EE 577 - Wireless and Personal Communications

Chapter 06: Spread Spectrum and Multi-Carrier Modulation

Spread Spectrum Communications

- Originated in military communications
- Spread the signal over a band much wider than the signal bandwidth
- **Advantages:**
  - Low probability of intercept (LPI)
  - Interference rejection and anti-jamming capability
  - Multiple-access capability
  - Multi-path diversity

How is SS different?

- SS makes the transmitted signal occupy a very large transmission bandwidth
- Trades off frequency domain for signal orthogonality
- Allows multiple users to occupy the same frequency band at the same time with minimal interference

Spread Spectrum Techniques

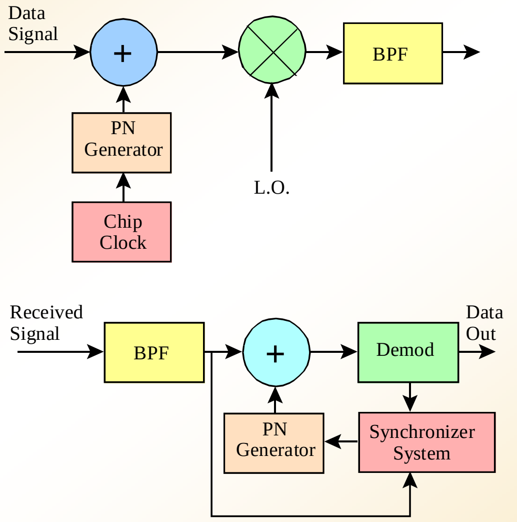
- Direct Sequence Spread Spectrum (DSSS)
- Frequency Hopping Spread Spectrum (FHSS)
- Hybrid (DS/FH)

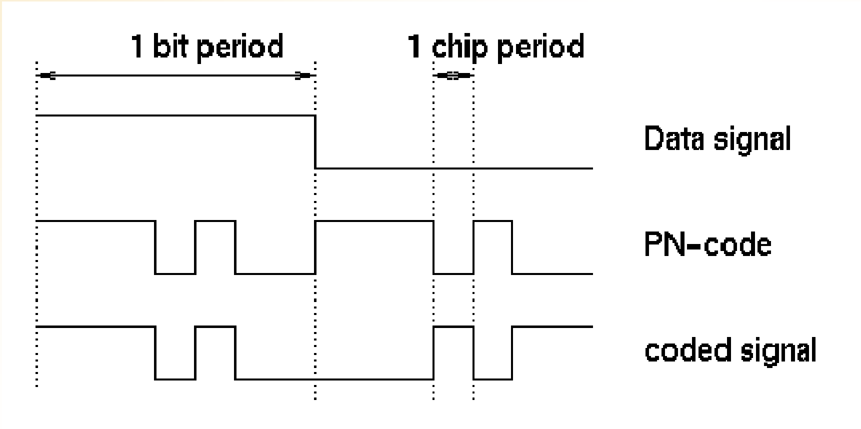
Both DSSS and FHSS require a PN sequence that appears to be random noise signal

Direct Sequence (DSSS)

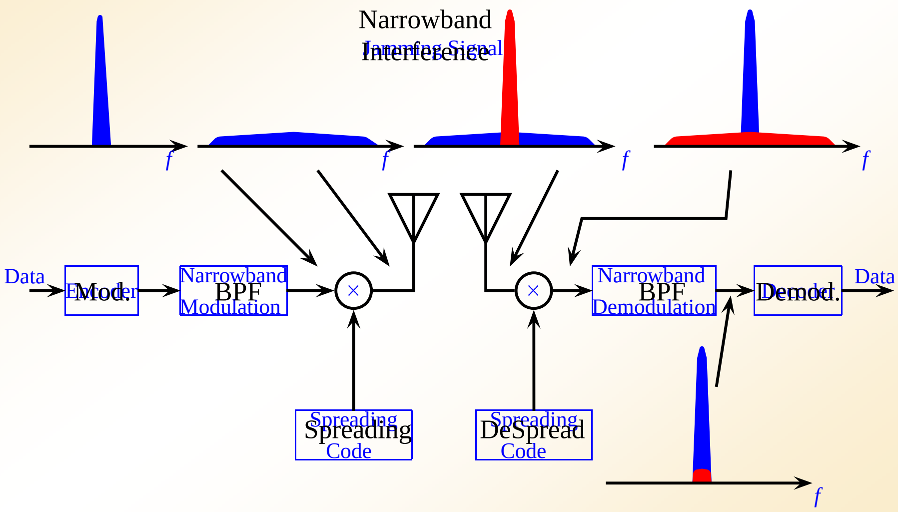
- Data stream is XORed with a high-rate Pseudorandom Noise (PN) random sequence
- At the receiver, the received high-rate signal is XORed with the PN sequence again to recover the original signal
- Can be coherently demodulated
- Suffers from near-far problem
- Resistant to multipath fading
- Less expensive receivers

DSSS Implementation



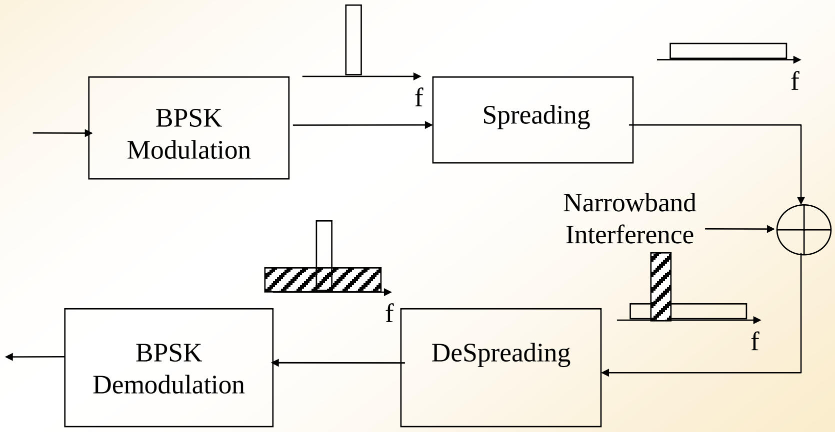


DSSS - Interference Rejection

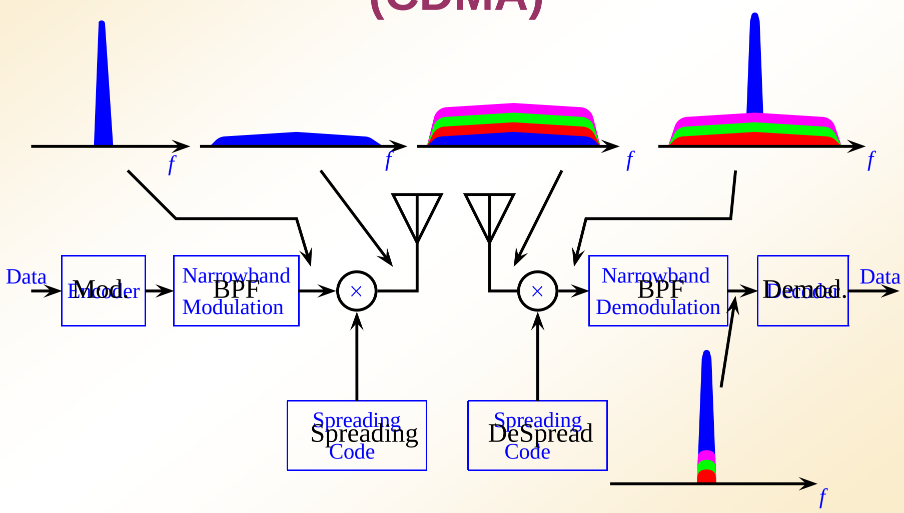


Narrowband Interference Rejection

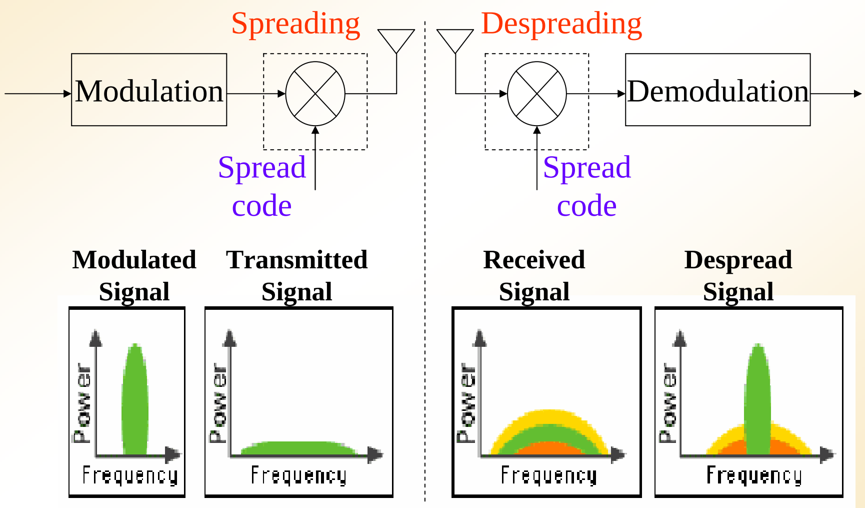
PSD Interpretation: After despreading (which is the same operation as spreading), the narrowband interference is spread evenly over a bandwidth *W*. Hence,



DSSS – Code Division Multiple Access (CDMA)



CDMA



The Processing Gain

- The "Processing Gain" of the system is a figure of merit for how well the system works

$$PG = \frac{T_S}{T_C} = \frac{B_C}{B_S}$$

- This is a ratio of the bandwidth of the spread signal to the baseband bandwidth of the data

Pseudorandom Noise (PN) Sequence

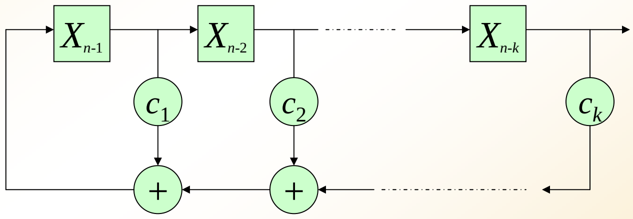
- PN sequence is usually generated at a rate greater than the data rate: (chip rate >> data rate)
- PN sequence has the effect of spreading the spectrum of the data stream over a large frequency band
- PN sequences are based on shift registers and "good" one have a period of $2^m - 1$, where m is the length of the shift register

Popular PN Sequences

- Maximal Length PN sequences
- Walsh Hadamard sequences
- Gold sequences
- Kasami Sequences

Maximal Length Shift Register (MLSR) Sequences

- Also known as PN or *m*-sequences
- Structured sequences



$$c_i = \begin{cases} 0 & \text{no connection} \\ 1 & \text{connection} \end{cases}$$

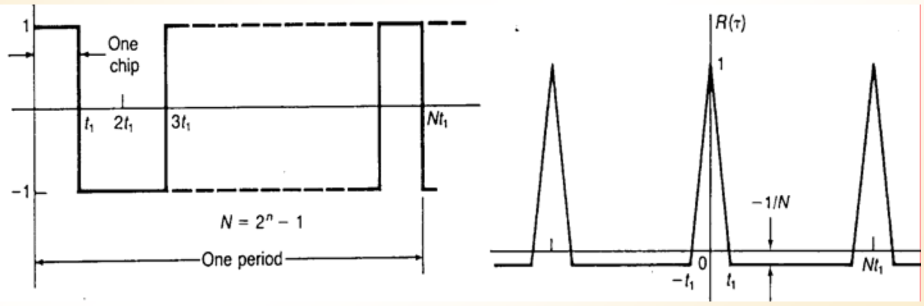
Properties of MLSR Sequences

- Periodic with period 2^r-1, where r is the number of registers (Maximal-length)
- Balanced property, i.e., # of 1's = # of 0's + 1
- Sequences of length n occur with probability 2^{-n} for $n < m$ and $2^{-(m-1)}$ for $n = m$
- The addition of two *m*-sequences is also an *m*-sequence (linear operation)

Autocorrelation of MLSR Sequences

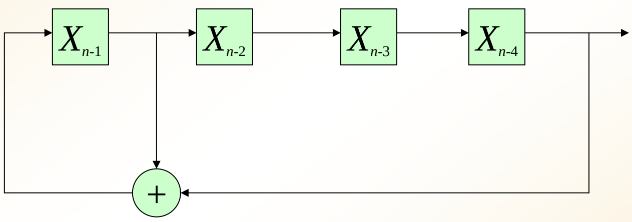
$$R(\tau) = \frac{1}{N}\sum_{k=1}^{N} y_k y_{k+\tau}$$

Map 0 to -1



The peak autocorrelation is useful for PN phase synchronization

Example



PN sequence:

1 0 0 0 1 1 1 1 0 1 01 1 0 0

Walsh Codes

- Walsh codes are the rows (or columns) of a Hadammard matrix
- Hadammard matrix are square, symmetric and of size [2^m x 2^m]
- They are generated recursively as illustrated.

$$A_0 = [0] \quad \Rightarrow \quad A_1 = \begin{bmatrix} A_0 & A_0 \\ A_0 & \overline{A_0} \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}$$

General Form

$$A_{m+1} = \begin{bmatrix} A_m & A_m \\ A_m & \overline{A_m} \end{bmatrix}$$

$$A_2 = \begin{bmatrix} A_1 & A_1 \\ A_1 & \overline{A_1} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 \end{bmatrix}$$

Multipath Mitigation

- SS techniques can be used to improve performance over multipath channels
- SS produces a data stream that has very narrow autocorrelation functions
- Delayed versions of the same spread signal look like uncorrelated with other users to the receiver
- Thus, the receiver can ignore the time-delayed versions of the same signal just as the receiver ignores other users!

The RAKE Receiver

- A RAKE receiver can be used to combine the different multipath components
- The received signal is separated into different branches
- Each branch is multiplied by a PN sequence at a different delay corresponding to the multipath delay
- Resultant signals from branches are then combined to improve detected signal
- So, the RAKE receiver gives diversity reception

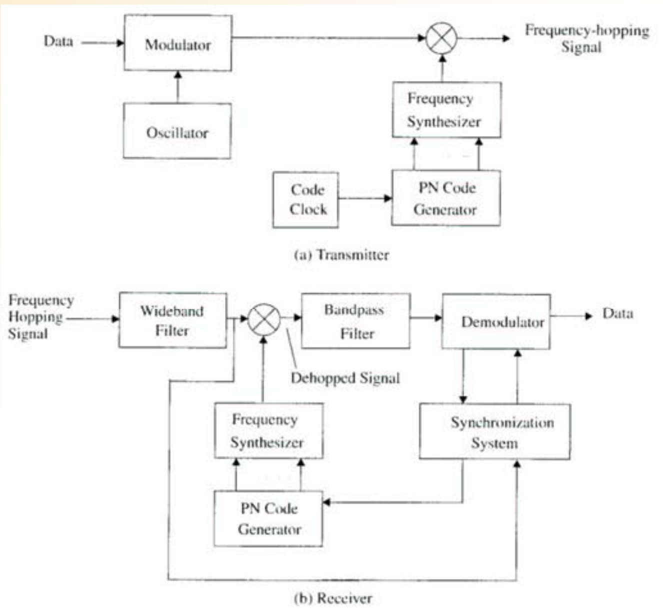
The Near-Far Problem

- Signals closer to the receiver of interest are received with smaller attenuation than are signals located further away
- So, the strong signal from the nearby transmitter will mask the weak signal from the remote transmitter
- The near-far effect combined with imperfect orthogonality between codes leads to substantial interference
- Accurate and fast power control is essential

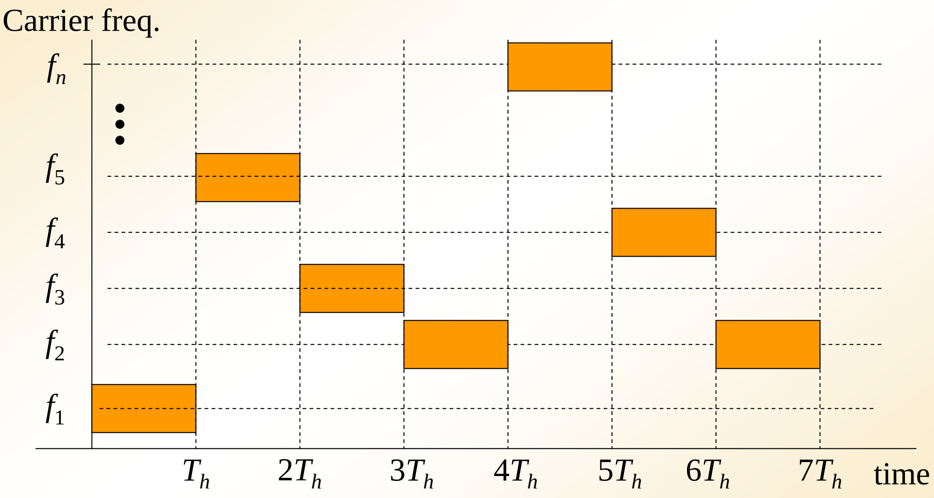
Frequency Hopping (FH-SS)

- The carrier frequency is changed according to a PN sequence
- The carrier only stays at a given frequency for a short time (**dwell or hop duration**, T_h)
- **Slow hopping:** Multiple bits is transmitted during a hop ($T_h > T_s$)
- **Fast hopping:** Multiple hops per bit ($T_h < T_s$)
- No near-far problem
- Non-coherent demodulation is suitable
- Less resistant to multipath fading

FHSS



FHSS in Bluetooth



Random hopping among 79 carrier frequencies

Error Performance of SS

- The Error performance of the system is based on:
  - Channel noise
  - Interference from the other users on the channel that do not correlate with the receiver
- Typically, the other users can be considered to be a Gaussian noise source

Error Performance of SS

- The probability of error is:

$$P_e = Q\left(\left[\frac{K-1}{3N} + \frac{N_0}{2E_b}\right]^{-1/2}\right)$$

- Where K is the number of users on the channel and
- N is the number of chips per bit (the processing gain)

FHSS

- If two users send in the same frequency

  => collision (hit) occurs
- BFSK: $P_e = \frac{1}{2}\exp(-\frac{E_b}{2N_o})$
- For K users, collision (hit) probability:

$$P_h = 1 - \left(1 - \frac{1}{M}\right)^{K-1}$$

- For large M, $P_e = \frac{1}{2}\exp\left(-\frac{E_b}{2N_o}\right)\left(1 - \frac{K-1}{M}\right) + \frac{1}{2}\frac{K-1}{M}$

Multi-Carrier (MC) Modulation

- Mitigates the ISI by dividing the transmit bit stream into N parallel substreams, each modulated by a separate carrier
- The transmission bandwidth of the subcarriers can be made less than the channel coherence bandwidth
- Each subcarrier experiences flat instead of frequency-selective fading

Performance of MC Over FS channels

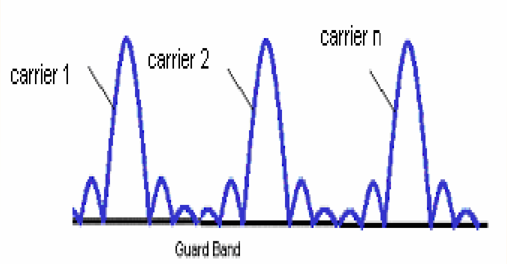
- Frequency selective fading leads to different BERs on the different subcarrier channels
- This can be compensated using a frequency domain equalizer, which inverts the channel gain on each subcarrier
- This inversion leads to noise enhancement on carriers with low SNR
- Alternatively, coding can be used across subchannels

Orthogonal Frequency Division Multiplexing (OFDM)

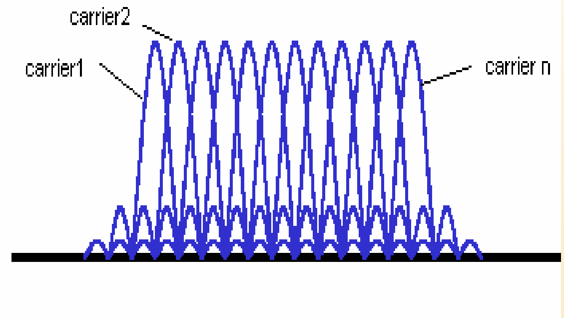
- OFDM is multi-carrier modulation in which the total bandwidth is split between many narrow band sub-carriers
- High-rate data stream is transformed into several low-rate parallel streams
- Parallel streams are transmitted in parallel over orthogonal sub-carriers with spacing of $1/(NT)$, where T is the symbol duration over each sub-carrier
- Sub-carriers are orthogonal => overlapping spectra => high spectral efficiency

Spectrum of OFDM

FDM Spectrum



Subcarriers in OFDM

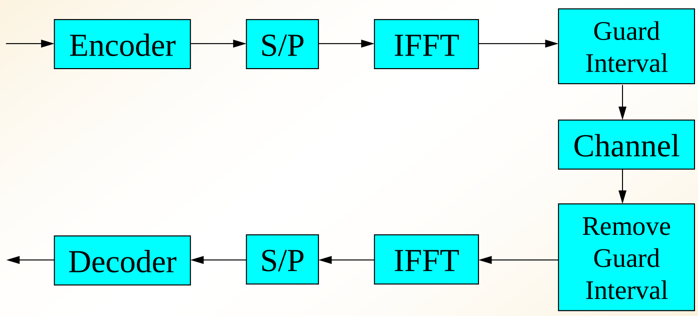


OFDM

- OFDM can be implemented using:
  - IFFT at the transmitter combined with a single modulator
  - FFT at the receiver combined with a single demodulator

- Inter-Symbol-Interference (ISI) can be avoided in OFDM system by adding guard interval to each of the OFDM symbols

OFDM

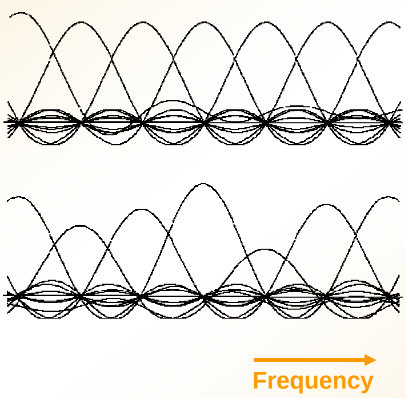


Advantages of OFDM

- Robust in mutipath fading channels
- More tolerant to delay spread:
  - Symbol duration on each sub-carrier is large relative to delay spread => reduced ISI
  - Simplified or eliminated equalization needs
- Different channel coding is used to correct for sub-carriers that suffer from deep fades
- Different modulation techniques can be employed on each sub-carrier => adaptive rate
- Narrow-band interference is reduced

Sub-carriers Orthogonality

Assuming rectangular pulses over each sub-carrier



Before channel

After channel
=> Inter-carrier interference (ICI)

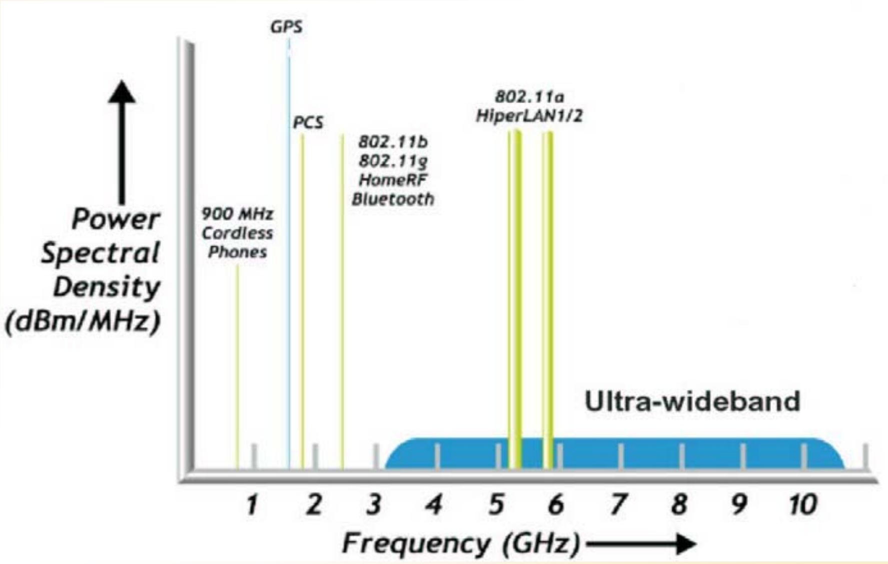
Design Challenges in OFDM

- Sensitive to **frequency offset** => results in ICI – need frequency offset correction in the receiver
- Sensitive to **oscillator phase noise** – "clean" and stable oscillators are required.
- Large **peak-to-average power ratio** (PAPR) – distortion with nonlinear amplifiers - reduced power efficiency
- IFFT/FFT complexity – **fixed point implementation** to optimize latency and performance.
- **ISI due to multipath** – use guard intervals.

Ultra-Wide Band (UWB)

- Transmission BW is ultra-wide (several GHz)
- **Feb 2002:** FCC approved UWB (3.1-10.6 GHz)
- **IDEA:** Spread the signal spectrum over very wide band (much wider than DSSS)
- An UWB signal has a BW that exceeds third its center frequency
- Average transmission power has to be lower than the allowed noise levels of existing systems
- UWB signals appear as low-level noise
- Hence, it can co-exist with existing systems
- Range is limited to several meters (low power)

Ultra-Wide Band (UWB)



UWB Techniques

- **Impulse Radio:**
  - Transmits very narrow pulses (in the order of *ps*)
  - Employs pulse-position modulation (PPM): information is carried in the pulse position
  - Time-Hopping (TH) is used to allow multiple users
  - Very good communication link
  - Accurate positioning capabilities (in the order of cm)
- **DSSS, FH-SS or Hybrids:**
  - Very similar to SS concepts
  - Processing gain is much larger in this case
- **Hybrid use of TH and SS**