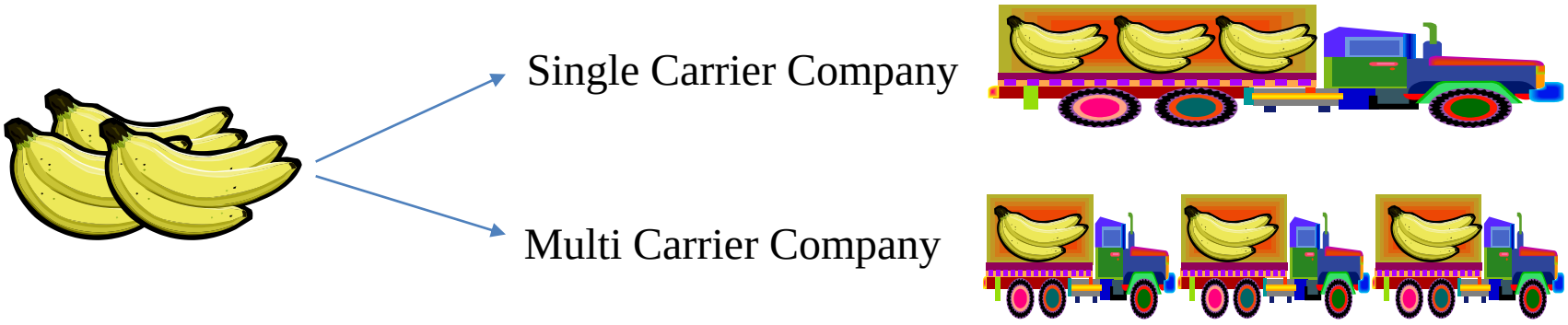
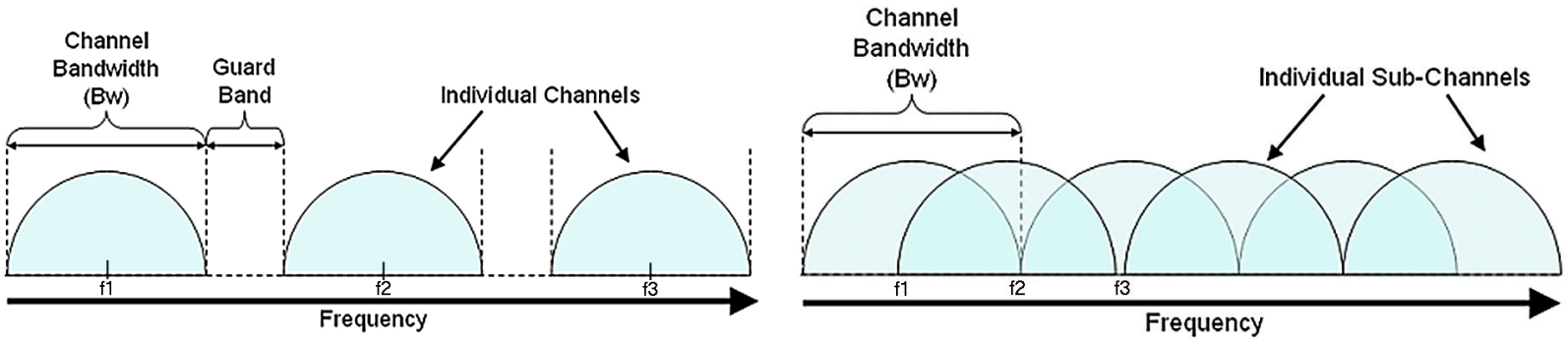
OFDM Basic Concept

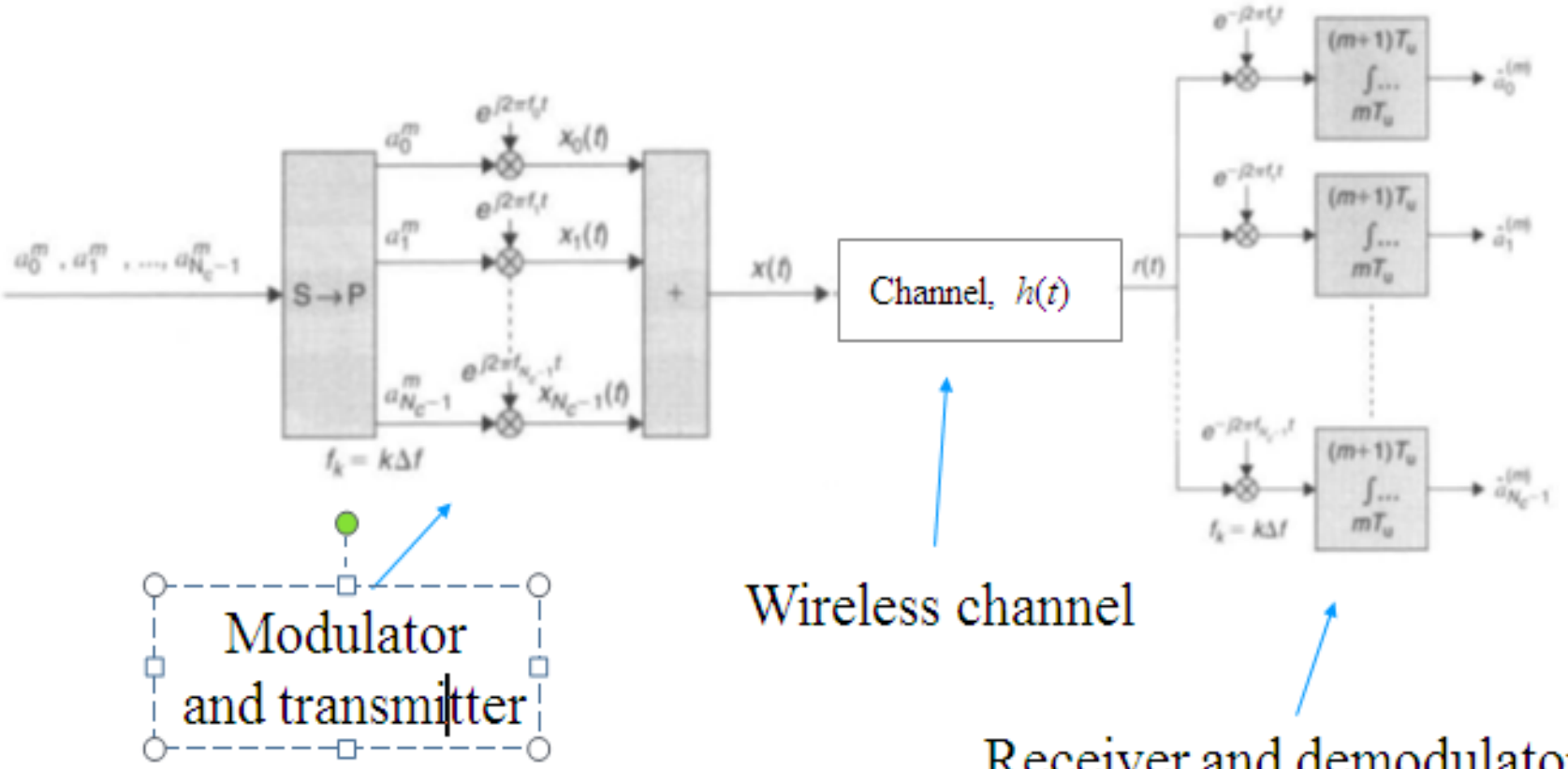
- *Orthogonal Frequency Division Multiplexing* (OFDM) is a multi-carrier modulation scheme
  - First break the data into small portions
  - Then use a number of parallel **orthogonal** sub-carriers to transmit the data
- Conventional transmission uses a single carrier, which is modulated with all the data to be sent



- OFDM is a special case of *Frequency Division Multiplexing* (FDM)
- For FDM
  - No special relationship between the carrier frequencies
  - Guard bands have to be inserted to avoid *Adjacent Channel Interference* (ACI)
- For OFDM
  - Strict relation between carriers: $f_k = k \cdot Df$ where $Df = 1/T_U$ (T_U - symbol period)
  - Carriers are orthogonal to each other and can be packed tight



OFDM Transmission model



Orthogonality – the essential property

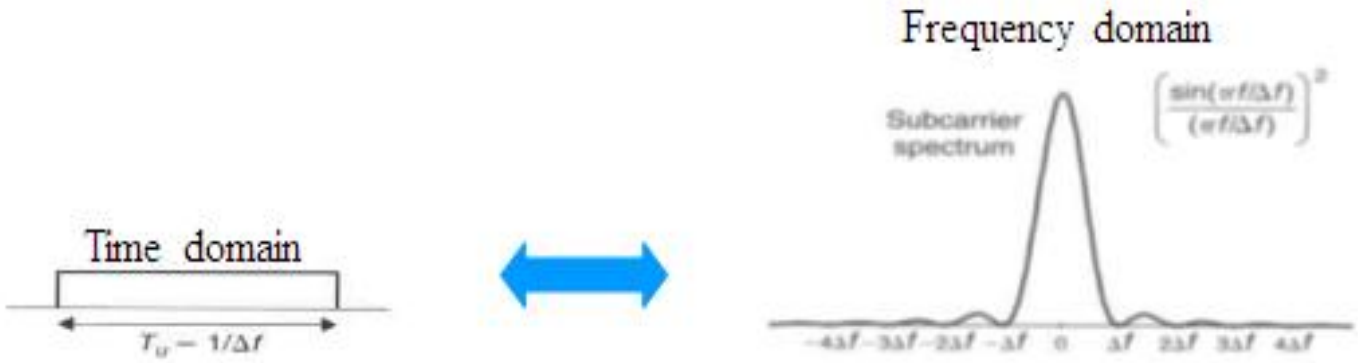
- Example: Receiver branch *k*
  - Ideal channel: No noise and no multipath

$$\frac{1}{T_U}\int_0^{T_U}\underbrace{\left(\sum_{q=0}^{N_c-1} a_q \cdot e^{j2\pi q\Delta f t}\right)}_{\text{Received signal, } r(t)} \cdot e^{-j2\pi k\Delta f t}dt = \sum_{q=0}^{N_c-1}\frac{a_q}{T_U}\int_0^{T_U} e^{j2\pi(q-k)\frac{1}{T_U}\cdot t}dt = \begin{cases} a_k, & k=q \\ 0, & k\neq q \end{cases}$$

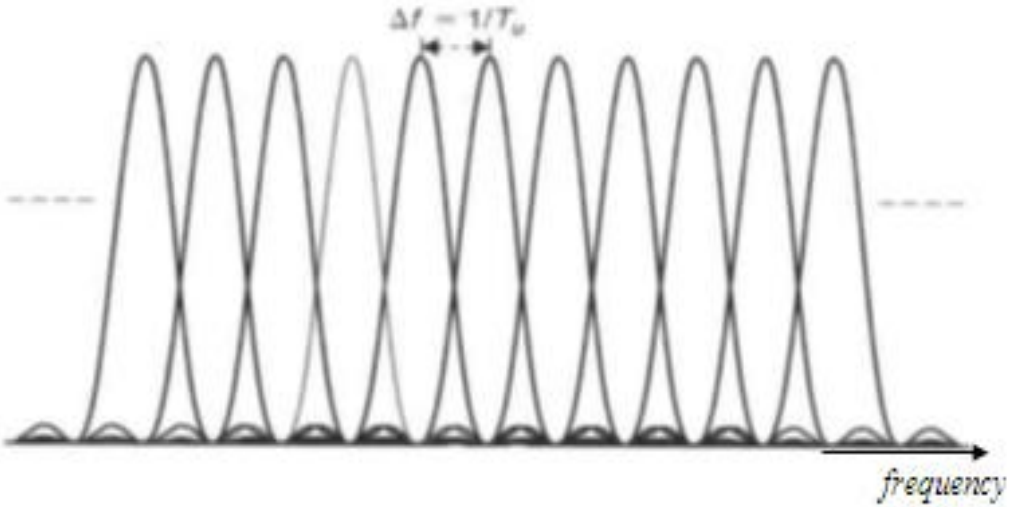
$T_u = 1/\Delta f$ gives subcarrier orthogonality over one T_u

=> possible to separate subcarriers in receiver

OFDM – Signal properties

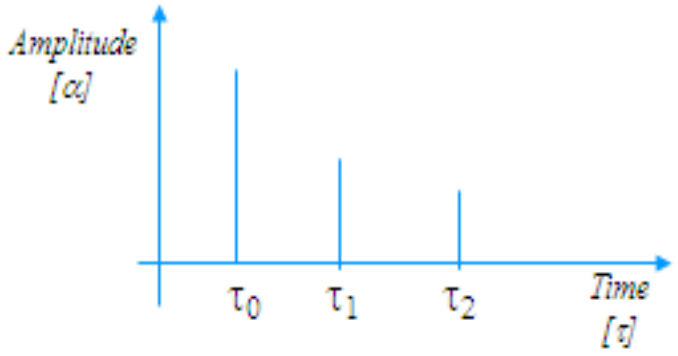


Power Spectrum for OFDM symbol

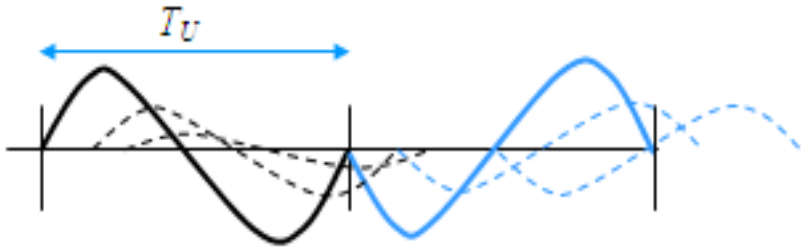


Multipath channel (cyclic prefix)

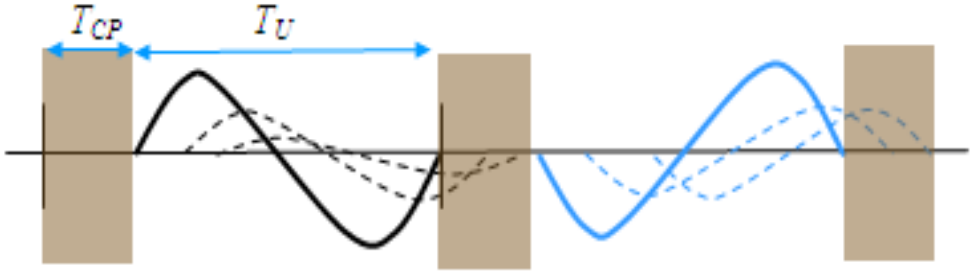
Example multipath profile



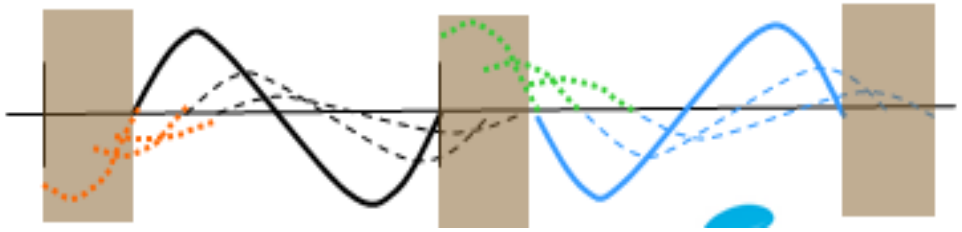
Multipath introduces *inter-symbol-interference* (ISI)



Prefix is added to avoid ISI

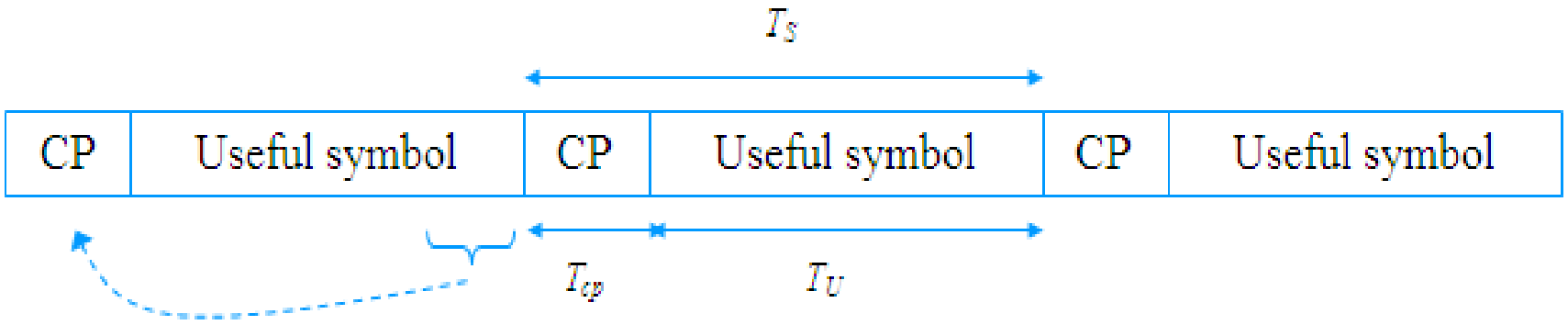


The prefix is made cyclic to avoid *inter-carrier-interference* (ICI) (maintain orthogonality)



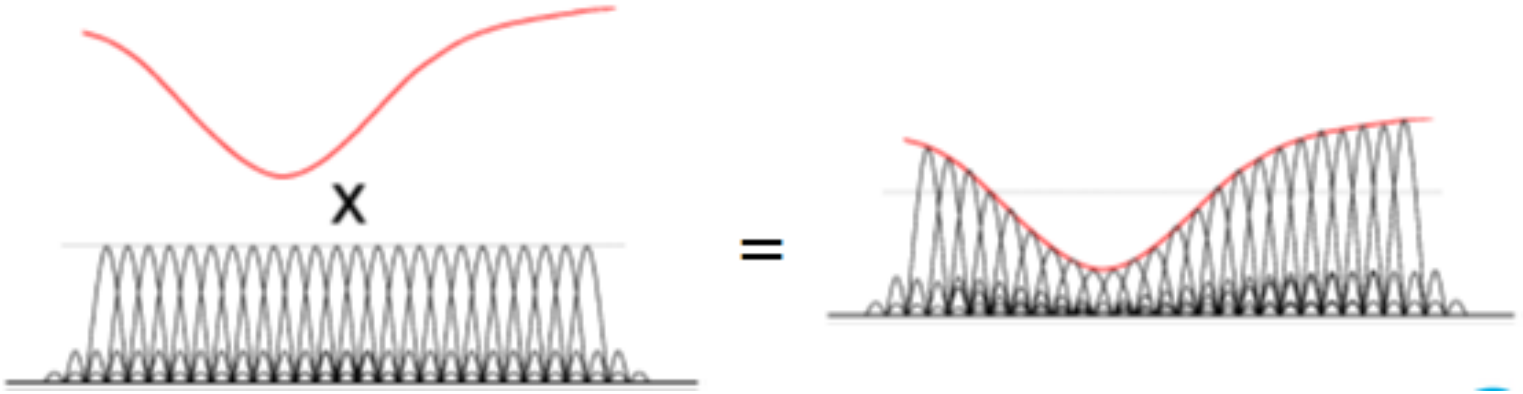
Multipath channel (cyclic prefix)

- T_{cp} should cover the maximum length of the time dispersion
- Increasing T_{cp} implies increased overhead in power and bandwidth ($T_{cp}/\ T_S$)
- For large transmission distances there is a trade-off between power loss and time dispersion



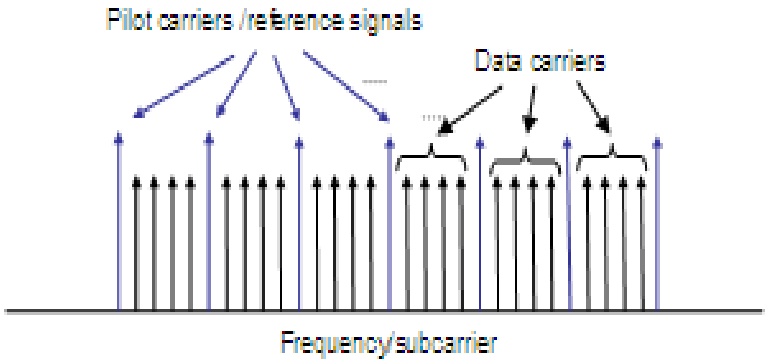
Multipath channel (frequency diversity)

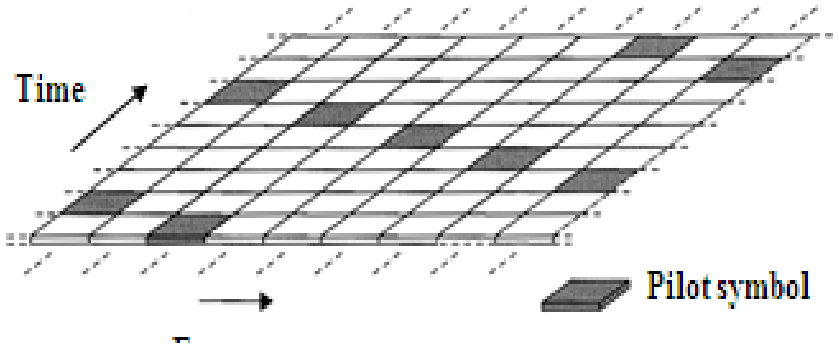
- The OFDM symbol can be exposed to a frequency selective channel
- The attenuation for each subcarrier can be viewed as "flat"
  - Due to the cyclic prefix there is no need for a complex equalizer
- Possible transmission techniques
  - *Forward error correction* (FEC) over the frequency band
  - Adaptive coding and modulation per carrier



Multipath channel (pilot symbols)

- The channel parameters can be estimated based on known symbols (pilot symbols)
- The pilot symbols should have sufficient density to provide estimates with good quality (tradeoff with efficiency)
- Different estimation methods exist
  - Averaging combined with interpolation
  - *Minimum-mean square error* (MMSE)



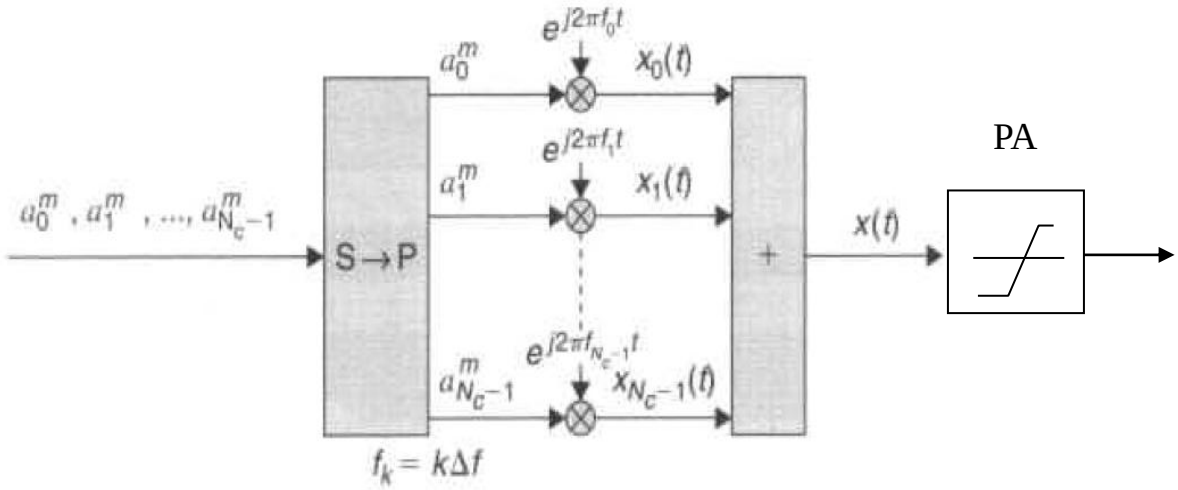


The Peak to Average Power Problem

- A OFDM signal consists of a number of independently modulated symbols
- The sum of independently modulated subcarriers can have large amplitude variations

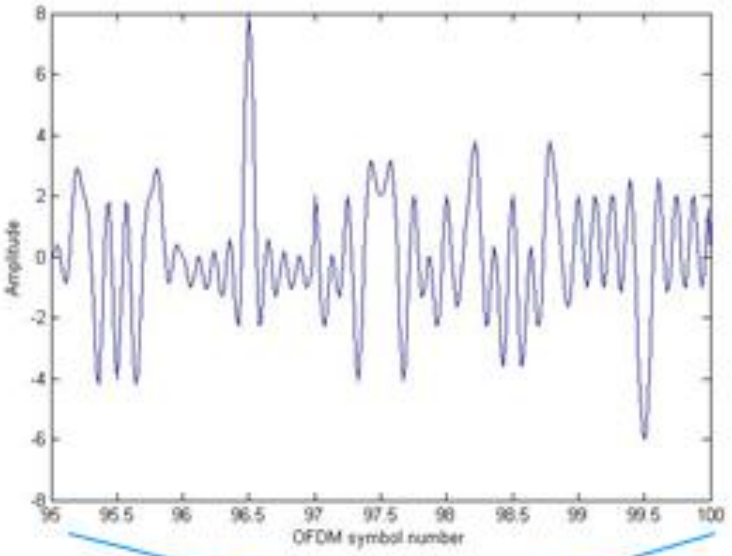
$$x(t) = \sum_{k=0}^{N_c-1} a_k \cdot e^{j2\pi k \Delta f\, t}$$

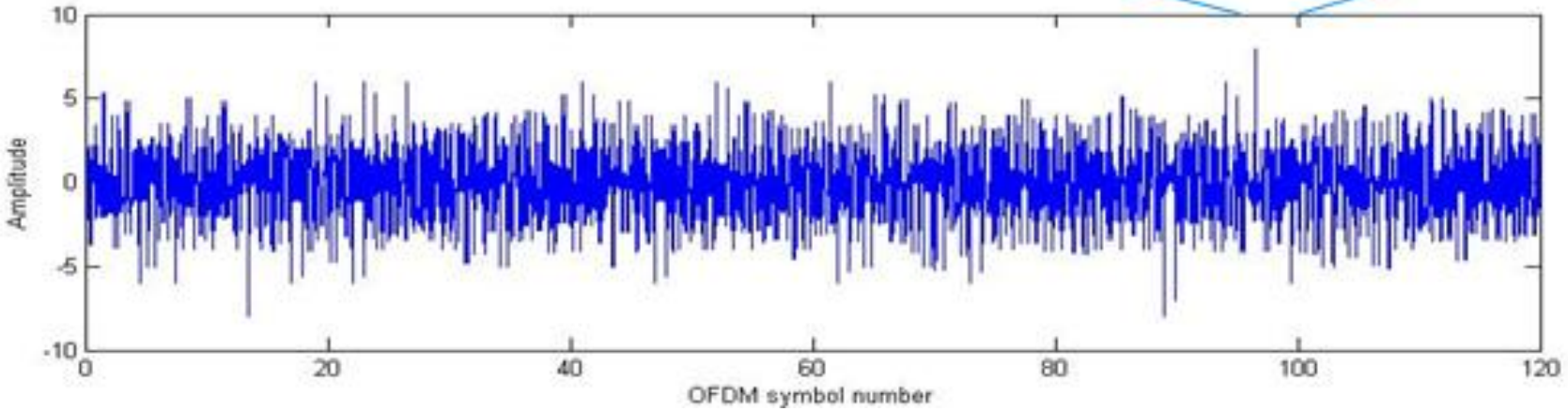
- Results in a large *peak-to-average-power ratio* (PAPR)



The Peak to Average Power Problem

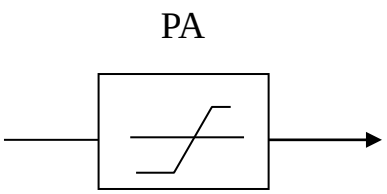
- Example with 8 carriers and BPSK modulation
  - x(t) plotted
- It can be shown that the PAPR becomes equal to N_c



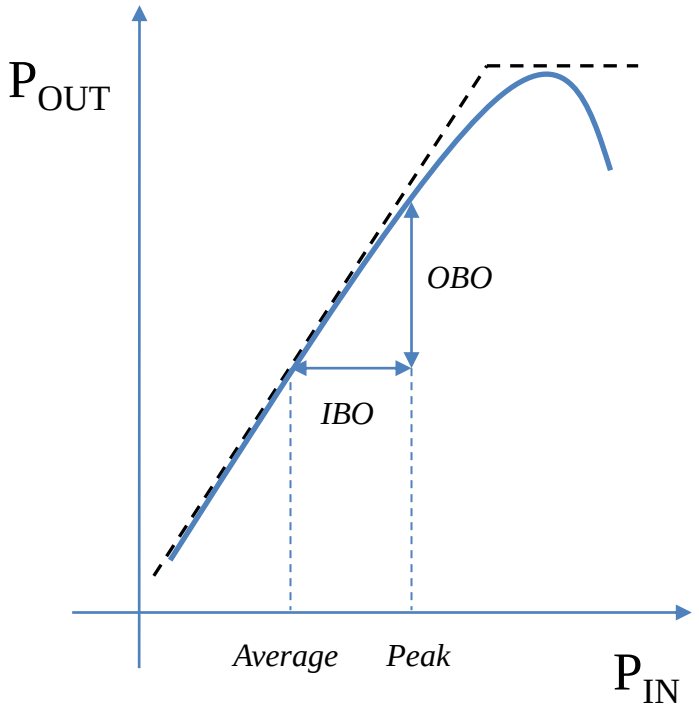


The Peak to Average Power Problem

- High efficiency power amplifiers are desirable
  - For the handset, long battery life
  - For the base station, reduced operating costs
- A large PAPR is negative for the power amplifier efficiency
- Non-linearity results in inter-modulation
  - Degrades BER performance
  - Out-of-band radiation



AM/AM characteristic



Choosing the OFDM parameters

- Symbol time (T_U) and subcarrier spacing (Δf) are inverse
  - $T_U = 1/\Delta f$
- Consequences of increasing the subcarrier spacing
  - Increase cyclic prefix overhead
- Consequences of decreasing the subcarrier spacing
  - Increase sensitivity to frequency inaccuracy
  - Increasing number of subcarriers increases Tx and Rx complexity