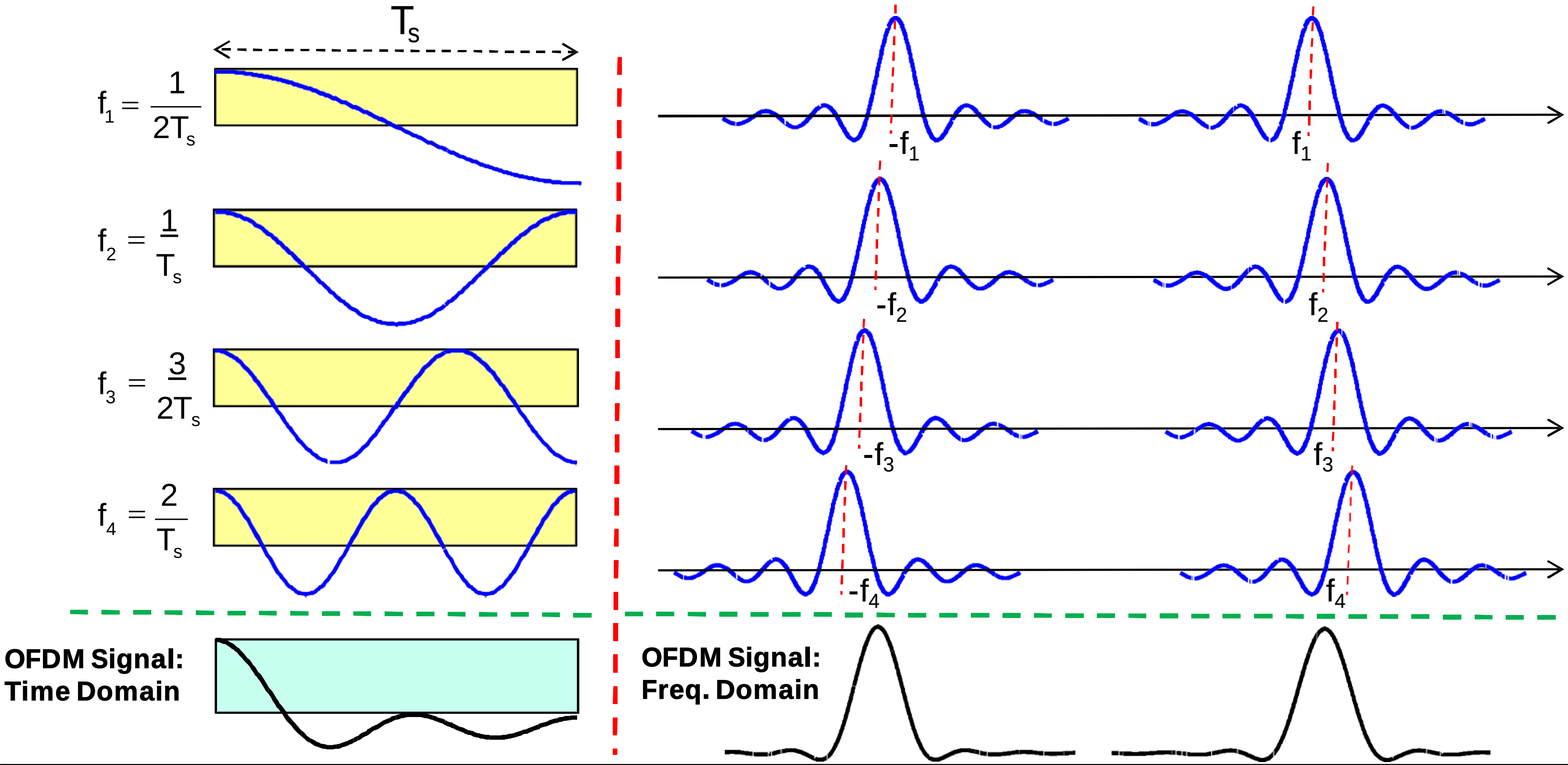
Two possible subcarrier values

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

OFDM & DFT (Discrete Fourier Transform)

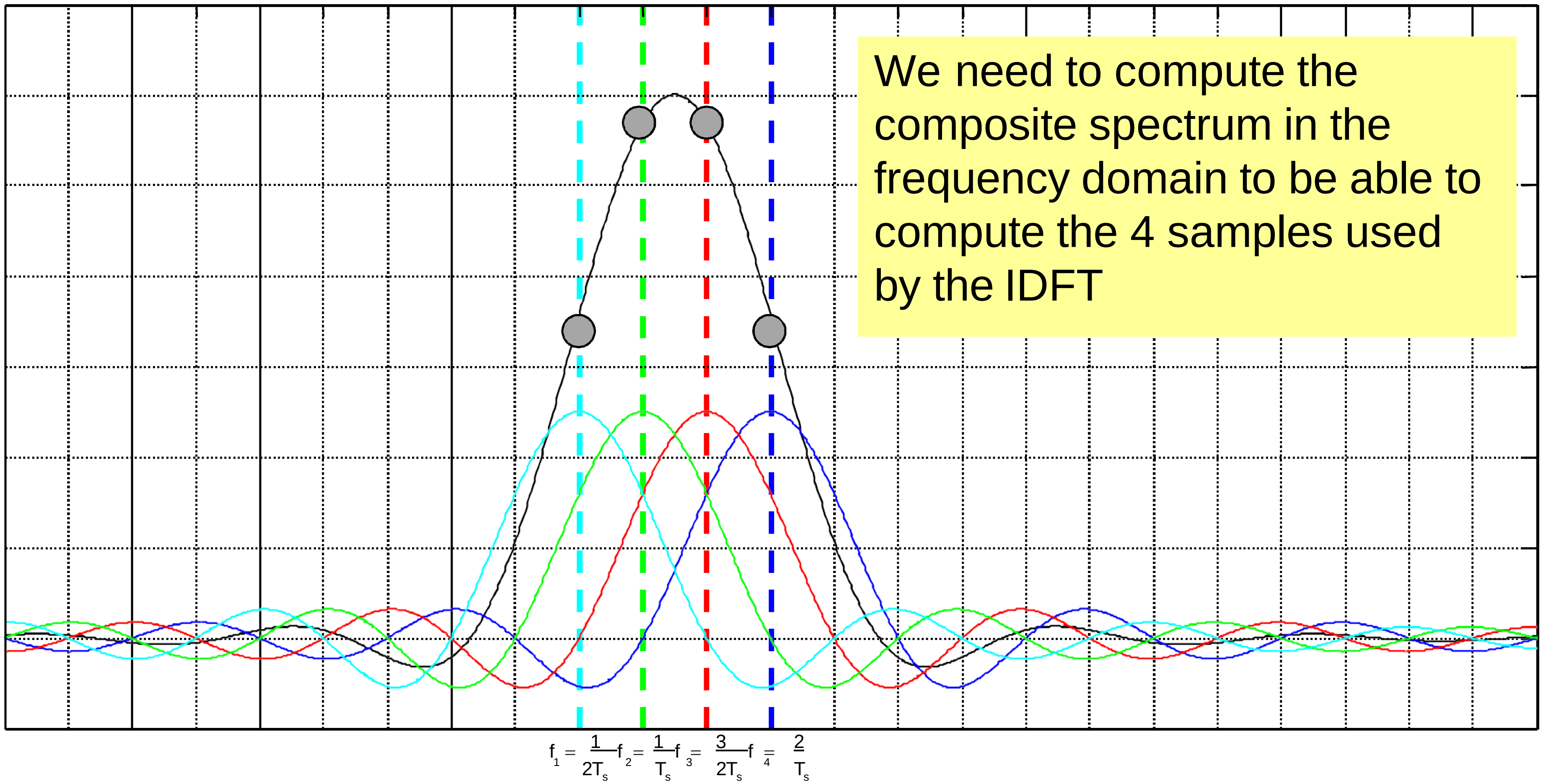
OFDM Signal over 4 Sub-carriers $f_1 = \cos(\pi t/T_s)$ $f_2 = \cos(2\pi t/T_s)$

$f_3 = \cos(3\pi t/T_s)$ $f_4 = \cos(4\pi t/T_s)$



OFDM & DFT (Discrete Fourier Transform)

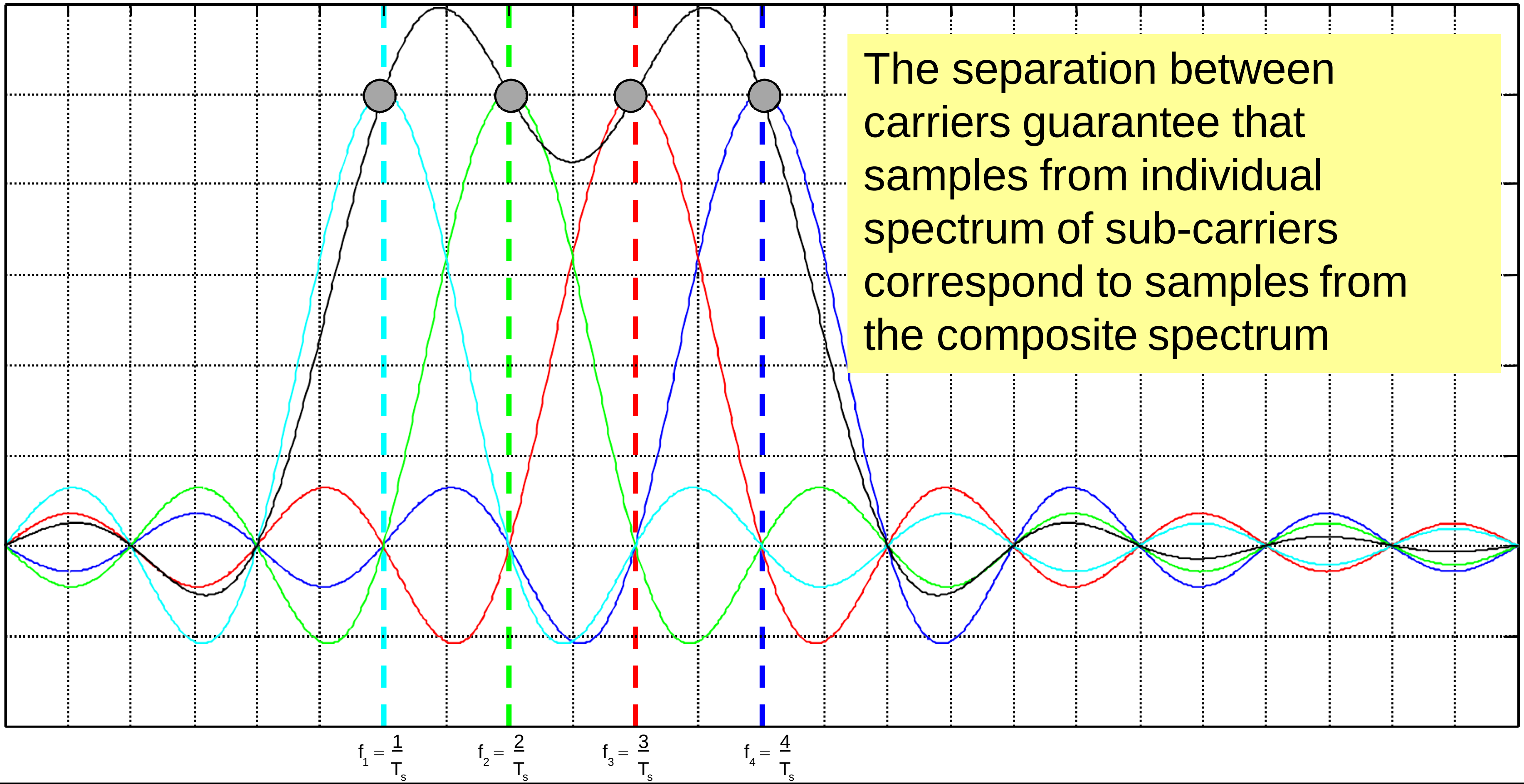
OFDM Signal over 4 Sub-carriers $f_1 = \cos(\pi t / T_s)$ $f_2 = \cos(2\pi t / T_s)$ $f_3 = \cos(3\pi t / T_s)$ $f_4 = \cos(4\pi t / T_s)$ (Separated by $1/2T_s$)



OFDM & DFT (Discrete Fourier Transform)

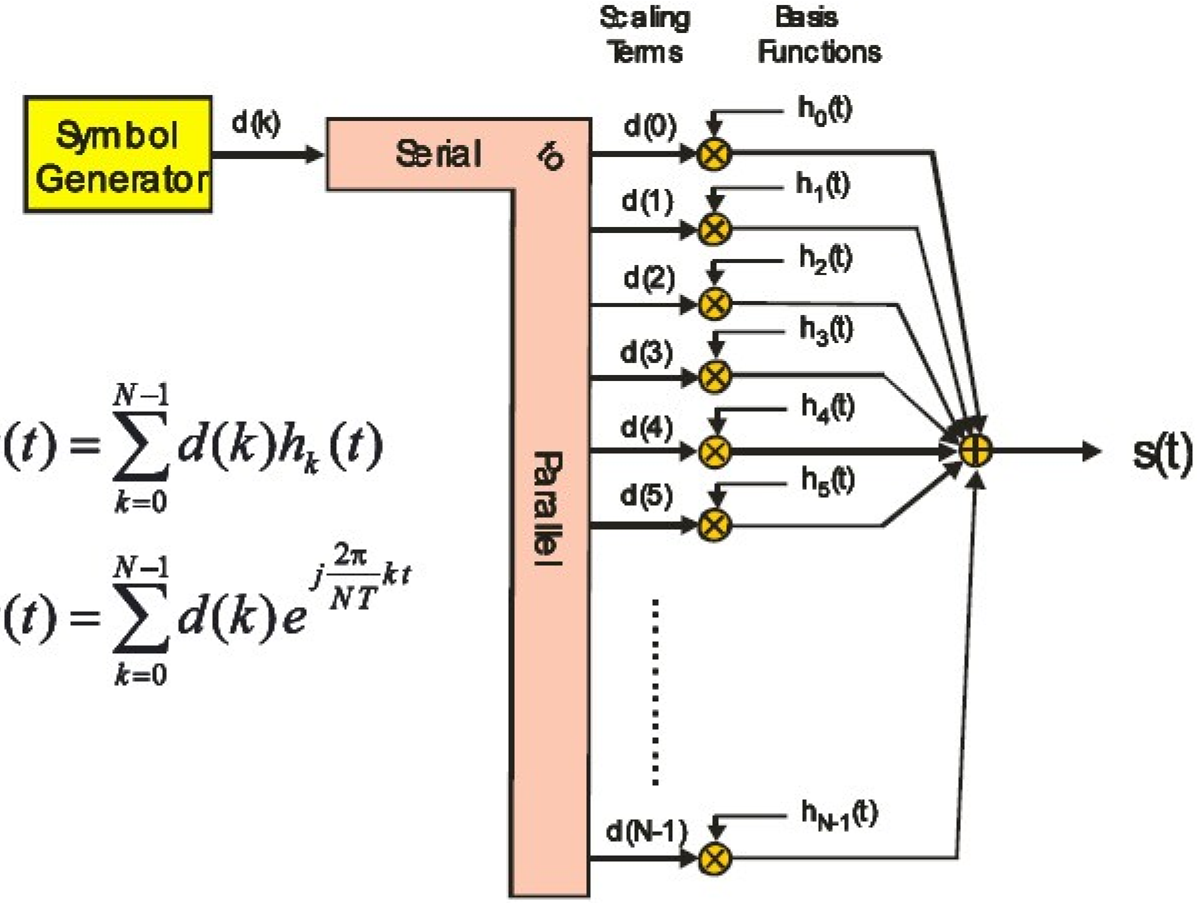
OFDM Signal over 4 Sub-carriers $f_1 = \cos(2\pi t/T_s)$ $f_2 = \cos(4\pi t/T_s)$

$f_3 = \cos(6\pi t/T_s)$ $f_4 = \cos(8\pi t/T_s)$ (Separated by $1/T_s$)



The separation between carriers guarantee that samples from individual spectrum of sub-carriers correspond to samples from the composite spectrum

OFDM Modulator



$$s(t) = \sum_{k=0}^{N-1} d(k) h_k(t)$$

$$s(t) = \sum_{k=0}^{N-1} d(k) e^{j\frac{2\pi}{NT}kt}$$

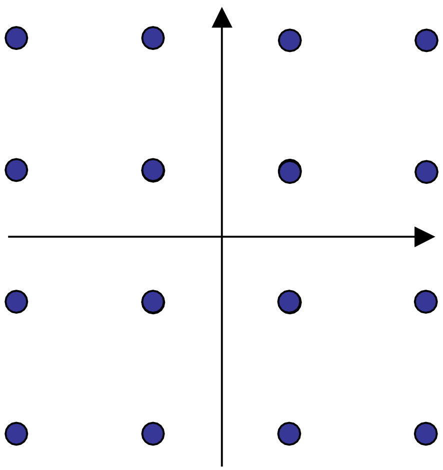
How are OFDM signals generated?

Typical IFFT Output Samples

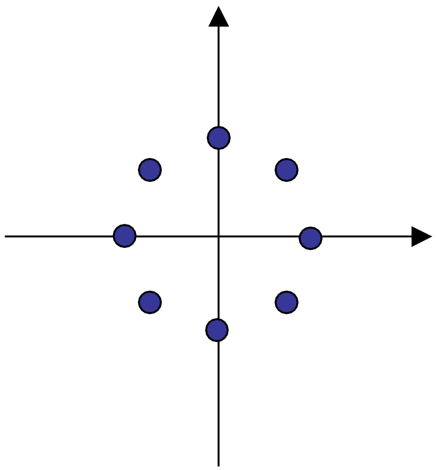
Signal values at the output of the IFFT are the sum of many samples of many sinusoids - looks random

- Parallel data streams are used as inputs to an IFFT
- IFFT output is <u>sum</u> 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

Subcarrier modulation (IEEE 802.11a&g)

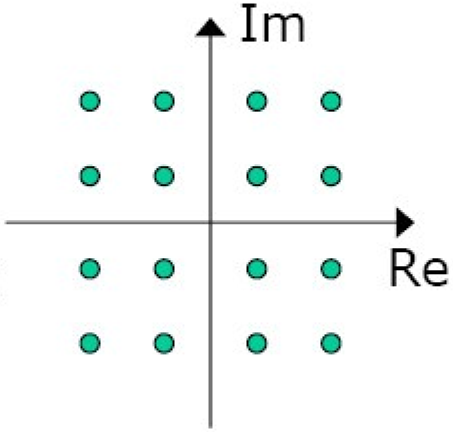
Modulation	Bit rate
BPSK	6 Mbit/s
BPSK	9 Mbit/s
QPSK	12 Mbit/s
QPSK	18 Mbit/s
16-QAM	24 Mbit/s
16-QAM	36 Mbit/s
64-QAM	48 Mbit/s
64-QAM	54 Mbit/s

BPSK = Binary Phase Shift Keying (PSK)

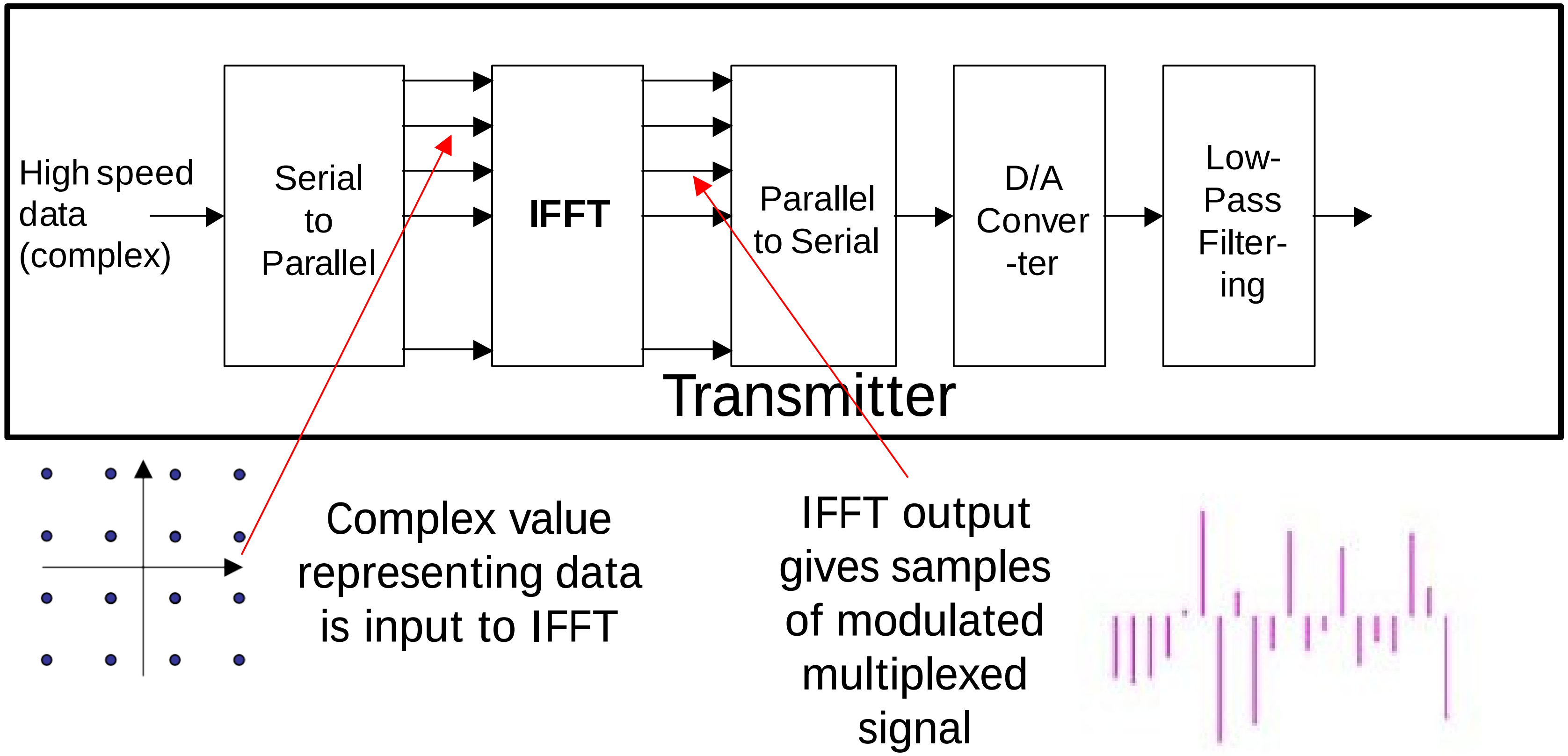
QPSK = Quaternary PSK

QAM = Quadrature Amplitude Modulation

16-QAM signal constellation in the complex plane



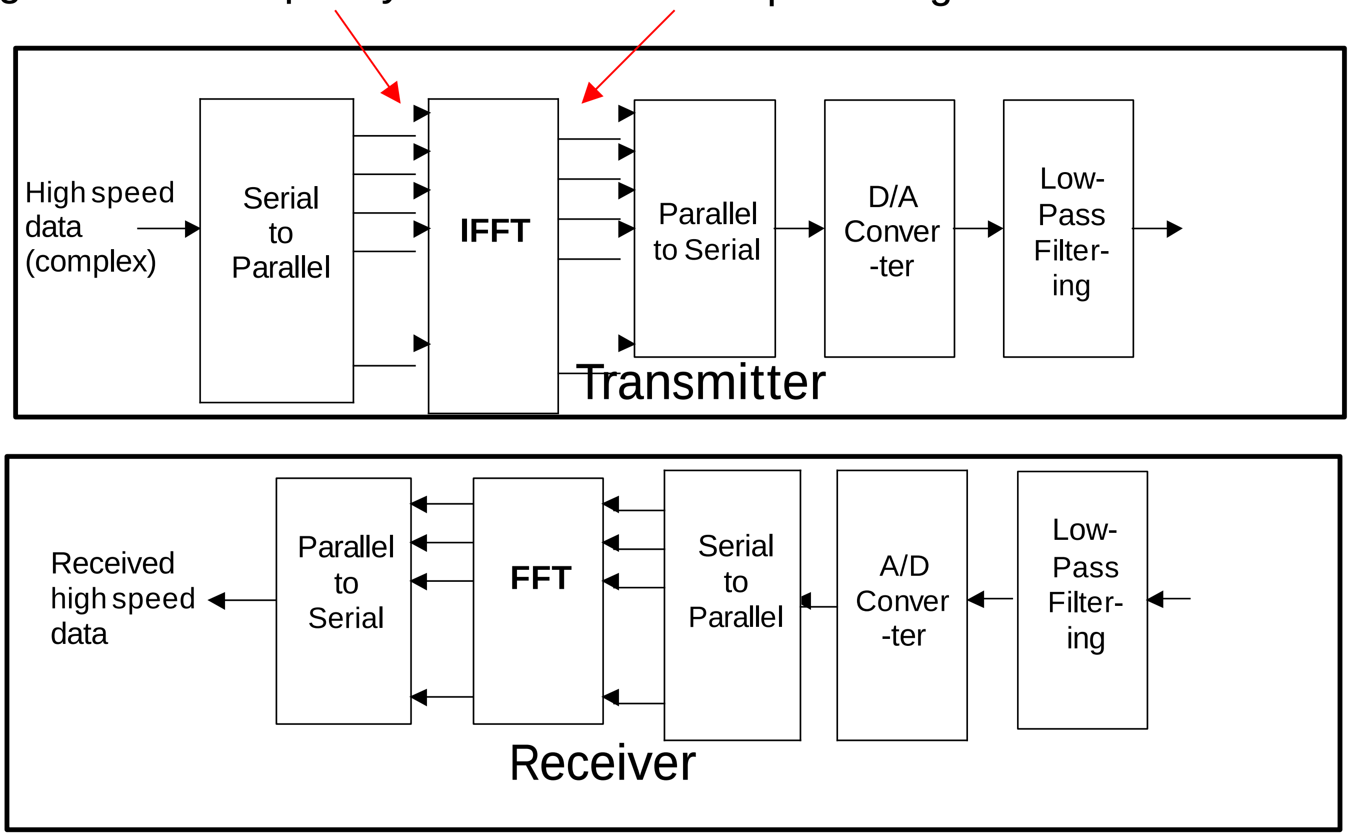
Signals at Input and Output of Transmitter IFFT



Baseband OFDM system

Discrete frequency domain
Each input controls
signal at one frequency

Discrete Time Domain
Samples of modulated
and multiplexed signals

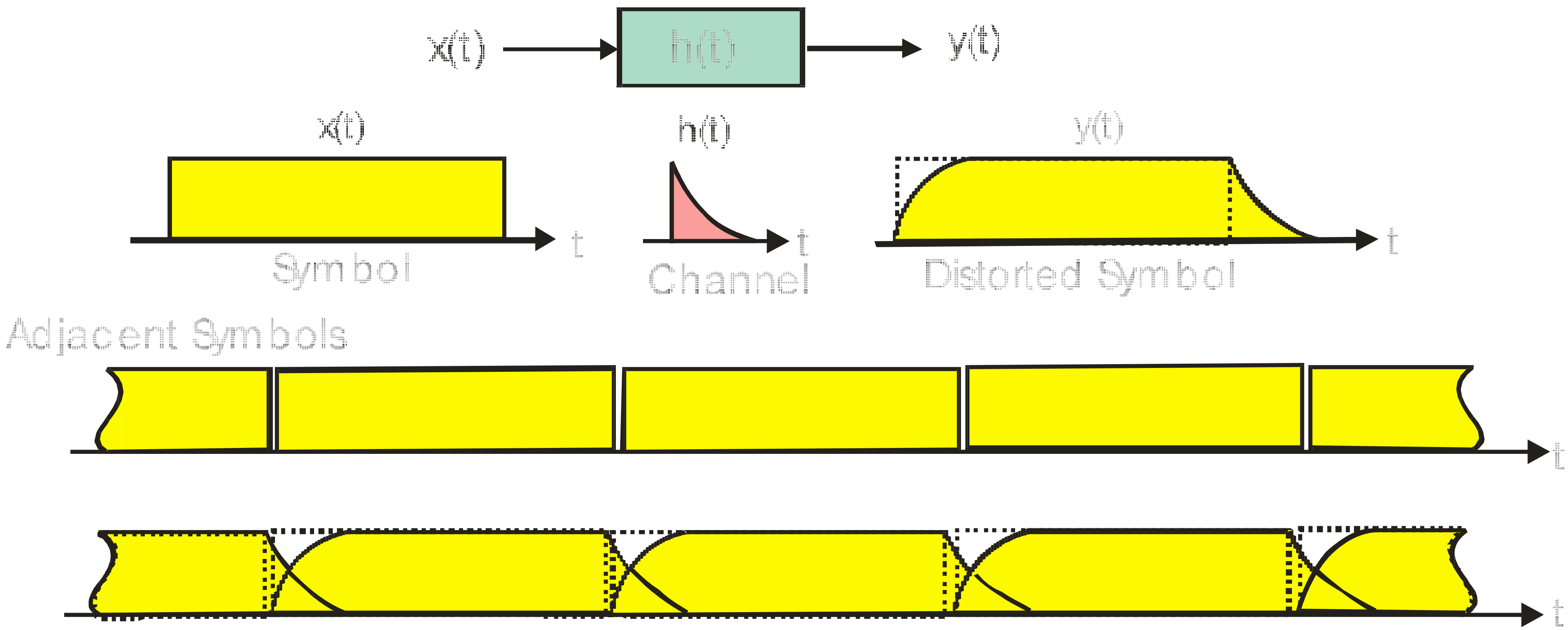


How does OFDM solve the multipath problem?

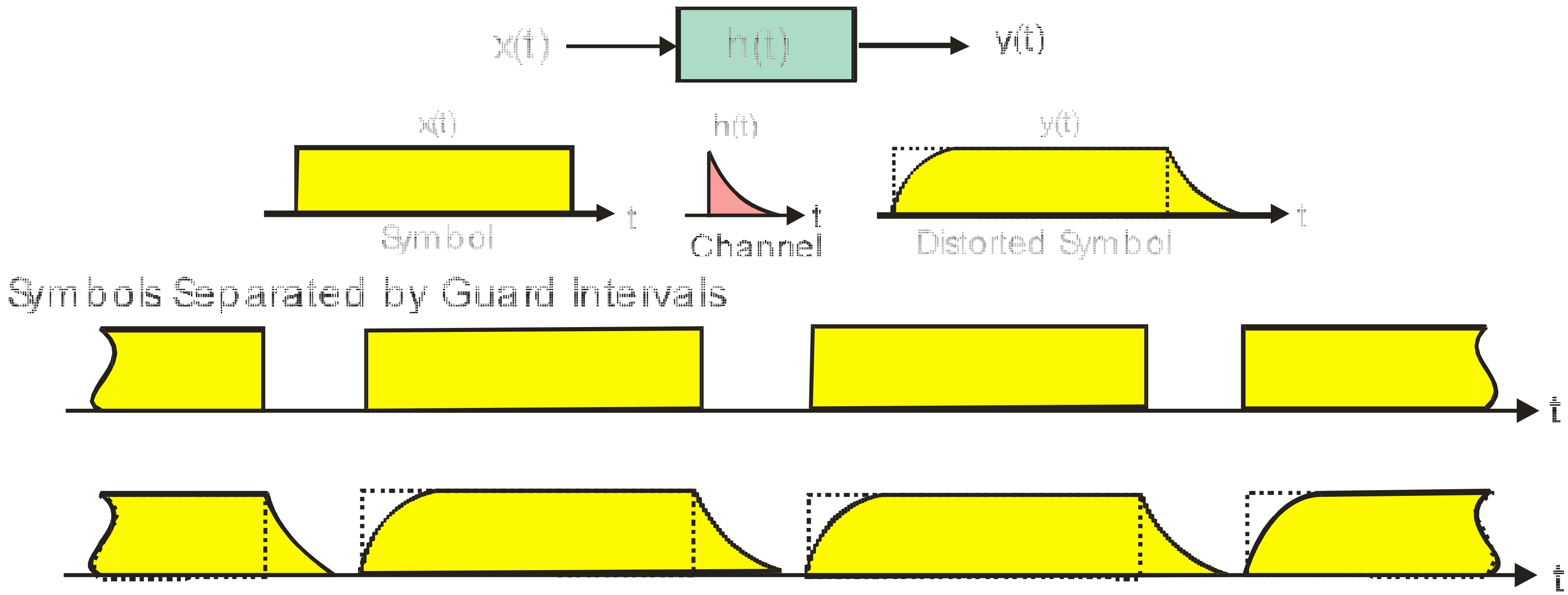
- Data is transmitted in parallel
  - longer symbol period
  - e.g. for N parallel streams, symbol period is N times as long
- Cyclic prefix
  - trick to avoid residual ISI

Adjacent Symbol Interference (ASI)

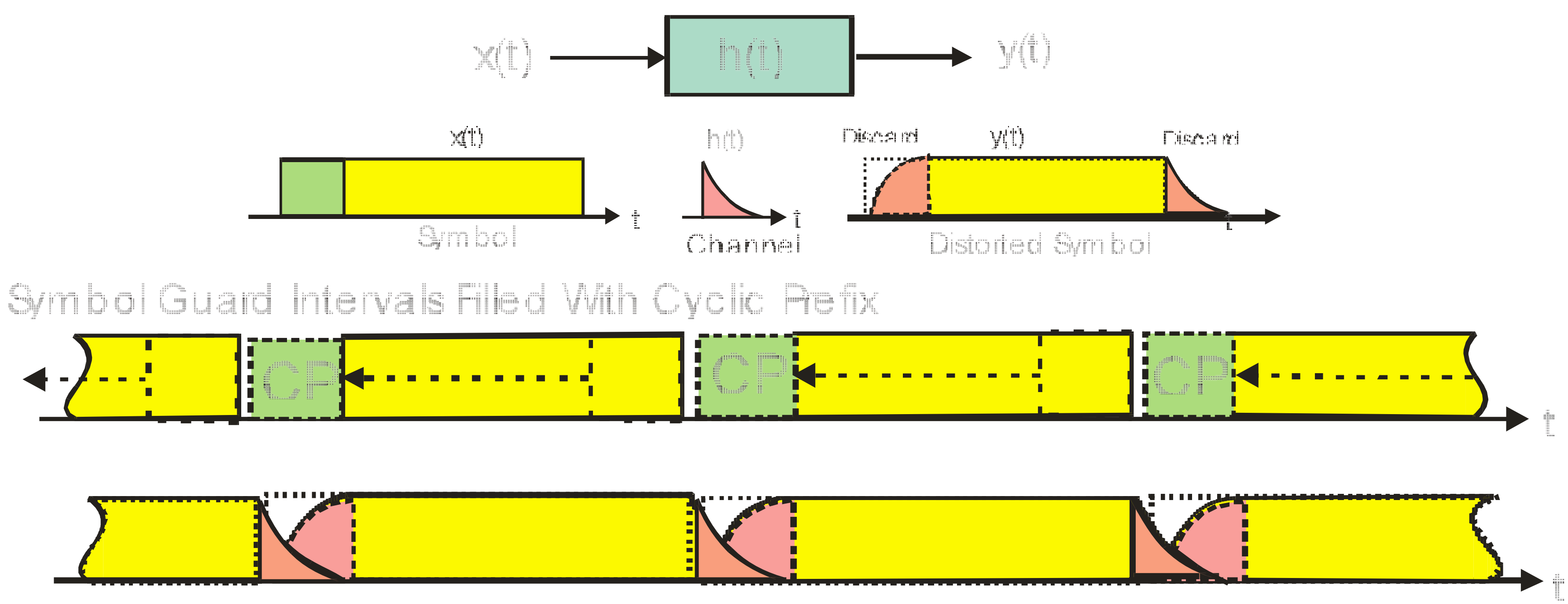
Symbol Smearing Due to Channel



Guard Interval Inserted Between Adjacent Symbols to Suppress ASI



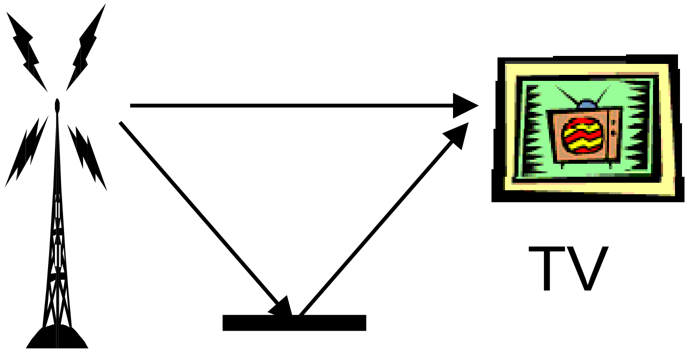
Cyclic Prefix Inserted in Guard Interval to Suppress Adjacent Channel Interference (ACI)



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?

Digital Video Broadcasting (DVB)

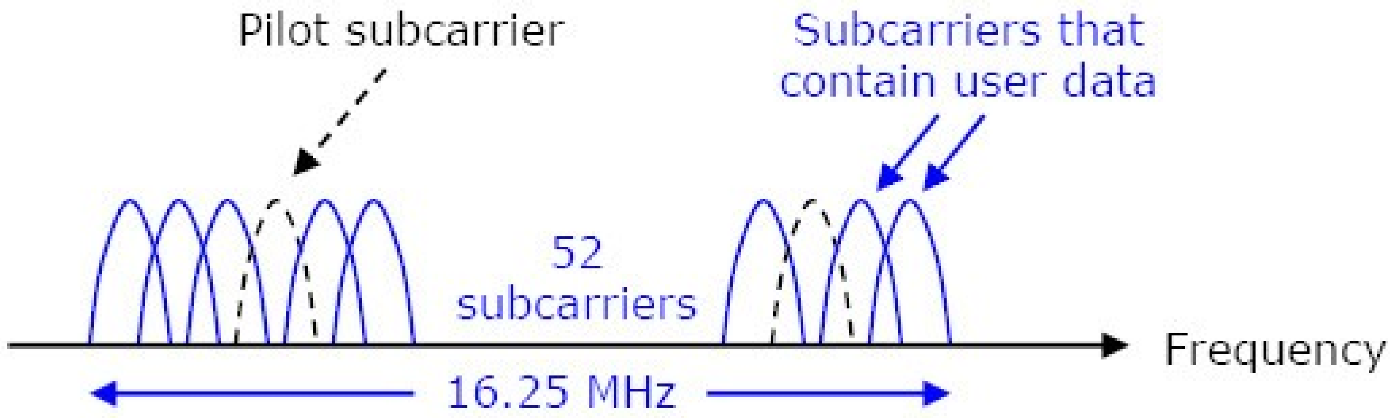


- OFDM is used in the Australian digital television system
- 2048 point IFFT
  - 1705 subcarriers used
- Flexible standard
  - variable error coding
  - variable cyclic prefix
  - variable constellation
    - 4QAM, 16QAM, 64QAM
- Broadcast system
  - mode determined by broadcaster

Hiperlan-2 - Wireless LAN

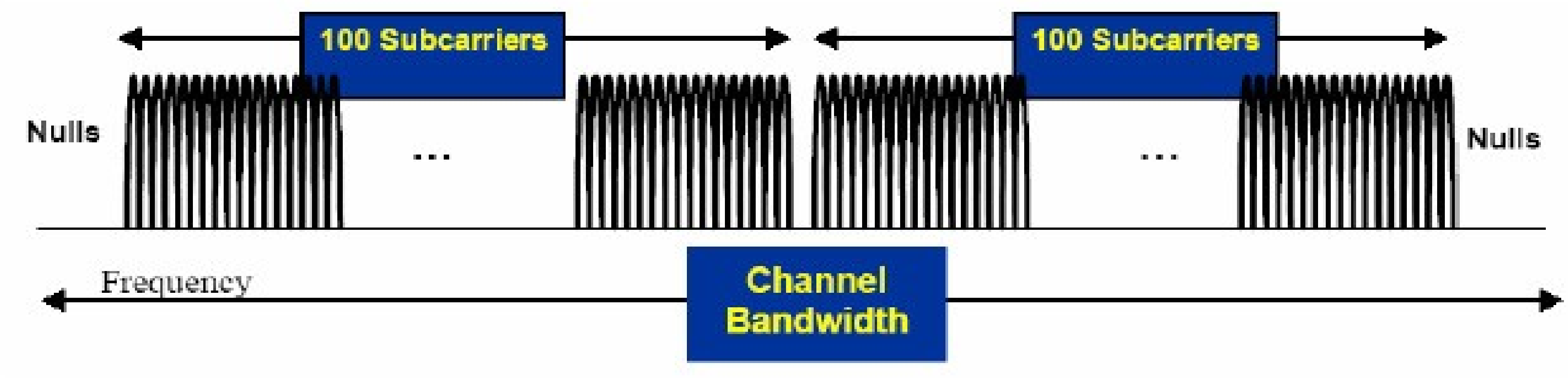
- 64 point FFT, 52 subcarriers used
- Different modes
  - signal constellation, error coding, cyclic prefix
- Two way channel
  - feedback be used to determine transmission mode

OFDM example 1: IEEE 802.11a&g (WLAN)



48 data subcarriers + 4 pilot subcarriers. There is a "null" at the center carrier. Around each data subcarrier is centered a subchannel carrying a low bitrate data signal (low bitrate => no intersymbol interference).

OFDM example 2: IEEE 802.16a (WiMAX)



Only 200 of 256 subcarriers are used: 192 data subcarriers + 8 pilot subcarriers. There are 56 "nulls" (center carrier, 28 lower frequency and 27 higher frequency guard carriers).

OFDM Systems

System	Transform Size	Number Carriers	Channel Spacing kHz	Bandwidth MHz	Sample Rate MHz	Symbol Duration µsec	Data Rate Mbits/s
HyperLAN/2	64	52 4	312.5	16.25	20	3.2 0.8	6-54
802.11a	64	52 4	312.5	16.56	20	3.2 0.8	6-54
DVB-T	2048 1024	1712 842	4.464	7.643	9.174	224	0.68- 14.92
DAB	2048 8192	1536	1.00	1.536	2.048	24/48/96 msec	3.072
ADSL	256 (down) 64 (up)	36-127 7-28	4.3125	1.104	1.104	231.9	0.64- 8.192

OFDM Data rate calculations: Example

-For HyperLAN2 which has total carriers N_t=64 out of which N_d=48 are data carriers while N_p=4 pilots. There are N_g=12 carriers for guard band to avoid adjacent channel interference.
-The channel bandwidth is W=20 MHz
Thus, channel spacing Δf would be,
$\boldsymbol{\Delta f}$**=W/**$\mathbf{N_t}$ = 20MHz/64=312.5 kHz
-Which means that the symbol duration, T_s,
$\boldsymbol{T_s = 1/\, \Delta f}$ =1/312.5kHz=3.2μsec
-If we add a guard interval of 0.8μsec, this would make total symbol duration equal to 4μse. Thus data rate R=1/4μsec=0.25Msymbols/sec.
-Each OFDM symbol has 48 data bits in BPSK mapping, 96 data bits in QPSK mapping, and so on depending upon the mapping scheme.
-This makes data rate of 12 Mbits/sec (48x0.25Msymbols/sec) and 24Mbits/s (96x0.25Msymbols/sec) for BPSK and QPSK mapping respectively.
-With half rate channel coder, the total rate would be 6Mbits/s and 12Mbits/sec for BPSK and QPSK respectively.

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

Cool and Interesting Tricks

- OFDMA
  - Different users on different subcarriers
- Adaptive Bit Loading
  - Seeking water filling capacity
  - Adaptation to Channel Fading
  - Adaptation to Interference