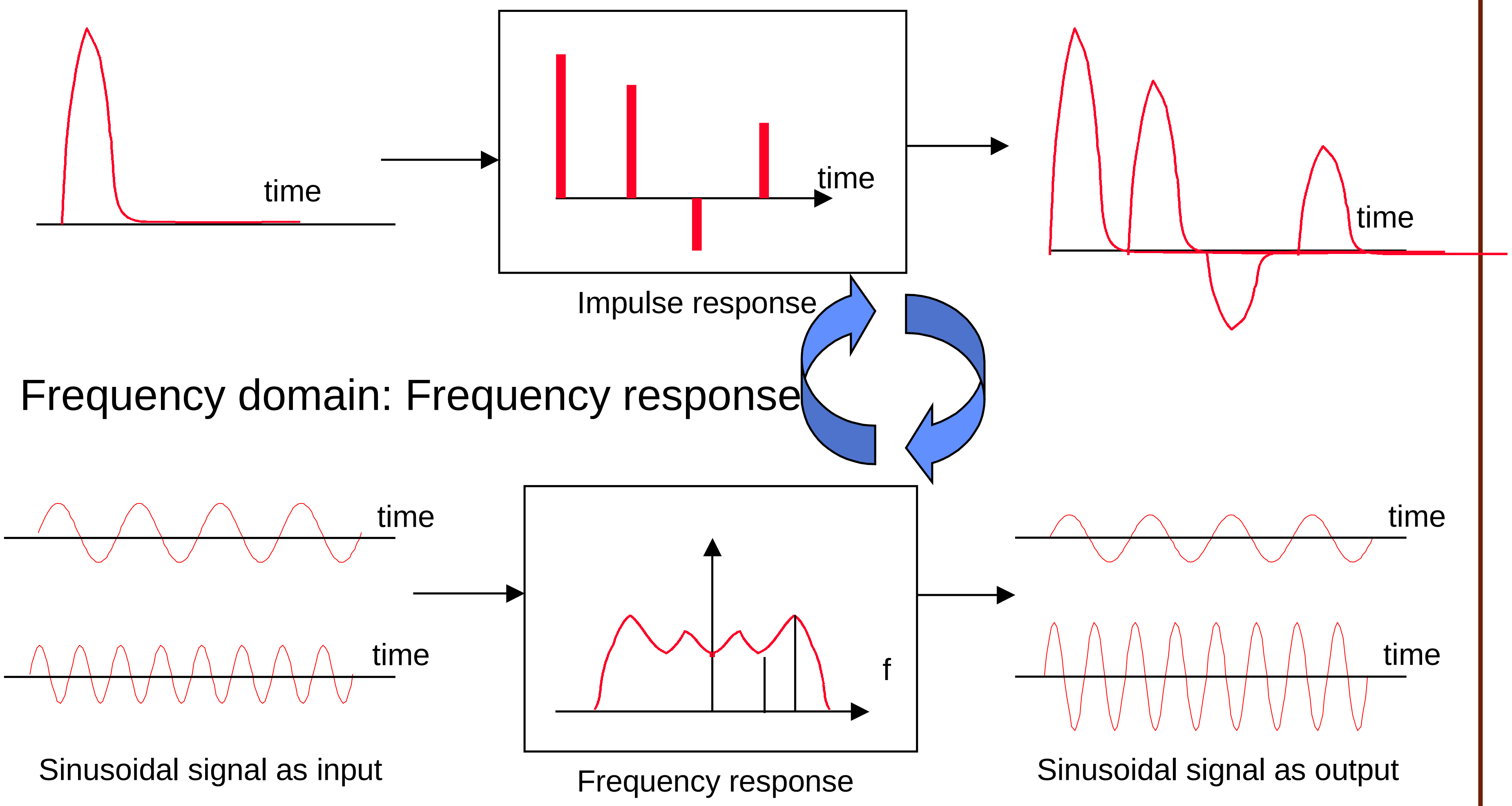
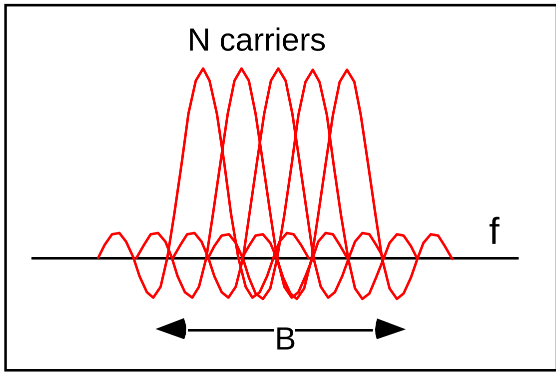
Multipath can be described in two domains: time and frequency

Time domain: Impulse response

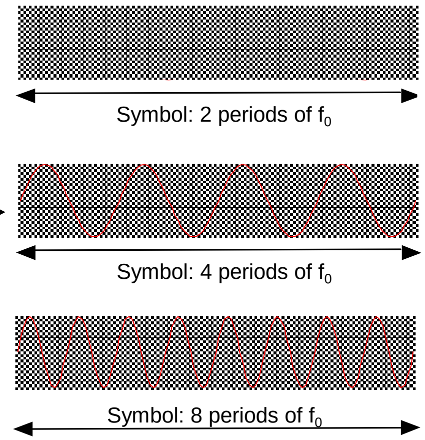
Frequency domain: Frequency response



Introduction to OFDM modulation

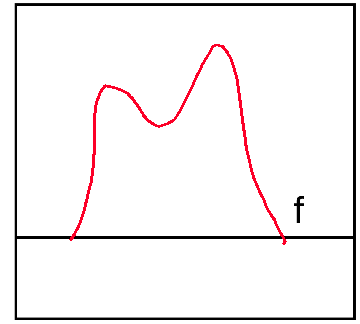


Data coded in frequency domain



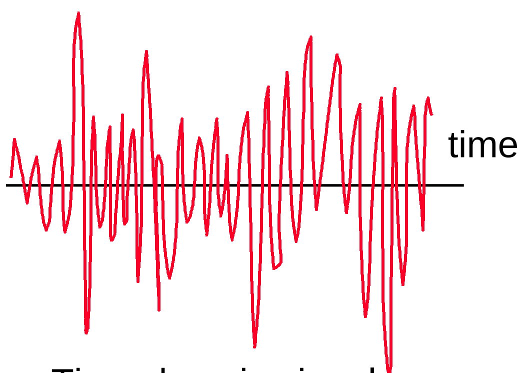
Transformation to time domain: each frequency is a sine wave in time, all added up.

+ Transmit

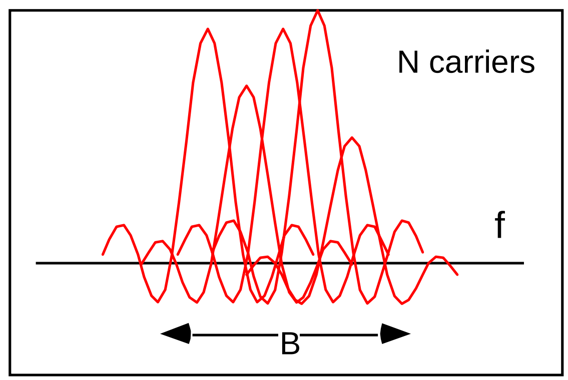


Channel frequency response

Receive



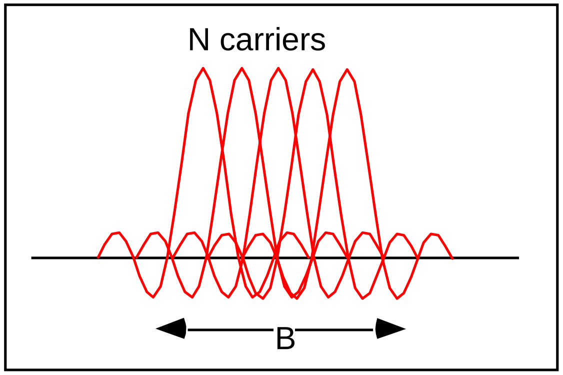
Time-domain signal

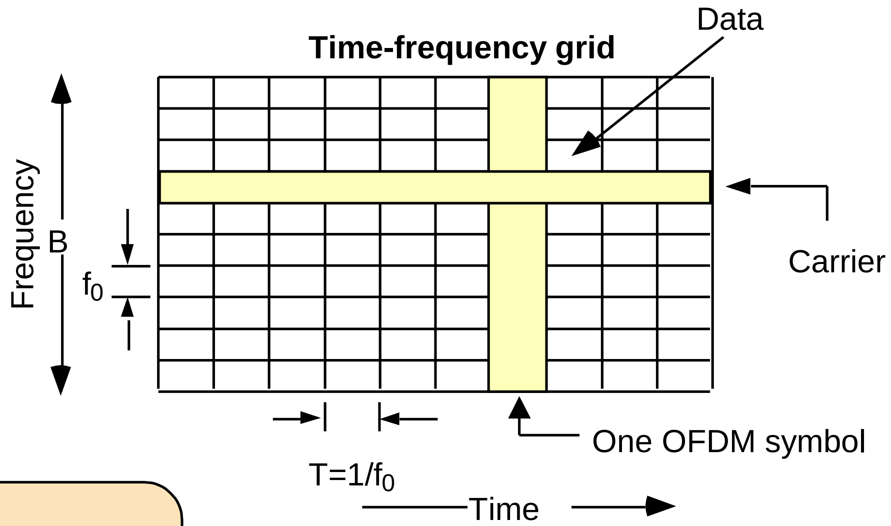


Frequency-domain signal

Decode each frequency bin separately

Introduction to OFDM (Orthogonal frequency division multiplex)





Features

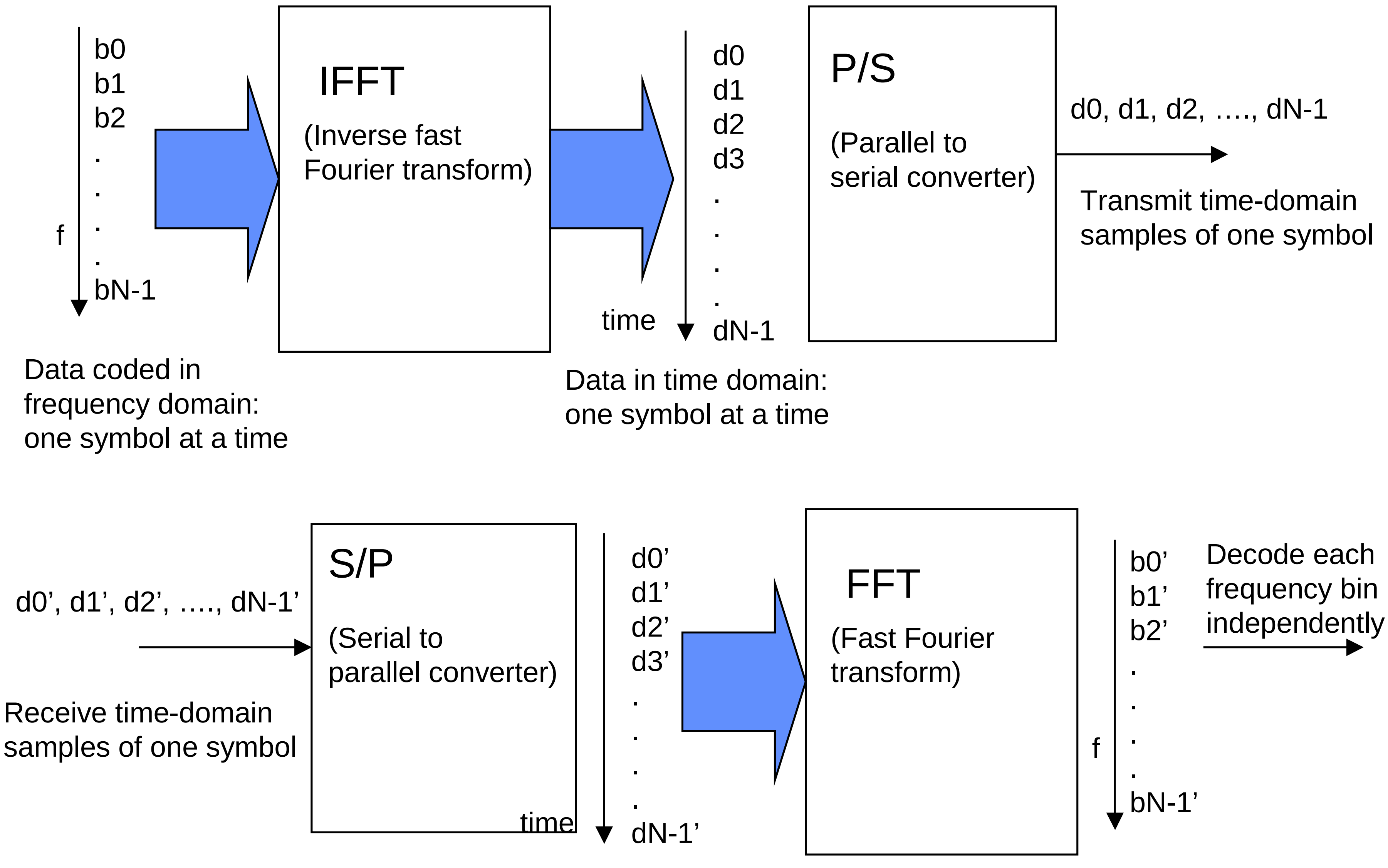
- **No intercarrier guard bands**
- **Controlled overlapping of bands**
- **Maximum spectral efficiency (Nyquist rate)**
- **Easy implementation using IFFTs**
- **Very sensitive to time-freq. synchronization**

Intercarrier Separation =
Any integer Multiple of 1/(symbol duration)

Modulation technique

A user utilizes all carriers simultaneously 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 $\psi_k(t) = \exp(jk2\pi t/T)$ y $\psi_{k+m}(t) = \exp\left(j2\pi(k+m)t/T\right)$

Reception pulse with offset δ $\psi^{\delta}_{k+m}(t) = \exp\left(j2\pi(k+m+\delta)/T\right)$ *con* $|\delta| \le 1/2$

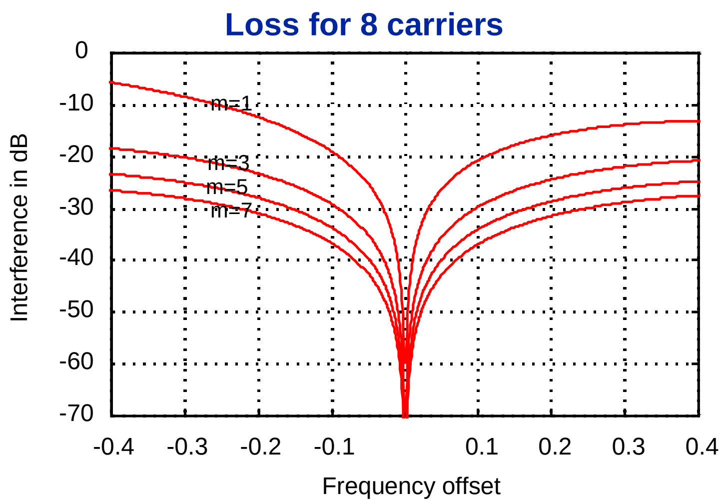
Interference between channels k and k+m

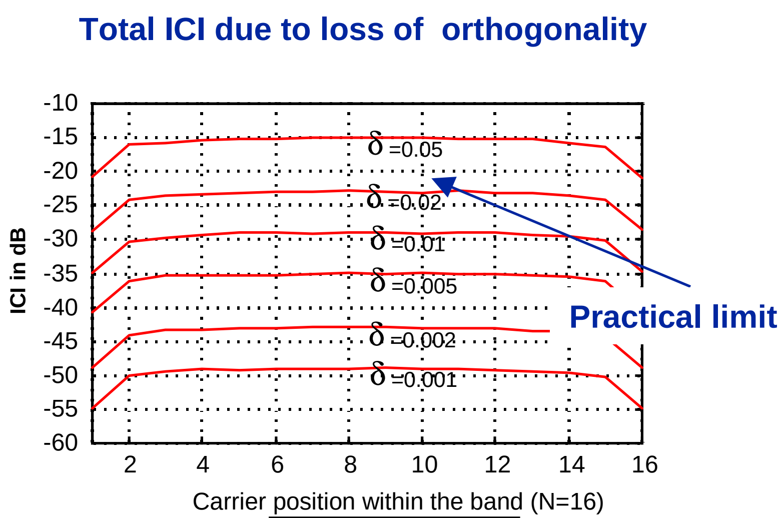
$$I_m(\delta) = \int_0^T \exp\left(jk2\pi t/T\right)\exp\left(-j(k+m+\delta)2\pi t/T\right)dt = \frac{T(1-\exp(-j2\pi\delta))}{j2\pi(m+\delta)}$$

$$|I_m(\delta)| = \frac{T|\sin \pi\delta|}{\pi|m+\delta|}$$

Summing up ∀ m

$$\sum_m I_m^2(\delta) \approx (T\delta)^2 \sum_{m=1}^{N-1} \frac{1}{m^2} \approx (T\delta)^2 \frac{23}{14} \quad \textit{for} \quad N >> 1 \ (N > 5 \textit{ Is enough})$$





δ assumed r.v.
Gaussian σ=δ

Loss of orthogonality (time)

Let us assume a misadjustment τ

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

2 consecutive symbols

Then

if m=k-l

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

Or approximately, when τ<<T

$$\frac{|X_i|}{T} \approx \frac{2m\pi \frac{\tau}{T}}{m\pi} = 2\frac{\tau}{T}$$

independent on m

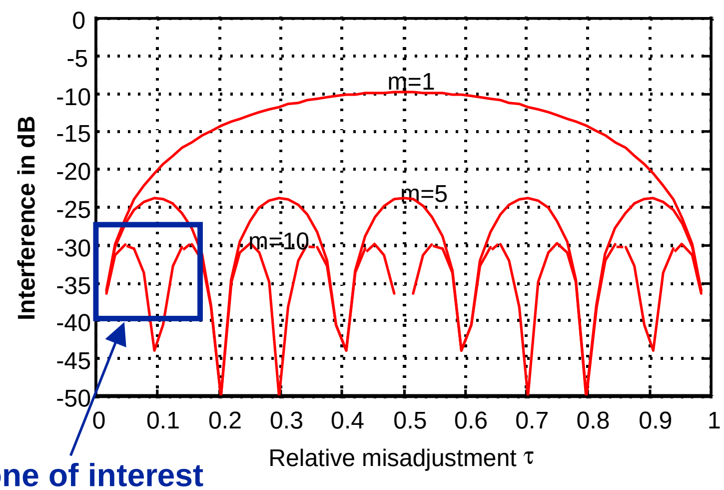
In average, the interfering power in any carrier is

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

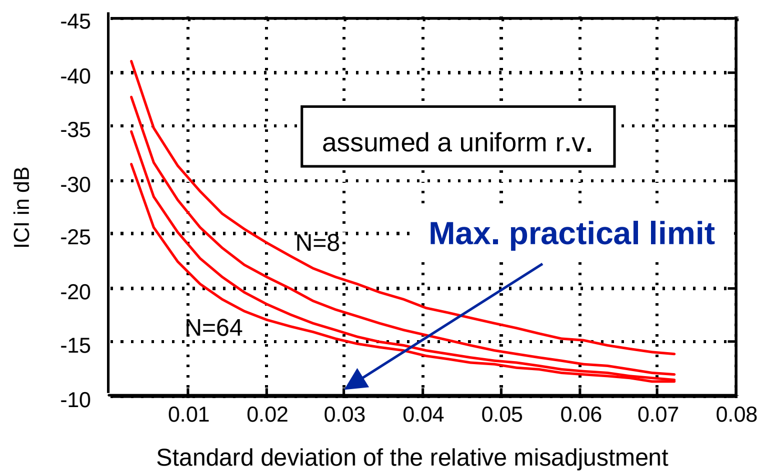
$$ICI \approx 20\log\left(\sqrt{2}\,\frac{\tau}{T}\right), \quad \tau << T$$

Per carrier

Loss for 16 carriers

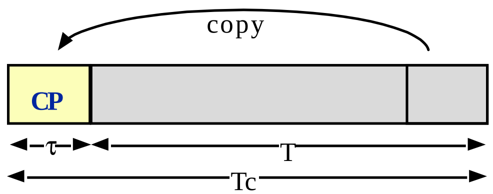


ICI due to loss of orthogonaliy

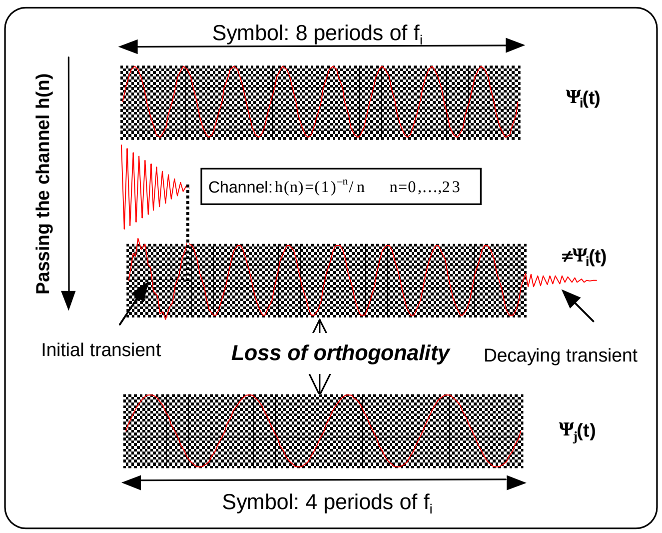


Including a cyclic prefix to each OFDM symbol

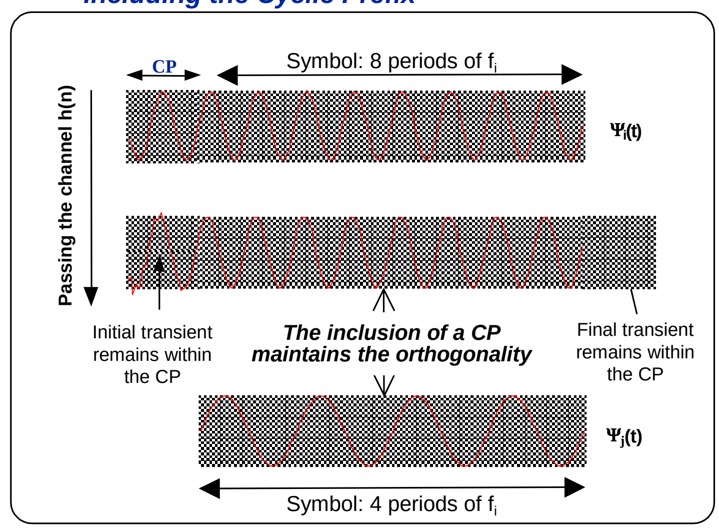
To combat the multipath: including time guards between the symbols



Without the Cyclic Prefix

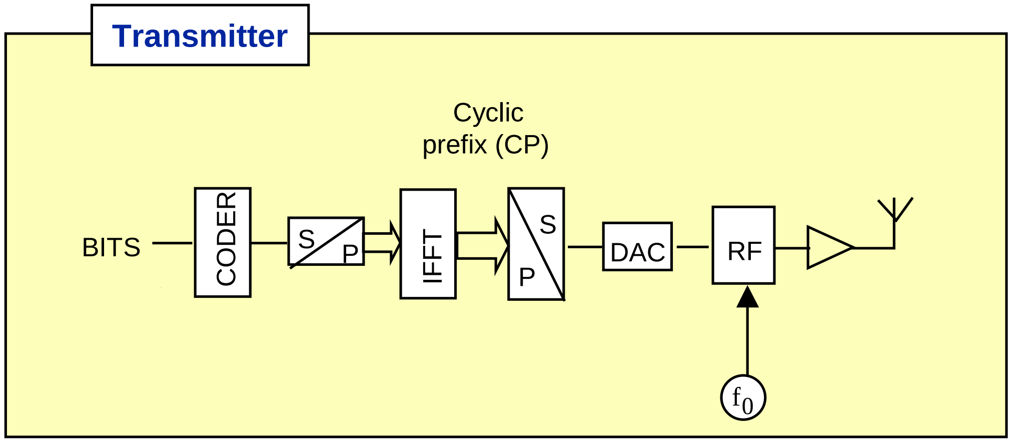


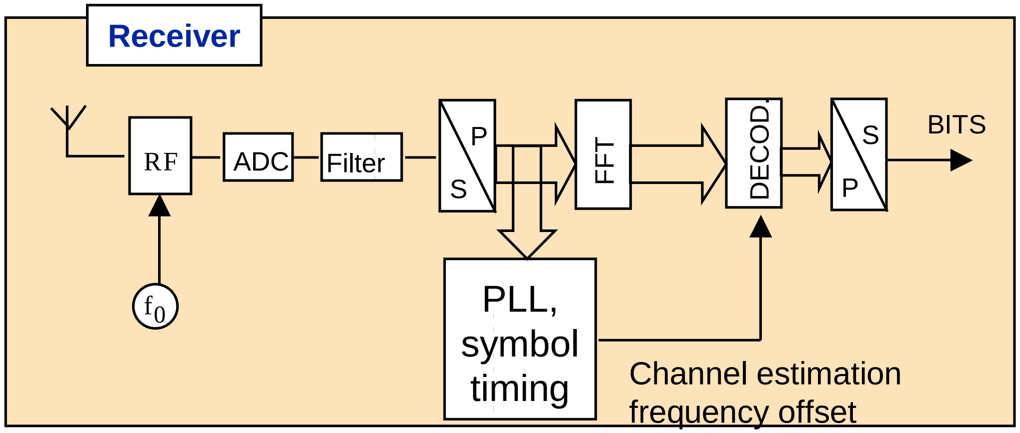
Including the Cyclic Prefix



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

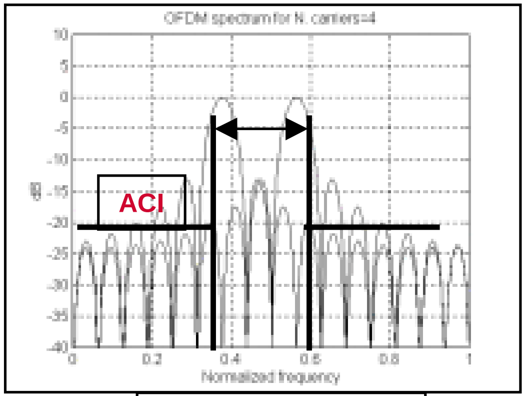
Symplified scheme of an OFDM transceiver



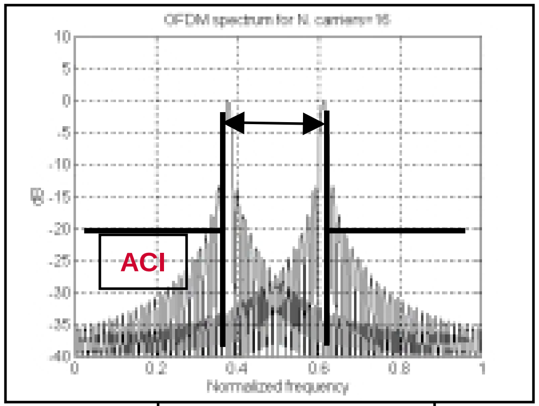


Windowing of the OFDM symbol

Total band used by OFDM: it depends on the number or carriers



Wide separation



Narrow separation

Maintainig a fix bandwidth, if **N increases** → **Adjacent channel interference decreases**

BUT

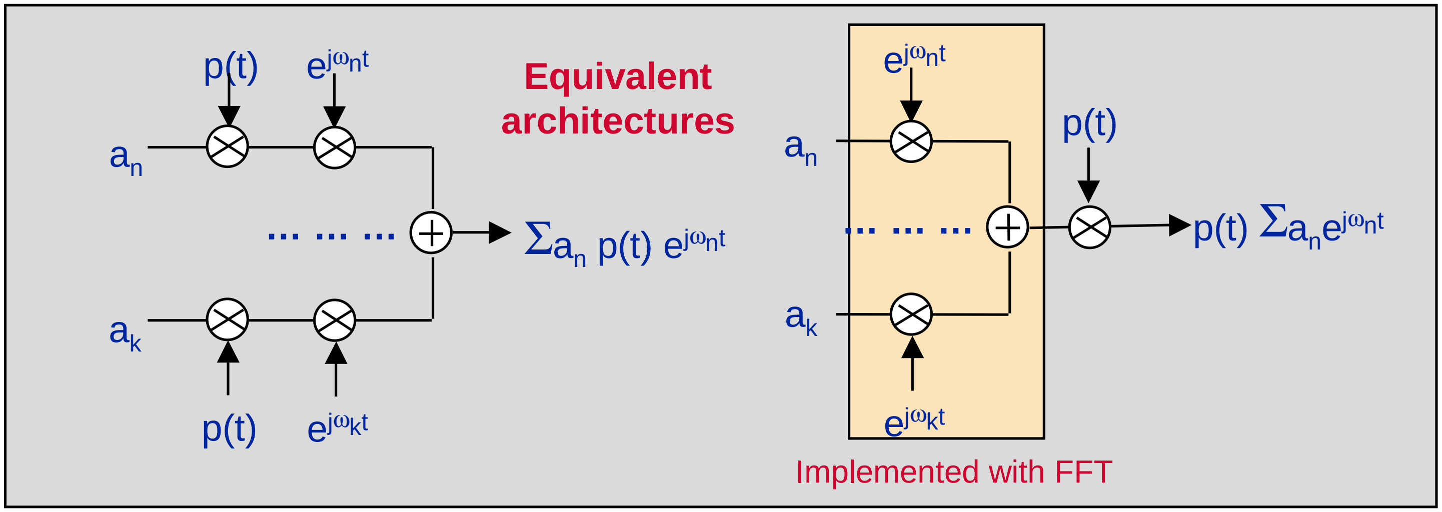
It is interesting to have few carriers as well:

- **To introduce short delay in data gathering and signal processing (FFTs)**
- **To have a bigger intercarrier separation --> It reduces the relative frequency offset**

Compromise

Need to shape the OFDM symbols

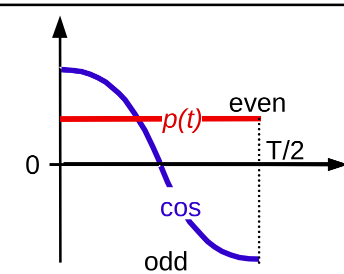
OFDM modulators with symbol shaping



After the synchronous reception

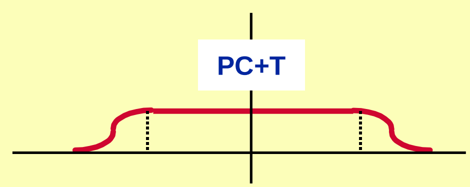
p(t) even

$$I = \int_{-T/2}^{T/2} p(t) e^{j2\pi(k-n)t/T} dt = 2\int_{0}^{T/2} p(t)\cos[2\pi(n-k)t/T]dt = \begin{cases} 0\ , & k \neq n \\ 1\ , & k = n \end{cases}$$

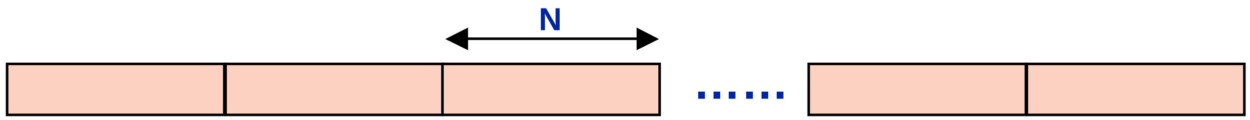


The simplest way to maintain symmetry within -T/2<t<T/2 is p(t)=k

- **Symbol shaping has to be carried out as part of the symbol duration + CP**
- **The total ACI can be condiderably reduced**

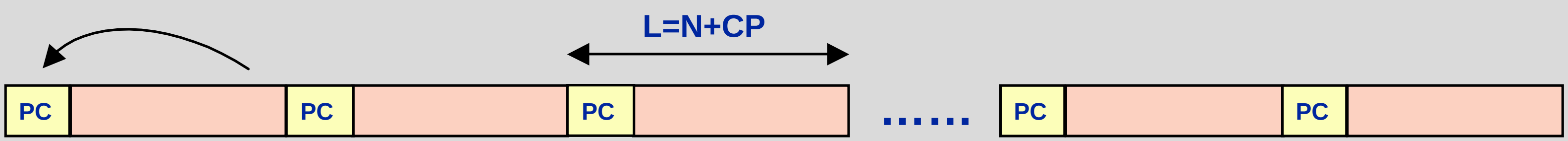


Robustness against the channel and ACI improvement



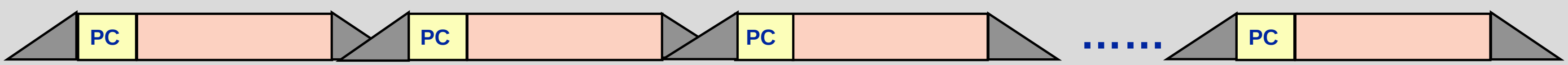
Virtual OFDM symbols within the slot

- With guards (Cyclic prefixes), the channel's time dispersion is avoided



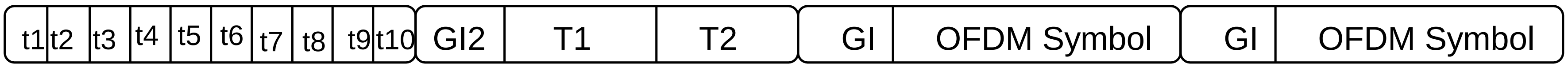
OFDM symbols with time guards (CPs)

- With smooth transitions between symbols, the adjacent channel interference is minimized



OFDM symbols with time guards and symbol shaping

802.11a Physical Layer Data Symbol Format



Short training sequence:
AGC and frequency offset

Long training sequence:
Channel estimation

Training symbols: 4 us each
t: 0.8 us, 16 samples
GI2: 1.6 us, 32 samples
T: 3.2 us, 64 samples

Data Symbols: 4 us each
GI: 0.8 us, 16 samples
OFDM Symbol: 3.2 us, 64 samples

* Only 52 of the 64 carriers are used.
* 4 of the 52 carriers are used for pilot carriers (no data).

Data rate for each 20 Mhz channel:
20 Msamples per second.
250 Ksymbols per second.
48 data carriers per symbol.
1/2 or 3/4 convolutional code.
1 bit/carrier (BPSK) to 6 bits/carrier (64 QAM).

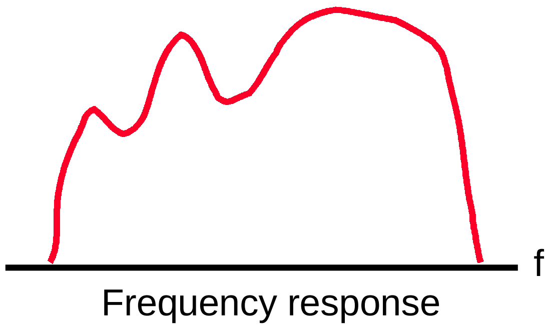
Overall:
Lowest: 48 * 1 * 1/2 * 250K = 6 Mbps.
Highest: 48 * 6 * 3/4 * 250K = 54 Mbps.

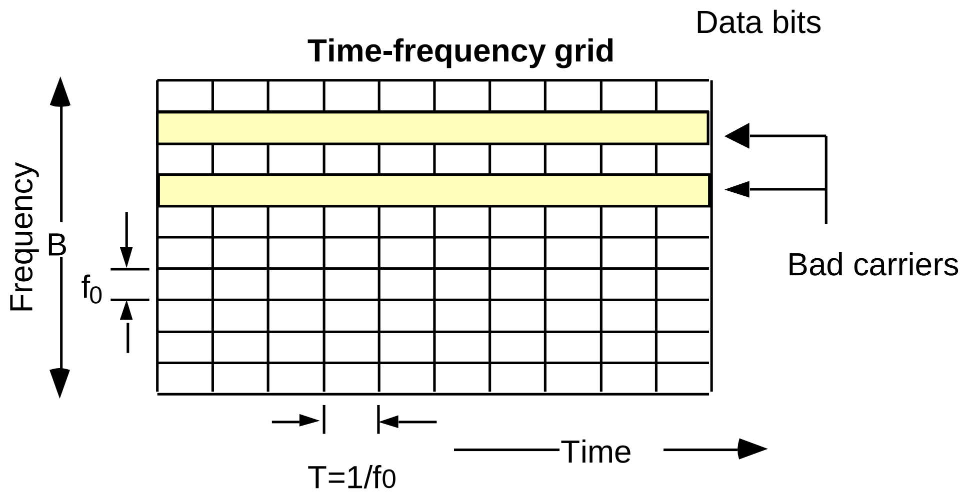
Turbo mode supports 108 Mbps using 40 Mhz channel.

Robustness against errors: random noise and channel-selected errors

Random noise: primarily introduced by thermal and circuit noise.

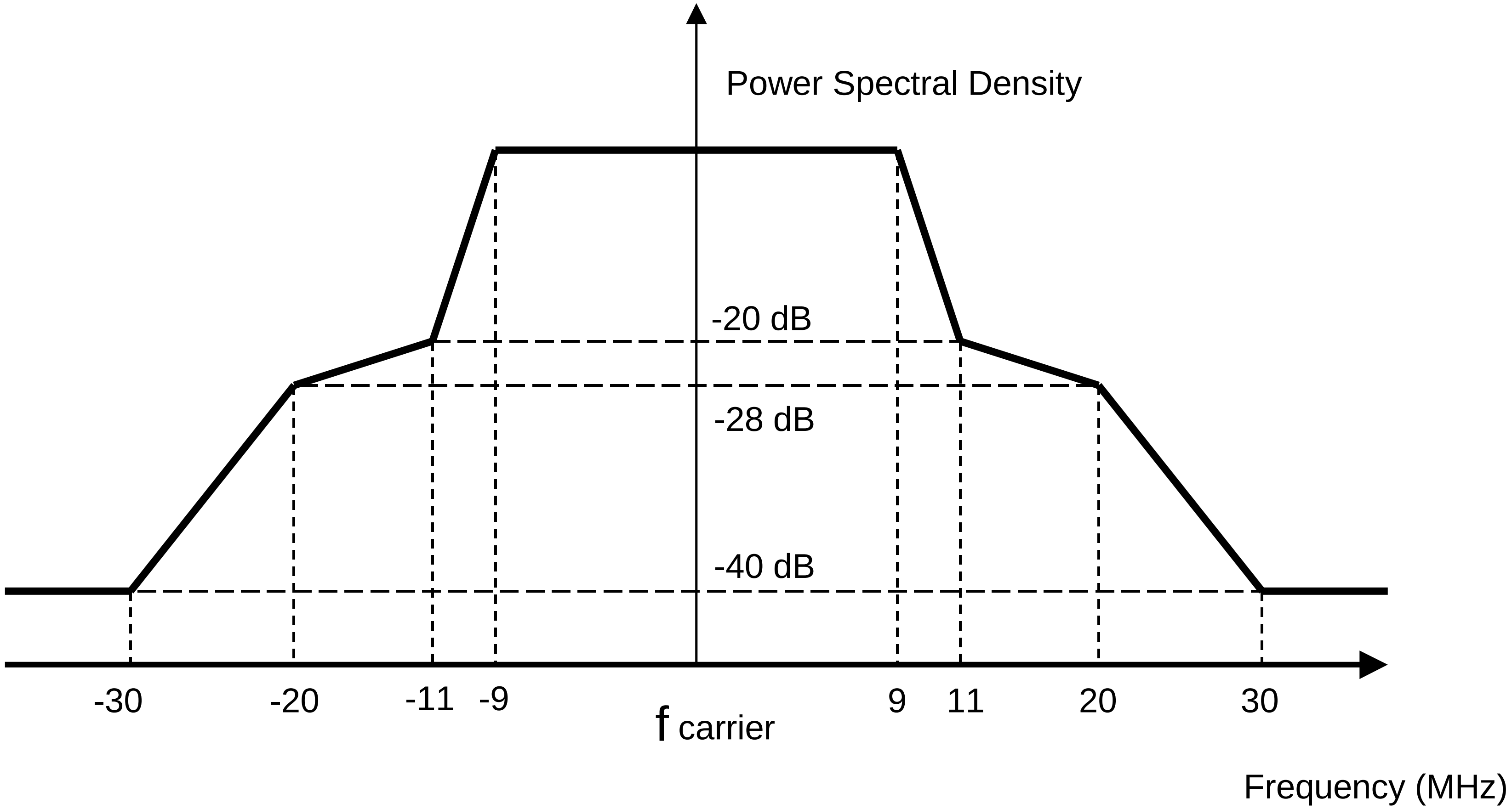
Channel-selected errors: introduced by magnitude distortion in channel frequency response.





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

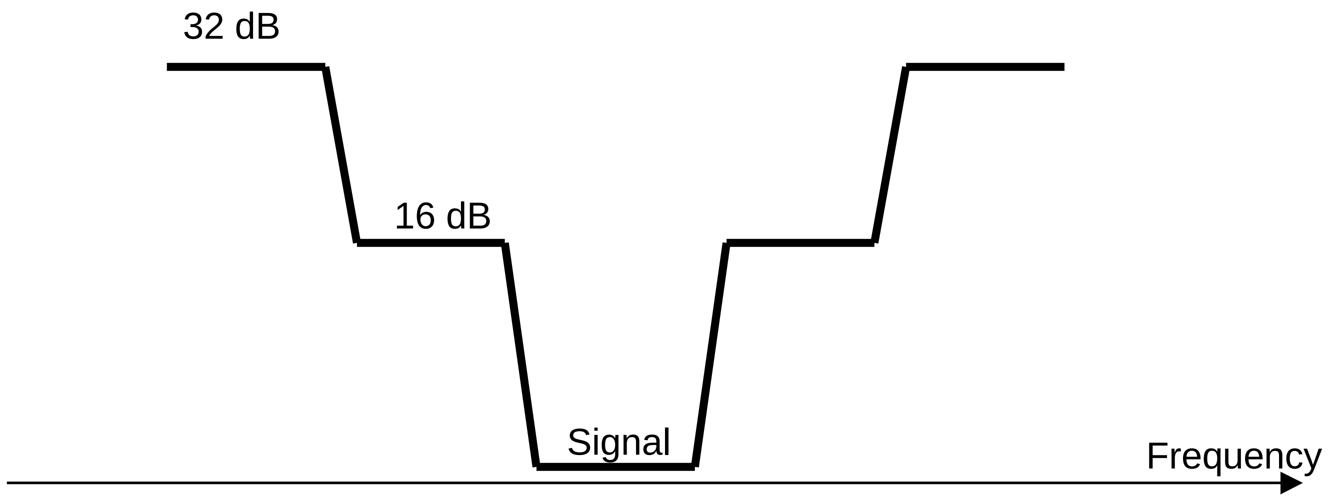
Spectrum Mask



• Requires extremely linear power amplifier design.

Adjacent Channel and Alternate Adjacent 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.