UESTC4004
Digital Communications

Orthogonal Frequency Division Multiplexing (OFDM)

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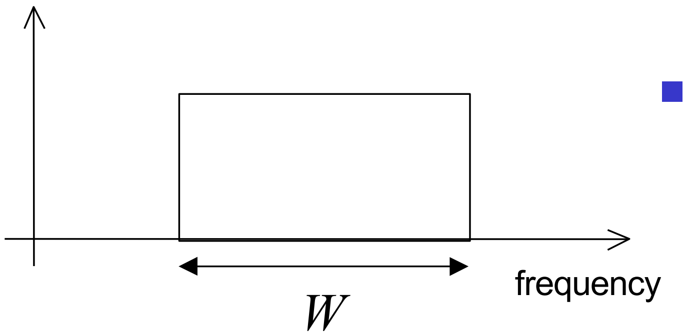
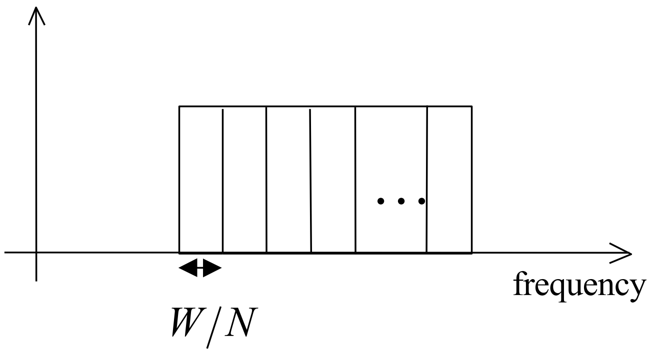
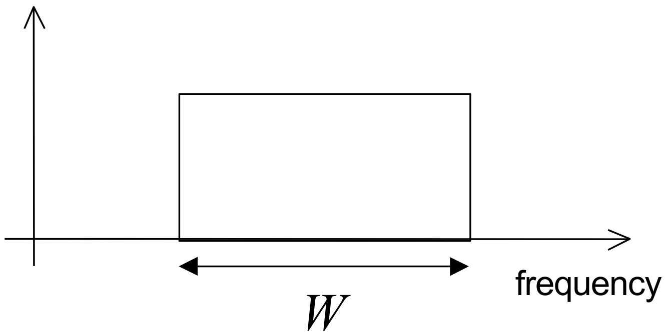
Multicarrier systems

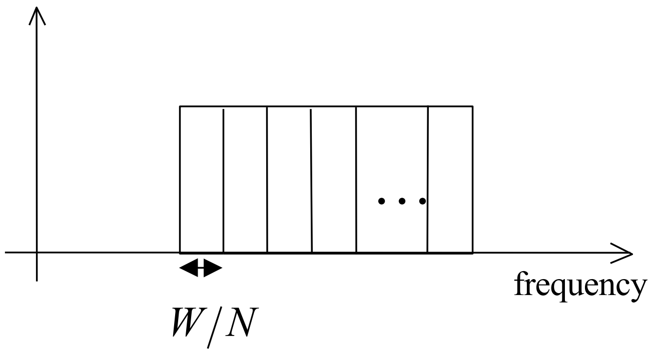




- Single carrier system
  - signal carrier is used to transmit all the bits or symbols
- Multicarrier system
  - available spectrum divided into many narrow bands
  - data is divided into N parallel data streams each transmitted on a separate band

Why Multicarrier systems?

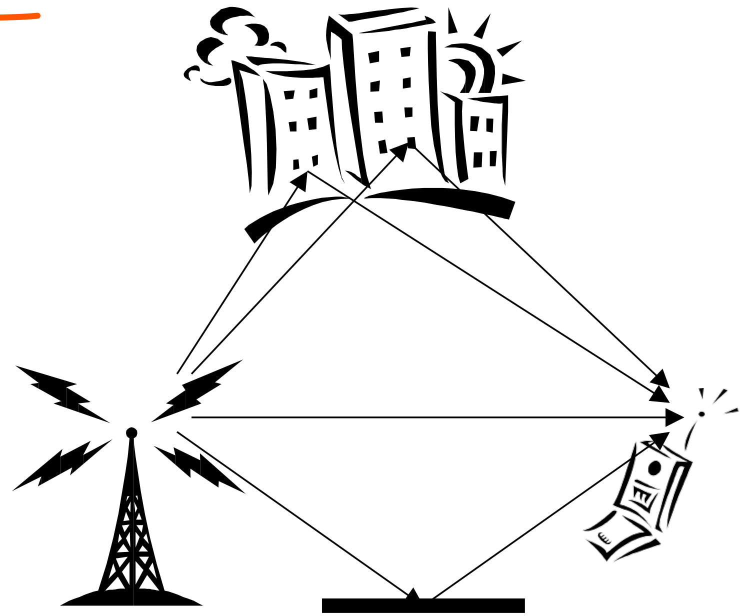




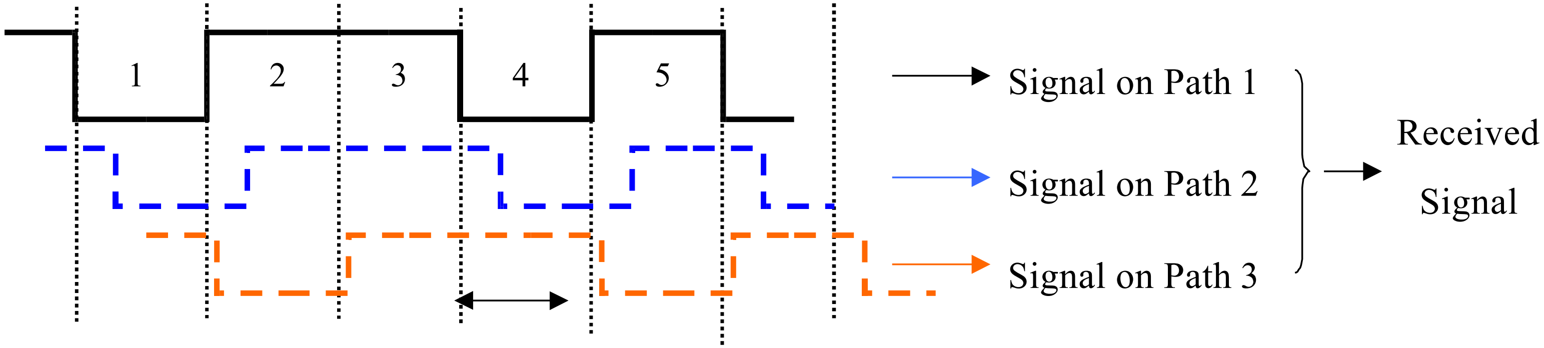
- Difference in data rate?
- Difference in Bandwidth?
- Why multicarrier system then?
  - Reduced multipath effect
    - Less inter symbol interference
    - Less multipath fading

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



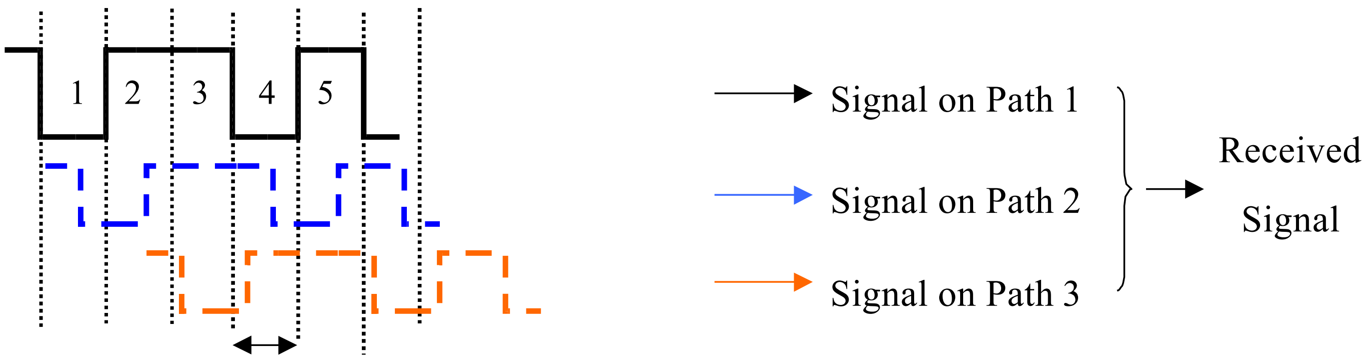
Effect of Multipath on Received Baseband Signal



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

Conclusion

- Change depends on bit or symbol duration – longer bit/symbol duration means less multipath effect and vice versa
- Multicarrier systems use narrow bands → longer bit/symbol durations → less ISI

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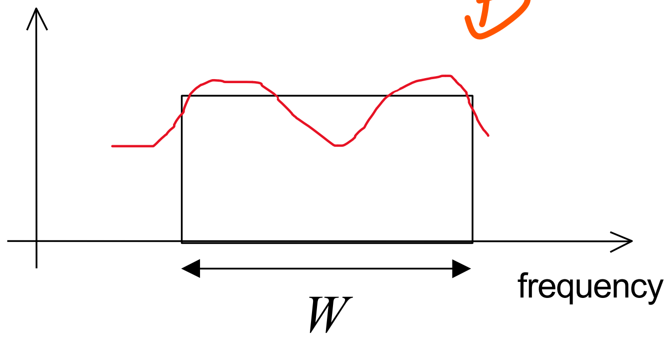
Reduced multipath fading for multicarrier signals

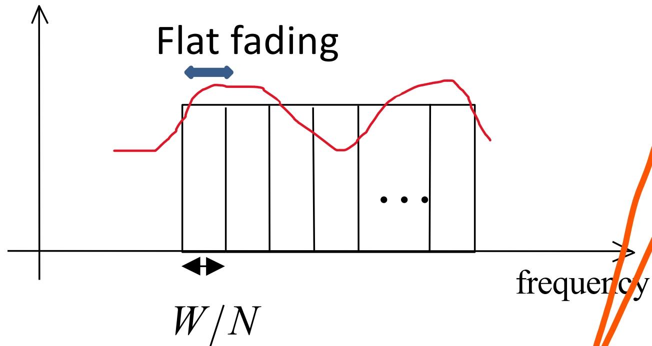
信号带宽 < 相关带宽

B Bc

- Due to multipath, some frequencies are attenuated differently than the others
- Wideband signal experiences multipath fading or frequency selective fading i.e., different frequencies undergo different attenuation
- Narrowband signals experience less multipath fading or almost flat fading i.e., the frequency response is almost constant on a subcarrier band
- Flat fading can be easily recovered at the receiver as opposed to frequency selective fading



Frequency selective fading



时延

Symbol Duration

$T > T_D$

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时延扩展 信号经过不同路径到达所用时间的差值

- **Delay spread D:**

The delay spread D informs us about the multipath richness of a communication channel.

Generally, it is interpreted as the difference between the time of arrival of the earliest significant multipath component and the time of arrival of the last multipath component. The value of D should be considerably smaller (around 10 times) than the symbol duration to have ISI-free channel.

- **Coherence bandwidth B_c:** 相干带宽

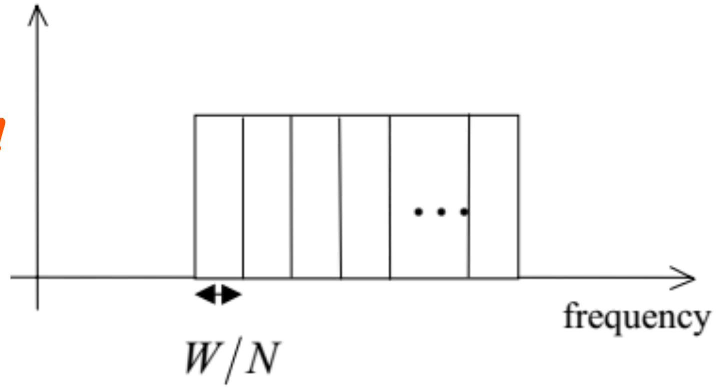
The bandwidth over which the channel can be assumed flat i.e., all the spectral components undergo approximately equal gain and liner phase.

Coherence bandwidth is the inverse of delay spread. The shorter the delays spread, the larger the coherence bandwidth and vice versa.

$$\boxed{B_c \approx \frac{1}{D}}$$

Multicarrier systems – bandwidth inefficient?

问题:频道利用率低



- Practically not possible as there should be some spectral gap between neighbouring carriers to avoid neighbouring channel interference

- But spectral gaps result in spectral inefficiency

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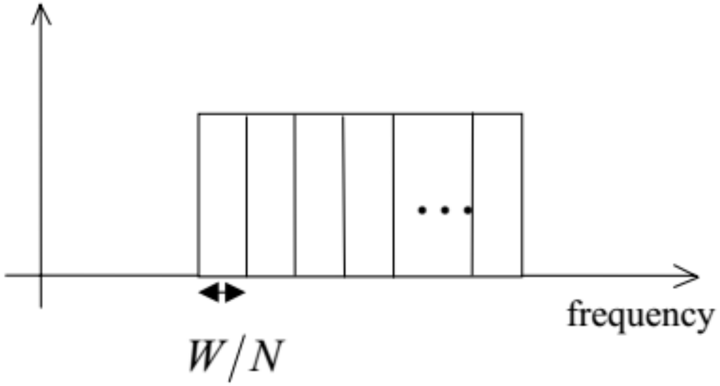
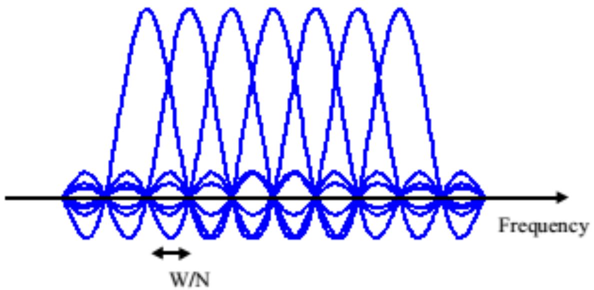
What is OFDM?



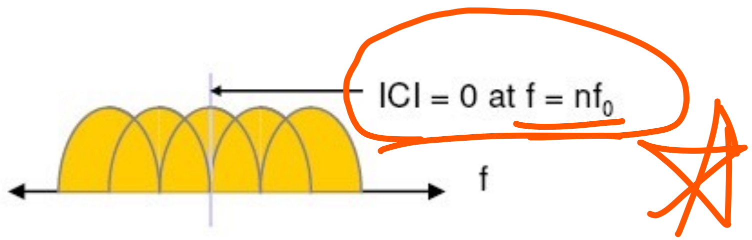


- OFDM is a multicarrier system
  - uses discrete Fourier Transform/Fast Fourier Transform (DFT/FFT)
  - sin(x)/x spectra for subcarriers
- Available bandwidth is divided into very many narrow bands
  - ~2000-8000 for digital TV
  - ~48 for Hiperlan 2
- Data is transmitted in parallel on these bands

以前信道：一次性一个载波 ⇒ 串行 in series

OFDM Spectrum

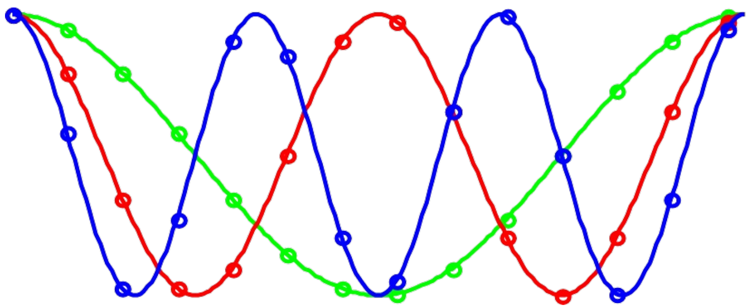
Some FDM systems achieve orthogonality through zero spectral overlap
⇒ BW inefficient!



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

How are signals transmitted in parallel without interference?

First three subcarriers



Symbol period

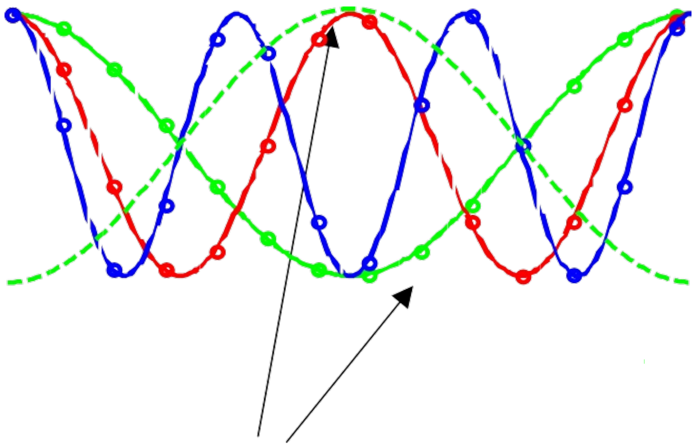
$$\int_0^T \sin\frac{2\pi kt}{T}\sin\frac{-2\pi lt}{T}\,dt = 0, \quad k \neq l$$

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

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

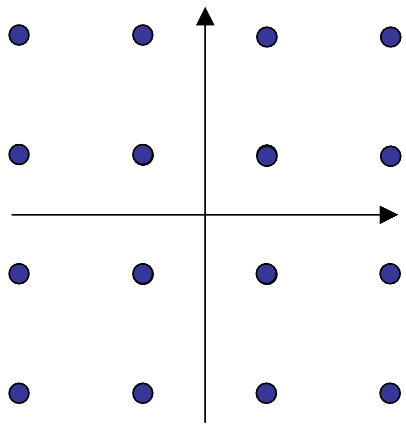
f_i f_j 正交

How is data carried on the subcarriers?

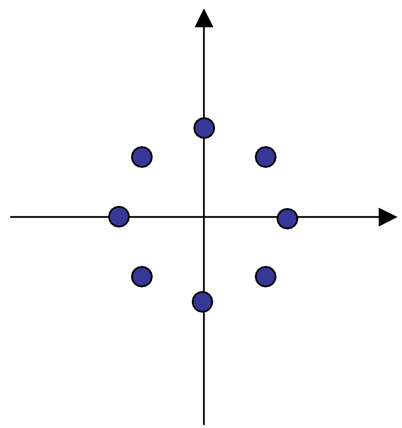


Two possible subcarrier values

- Each subcarrier carries the information bits which are mapped using modulation schemes such as QPSK, 4-QAM, 16-QAM, 64-QAM



16-QAM



8-PSK

Subcarrier modulation (IEEE 802.11a&g)

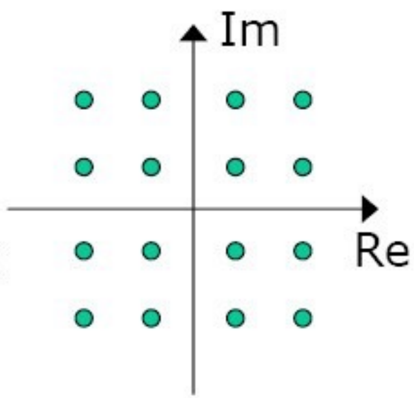
Modulation	Bit rate
BPSK	6 Mbit/s
BPSK	9 Mbit/s
QPSK	12 Mbit/s
QPSK	18 Mbit/s
16-QAM	24 Mbit/s
16-QAM	36 Mbit/s
64-QAM	48 Mbit/s
64-QAM	54 Mbit/s

BPSK = Binary Phase Shift Keying (PSK)

QPSK = Quaternary PSK

QAM = Quadrature Amplitude Modulation

16-QAM signal constellation in the complex plane



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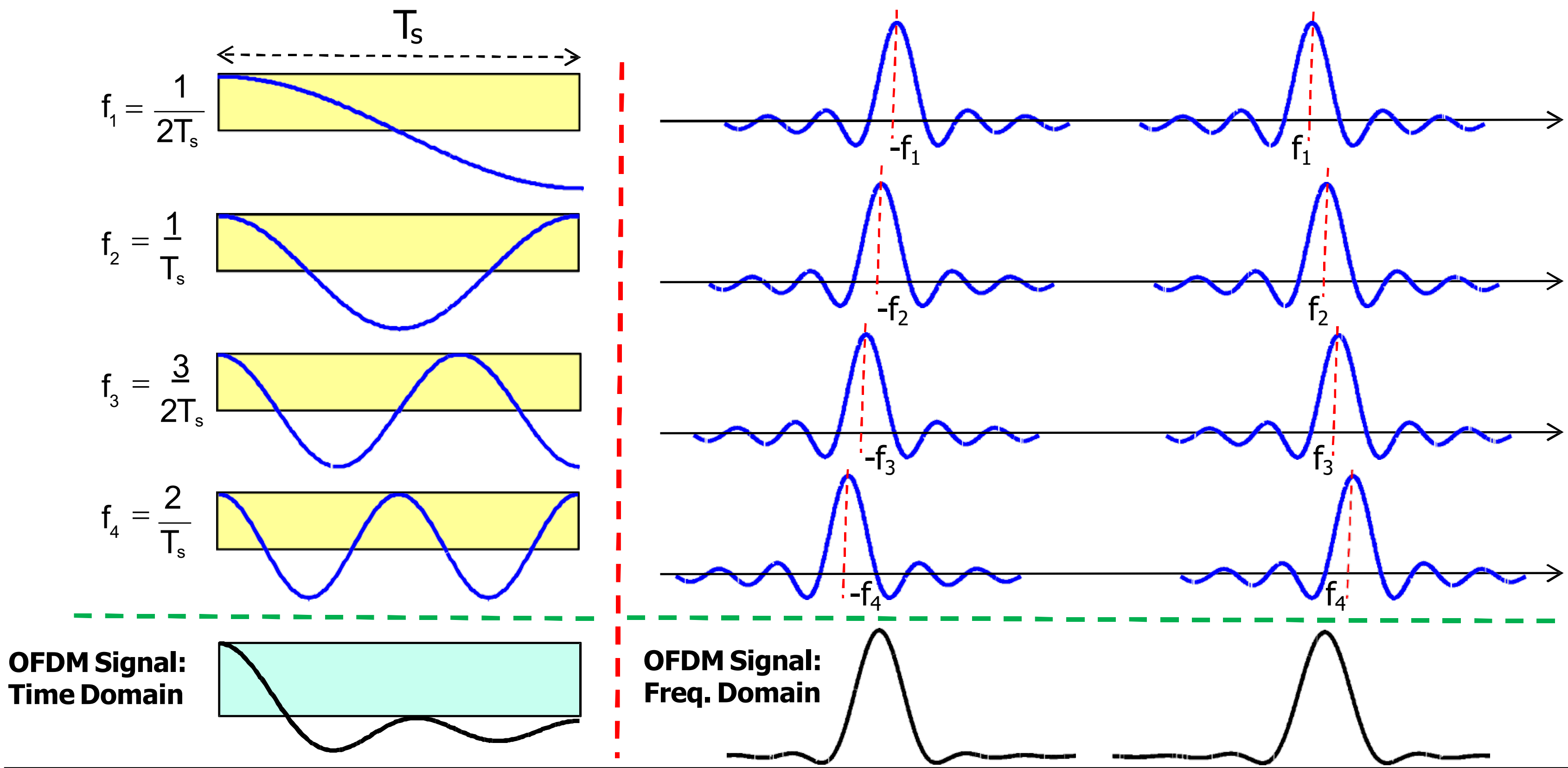
OFDM & DFT (Discrete Fourier Transform)

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



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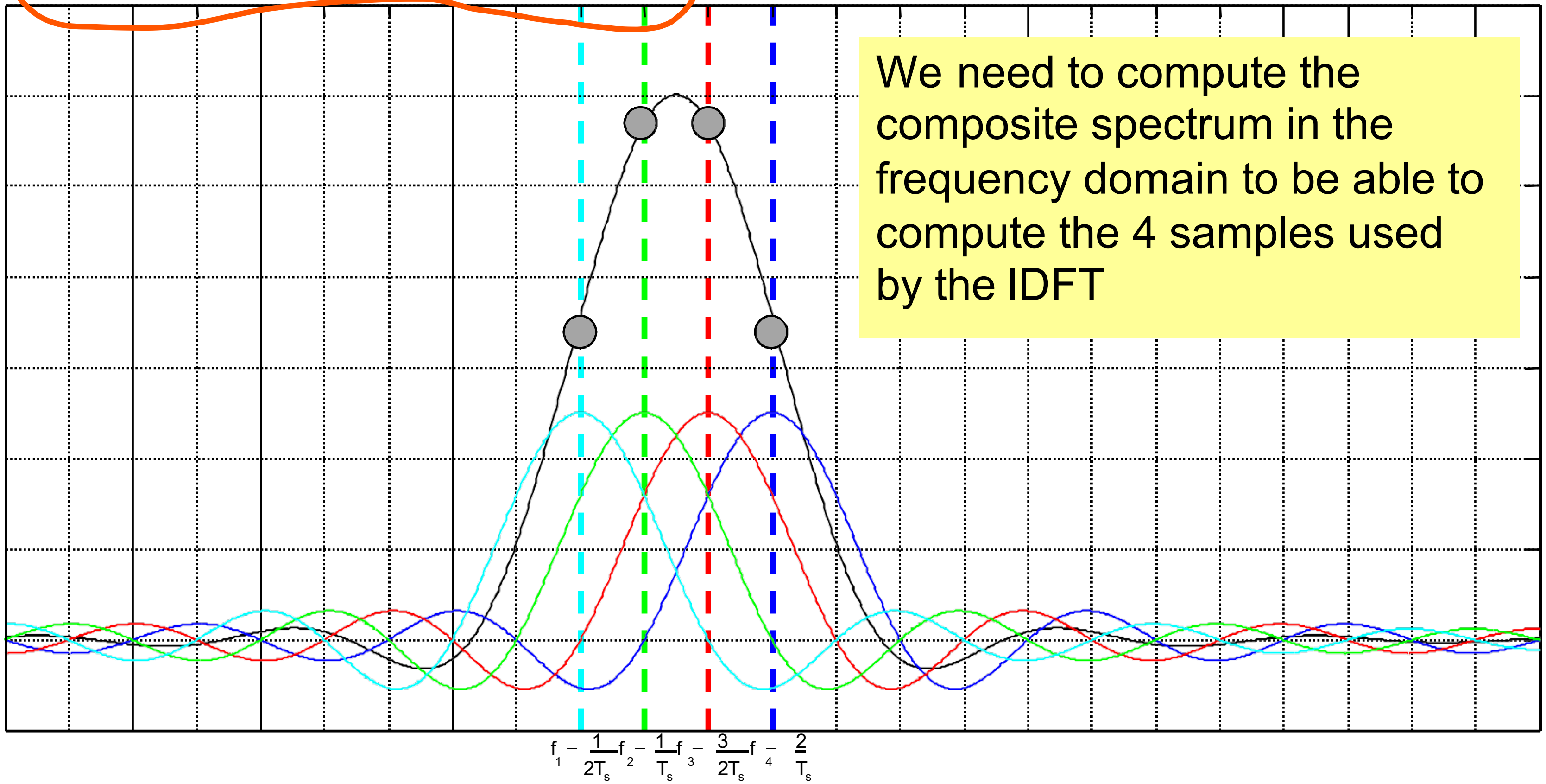
OFDM & DFT (Discrete Fourier Transform)

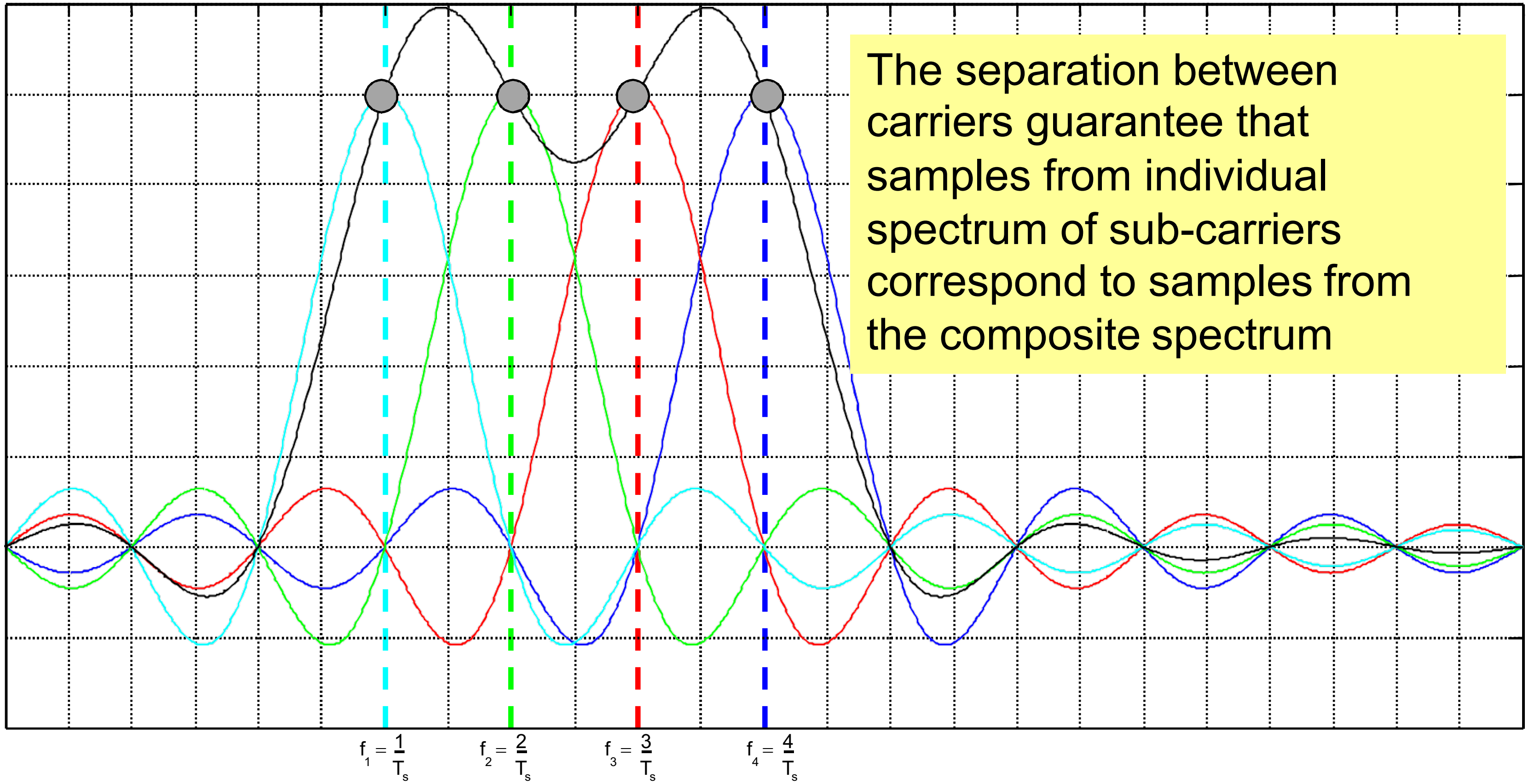
OFDM Signal over 4 Sub-carriers $f_1 = \cos(\pi t/T_s)$ $f_2 = \cos(2\pi t/T_s)$
$f_3 = \cos(3\pi t/T_s)$ $f_4 = \cos(4\pi t/T_s)$ (Separated by $1/2T_s$)



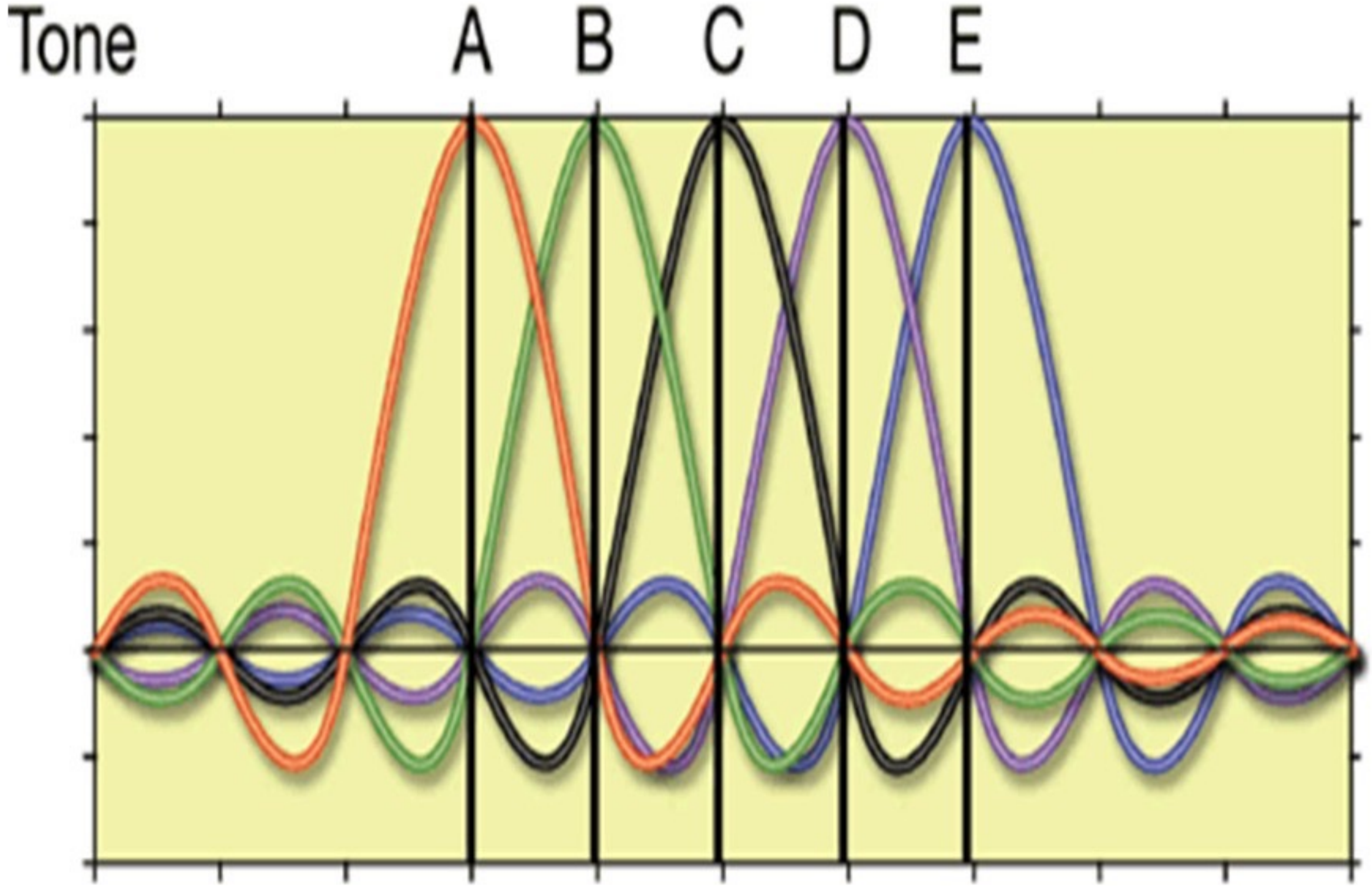
We need to compute the composite spectrum in the frequency domain to be able to compute the 4 samples used by the IDFT

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 Spectrum

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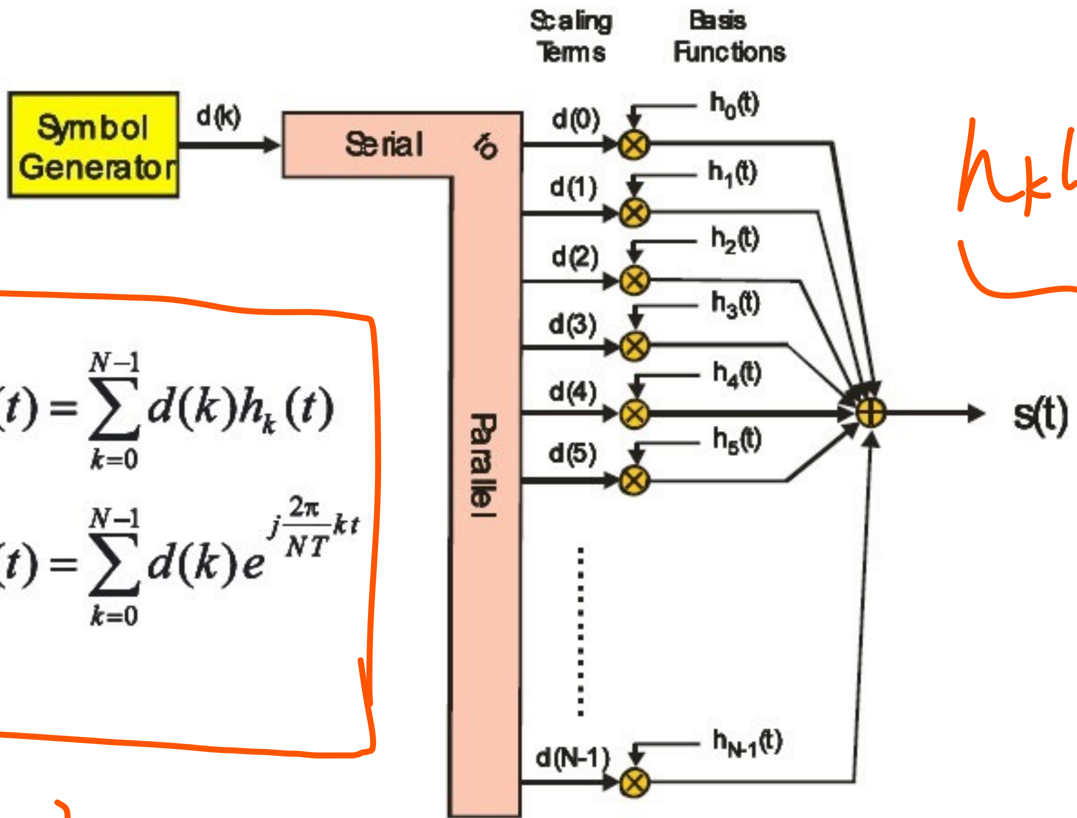
OFDM Modulator



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

$$h_k(t) = e^{j\frac{2\pi}{NT}kt}$$

$$Re\left[e^{j\frac{2\pi}{NT}kt}\right] = \cos\frac{2\pi k}{NT}t \Rightarrow f = \frac{2\pi}{NT}k$$

N#

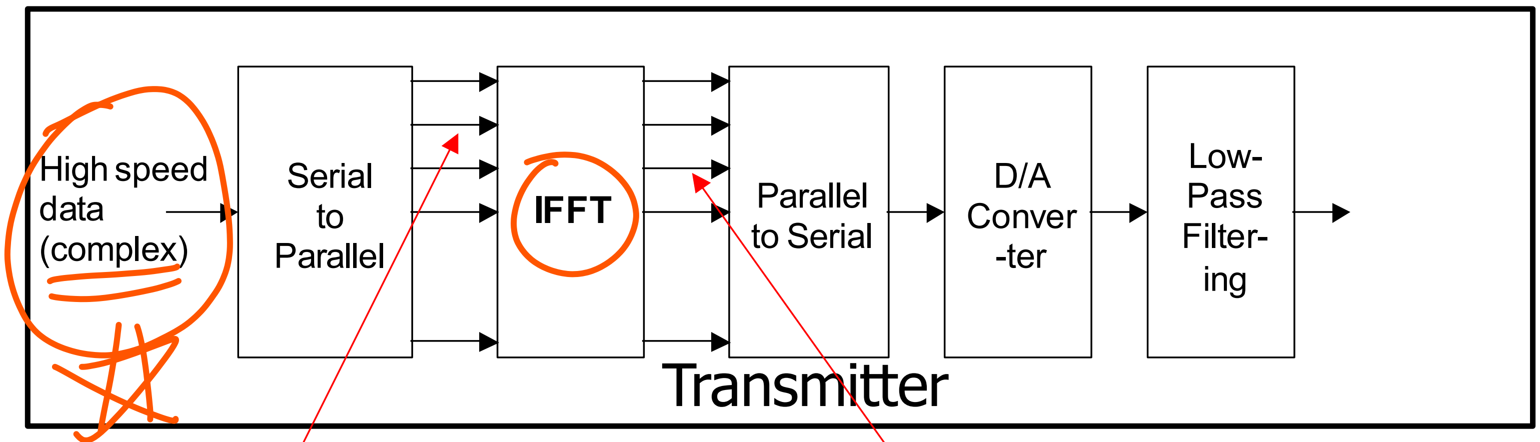
How are OFDM signals generated?

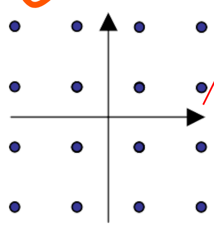
Typical IFFT Output Samples

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

Signals at Input and Output of Transmitter IFFT





Complex value representing data is input to IFFT

IFFT output gives samples of modulated multiplexed signal

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Baseband OFDM system

Discrete frequency domain
Each input controls
signal at one frequency

Discrete Time Domain
Samples of modulated
and multiplexed signals