Other power allocation algorithms for various CSIT, complexity reduction are available.
In particular, bit loading algorithms allow the distribution of data using practical constellations over the subcarriers in real time. These algorithms are used widely in digital subscriber lines (DSL).

4) Challenges of OFDM Systems.

i) Peak-to-average power ratio: (PAR)

- For OFDM signals, the output of the IFFT block is

$$x[n] = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X[k] e^{j2\pi \frac{kn}{N}}, \quad n = 0 \ldots N-1$$

- If the number of subcarriers N is large (in practice it can be hundreds ...) then by the central limit theorem, the distribution of $x[n]$ will be approximately Gaussian.

- The envelope of $x[n]$ is then Rayleigh distributed (since $x[n]$ is complex Gaussian).
Therefore the PAR for OFDM signal is high.

$$PAR \triangleq \frac{\max_t |x(t)|^2}{E_t[|x(t)|^2]} = \frac{\max_n |x[n]|^2}{E_n[|x[n]|^2]}$$

(cont. time) (discrete-time)

- For OFDM signals, the peak occurs when all symbols add coherently, resulting in a maximum PAR $= N$.

But the probability of this PAR = N happening is low. In particular we can show that for a Rayleigh distributed signal envelop:

$$\Pr(PAR \geq \beta) = 1 - (1 - e^{-\beta})^N.$$

- The PAR for OFDM signals nevertheless is high.

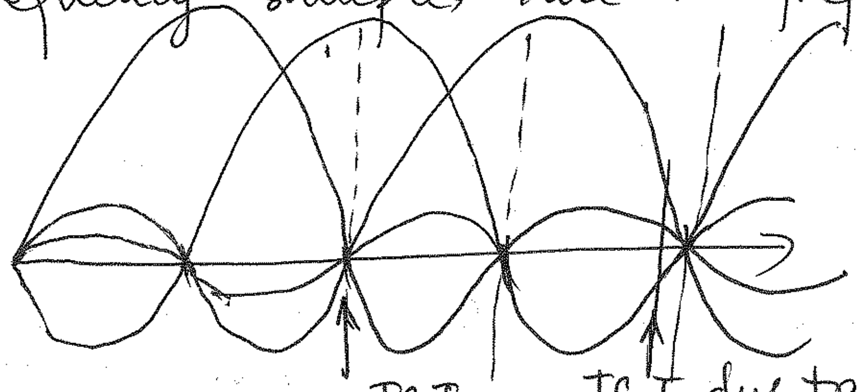
High PAR presents practical problems in that it saturates the linear region of power amplifiers.

There are techniques for reducing or tolerating the PAR of OFDM signals, but we will not go into the details.

ii) Frequency and timing offsets:

- Frequency and timing offsets are caused by hardware (mismatched oscillator, synchronization errors) and also by Doppler frequency shifts.

- Interference among subcarriers (ICI - Intercarrier interference) will result from the misplaced frequency samples due to frequency offsets.



- OFDM due to the sinc frequency response of each symbol is very sensitive to frequency offsets

Increasing the number of subcarriers makes each subcarrier narrower and also increases the sensitivity.

- Because of this challenge, OFDM performs well in low mobility environments but degrades quickly for high mobility.

Non rectangular window can help reduce ICI.

- OFDM is widely used in W-LAN systems because of low mobility.

+) MC with non-overlapping subcarriers:

- OFDMA is the multiple access version of OFDM to serve multiusers
- OFDMA works well under the following conditions:
  - long frame duration to alleviate cyclic prefix overhead.
  - perfect frequency synchronization and tight frame alignment in time of all user's signals at the receiver.

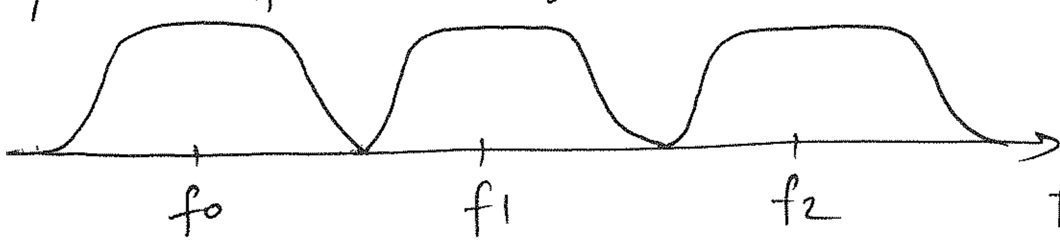
- OFDM is used in LTE (4G) systems. The strict synchronization requirement is achieved by applying a closed loop ranging mechanism and demanding very strict oscillator requirements.

Such closed loop synchronization is costly in terms of energy for message exchange and random access.

- Future cellular systems (5G) intend to support a wide range of applications, including both high data rate (video) and low data rate low power (IoT, sensors) applications. The heterogeneous set of devices to be supported also make synchronization challenging.

- Several other MC modulations are being considered as alternatives to OFDM in 5G systems.
  - FBMC: Filterbank multicarrier
  - UFMC: Universal Filtered multicarrier.

- FBMC method:
  - One way to construct a FBMC system is as in FMT (filtered multitone) where a bank of filters is used to separate the subcarriers as in FDM (freq. division mux)
  - Spectrum of FBMC signals:



  - Depending on the sharpness of the filter, there is some overhead or bandwidth penalty to ensure non-overlapping subcarriers.
  - For example, if we use the raised cosine pulse shaping function with a roll-off factor of α, then the actual bandwidth required for each subcarrier is $(1+\beta)/T_N$ (where T_N = symbol duration).
  - Thus the downside of FBMC is that it can be spectral inefficient. The efficiency ratio here is $\frac{1}{1+\beta}$. This is in contrast to OFDM which is highly spectral efficient but has cyclic prefix due to FFT implementation.

- To improve the spectral efficiency of FBMC, very sharp and therefore higher cost filters can be used.

- There is another FBMC method called SMT (staggered multitone) which allows the filters of the filter bank to overlap to improve spectral efficiency.

SMT is used with offset QAM (OQAM) where the real and imaginary components are separated and are modulated onto alternate (and overlapping) subcarriers.

The adjacent subcarriers are then separated at the receiver based on the timing offset of half a symbol duration between the real and imaginary parts.

We won't go into the details here but see reference [Farhang-Boroujeny] for more information.

+) <u>Hybrid approach</u>: UFMC – Universal Filtered Multicarrier.

- UFMC combines the ideas in both OFDM and FBMC to perform filter bank MC on a number of subchannels, each subchannel contains a group of subcarriers which are applied OFDM.

- The filters to separate the subchannels (also called sub-bands) are usually designed to have very low sidelobes to alleviate ICI.

- See the handout of a paper by Schaich et al. for examples of filter designs and performance of UFMC systems.