Digital modulation

SC - Single carrier systems
One carrier carries data stream

MC - Multi-carrier systems
Many carriers are used for data transmission. Data stream is divided into sub-streams and each of these sub-streams is transmitted using different carrier.
Multicarrier modulation

Parallel / Serial

Data

$R_b = 1/T_b$

Modulator 1

$R_b/N$

$f_1$

Modulator 2

$R_b/N$

$f_2$

Modulator N

$R_b/N$

$f_N$

$\sum$

Multicarrier transmission

$s(t)$
Signal propagation in radio channel

- Multipath propagation
- Signal attenuation
- Signal reflection
- Signal diffraction
- Signal refraction
- Signal fading
- Doppler effect
Multipath propagation
Multicarrier modulation

Received signal is a sum of signals which arrives to the receiver on different paths. Copies of the original signal reaches the receiver with different power level, different delays and are shifted in phase.

It causes overlapping (interference) of transmitted signal elements. Interference level depends on length (duration) of channel response and transmission speed.

**Inter-Symbol Interference (ISI)** reduction is possible by employment of multicarrier transmission - **OFDM (Orthogonal Frequency Division Multiplexing)**.
Orthogonal Frequency Division Multiplexing

- Type of multicarrier (multitone) transmission)

- Available bandwidth of the transmission channel is divided into many (N) narrowbands (subchannels).

- Data is transmitted parallelly in selected subchannels

- Subchannels carriers are orthogonal (gap between carriers is \( \Delta f = 1/T_m \), where \( T_m \) is a duration of modulated element)

- Signal generation and reception are realized using Fourier transform algorithms (IFFT in transmitter and FFT in receiver)
Channel with multipath propagation, max. channel response duration $\tau_{\text{max}} = 224 \mu s$

**System with single carrier**

transmission speed $R_b = 1/T_b = 7.4$ Mbit/s.
ISI (Inter-Symbol Interference) level:

$$\frac{\tau_{\text{max}}}{T_b} = 1600$$

**Multicarrier system (OFDM)**

Data stream with speed $R_b$ is divided into $N$ parallel sub-streams, each of speed $R_{mc} = 1/T_{mc} = R_b/N$.

ISI is reduced to level:

$$\frac{\tau_{\text{max}}}{T_{mc}} = \frac{\tau_{\text{max}}}{(T_bN)}$$

For DVB-T (number of carriers is $N=8192$):

$$\frac{\tau_{\text{max}}}{T_{mc}} = 0.2$$
Multicarrier modulation

- N carriers
- Data
-Carrier
-Symbol OFDM
-T = 1/f
-Data

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Multicarrier modulation - OFDM

Diagram showing the process of serial to parallel conversion, symbol mapping, parallel to serial conversion, guard interval insertion, and RF transmission. The reverse process is also shown for reception, including guard interval removal, serial to parallel conversion, and DFT conversion.
OFDM advantages

- **Reduction of signal distortions caused by InterSymbol Interference (ISI)**

  Employment of slow bitrate parallel transmission instead of high bitrate single stream transmission cause extension of modulated element duration to the value related to channel response length.

- **High spectral efficiency**

- **High flexibility enabling system optimization from point of maximal transmission speed.**
  It is realised by proper allocation of power and modulation format in frequency subchannels.
OFDM Disadvantages

- Susceptibility for signal fading (loss)

- Precise synchronization required
  Special training sequences and pilot signals are used.

- Cannot be used in nonlinear channels where constant envelope signals are required
  OFDM signals characterize high amplitude changes.
DMT is a type of OFDM modulation and is used in DSL (Digital Subscriber Loops) systems.

DMT uses 224 carriers in the downlink direction (downstream) and 32 carriers in the uplink direction (upstream), with a gap between adjacent carriers of 4.3125kHz.
Multicarrier modulation - OFDM

Applications:

✓ Digital TV
DVB-T (*Digital Video Broadcasting for Terrestrial*)

✓ Digital radio
DAB (*Digital Audio Broadcasting*)

✓ High speed data transmission on wired subscriber loops
ADSL (*Asymmetric Digital Subscriber Loops*)
VDSL (*Very High Speed Digital Subscriber Loops*)

✓ Wireless Local Area Networks (Wi-Fi)
(IEEE 802.11g,n)

✓ WiMax systems (802.16)

✓ Cellular telephone network LTE (*Long Term Evolution*)
Multiple Access Techniques
Fixed Assignment Protocols:
- ✓ FDMA (SCPC)
- ✓ TDMA
- ✓ CDMA

Demand Assignment Protocols:
- ✓ DAMA-TDMA
- ✓ DAMA- FDMA
- ✓ reservation ALOHA

Random Access Protocols:
- ✓ ALOHA
- ✓ S-ALOHA
- ✓ SREJ-ALOHA
Desirable Features

- High efficiency in terms of the throughput
- Low access delay
- Stability
- Efficient starting up of new stations
- Low complexity
Advantages:
- network timing not required

Disadvantages:
- intermodulation noise reduces the usable output power, hence there is a loss of capacity relative to single carrier capacity
- uplink control power required
- the frequency allocation may be difficult to modify

Advantages:
- uplink power control not needed
- no mutual interference between accesses
- digital circuitry

Disadvantages:
- network control (timing) required
- stations transmits high bit-rate bursts requiring large peak power

Advantages:
- antijamming capabilities
- network timing not required

Disadvantages:
- wide bandwidth per user required
- precision code synchronization needed
Multiple Access

Fixed Assignment

The Frequency or Time resource is shared between stations according to a scheme which does not vary with time.
The Frequency or Time resource is shared between stations according to the demand from individual stations.
FDMA

Frequency Division Multiple Access

Available Channel Bandwidth

\[ f \]

\[ f_1 \quad f_2 \quad f_3 \quad f_4 \]
Multiple Access

**TDMA**

Time Division Multiple Access

![Diagram of TDMA](image)

- Reference Burst
- Preamble
- Data
- Frame

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Multiple Access

Example:

FDMA
\[ R_{FDMA} = 64 \text{kbit/s} \]
Total throughput: \( 50 \times 64 = 3.2 \text{Mbit/s} \)

TDMA
\[ R_{TDMA} = \frac{R_{FDMA} \times T_F}{T_P} \]
\[ R_{TDMA} = 3.2 \text{Mbit/s} \]
17 dB power increase → high terminal cost

\[ R_b = 64 \text{kbit/s} \]
\[ N = 50 \text{ terminals} \]
Spread Spectrum technique

- Transmitter spreads baseband signal from bandwidth B to W
- $W/B$ - spreading factor (10-100000)
- Receiver despreads only signal with proper address
- Received signals with other addresses and jammer are spread by the receiver and act as a noise
- Addresses are periodic sequences that either modulate the carrier directly (**DIRECT SEQUENCE SYSTEMS**) or change the frequency state of the carrier (**FREQUENCY HOPPING SYSTEMS**)

CDMA is based on spread spectrum transmission
Spread Spectrum

Power spectral density

Data signal

Data signal after spreading

Data (information signal) \( R_b = \frac{1}{T_b} \)

Spreading sequence (code) \( R_c = \frac{1}{T_c} \)

\[
\frac{W}{B} = \frac{R_c}{R_b}
\]

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Direct Sequence System

Spread Spectrum

\[ d(t) \times \cos(2\pi f_c t) \Rightarrow \text{satellite} \]

\[ R_c >> R_b \]

\[ R_b = \frac{1}{T_b} \]

\[ R_c = \frac{1}{T_c} \]

\[ d(t)c(t) \]
Spread Spectrum

1. Data
2. Spreading
3. Satellite
4. Despreading

Undesired signals in the frequency domain. qosgl W >> B

PSD (Power Spectral Density)

1. PSD (power spectral density)
2. PSD
3. Jammer + Noise + Other Users Signals
4. PSD
Advantages:
- interference protection and antijamming capabilities (immunity increases with larger modulation gain)
- Many users can share the same frequency band
- Signal unavailable without spreading code knowledge
- CDMA do no require network synchronization

Disadvantages:
- Wide bandwidth required
- Precision synchronization of spreading code required
Coherent demodulation implies recovery of the transmitted carrier at the receiver side. Despreading is performed prior to demodulation in order to reduce interference from other than desired carriers and improve carrier recovery performance.
CDMA - code generation

Clock

\[ f = \frac{1}{T_c} \]

Shift register \( n \) stages

code rate: \( R_c = \frac{1}{T_c} \)

period: \( 2^{n-1} \) chips

Example:

\[ T_c \rightarrow T_c \rightarrow T_c \]

\( n=3 \)

Shift register status

| 0 0 1 |
| 1 0 0 |
| 1 1 0 |
| 1 1 1 |
| 0 1 1 |
| 1 0 1 |
| 0 1 0 |

1 period output code sequence

Code Correlation Function

\[ R_{\text{code}}(\delta) \]

\( \delta \)

\( 2^{n-1} \) chips

\( -\frac{1}{(2^{n-1})} \)

Code Power Spectral Density

\[ \Delta f = \frac{R_c}{(2^{n-1})} \]

\( -R_c \rightarrow 0 \rightarrow R_c \)

frequency

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Frequency hopping (FH)

- Generated frequency depends on spreading code and data and is changed every $T_c$
- Bit duration $T_b$
- Slow SFH ($T_c \geq T_b$, “hop” for a few data elements)
- Fast FFH ($T_c < T_b$, many “shops” per data element)
- Immunity to interference increasing with number of used frequencies
Spreading sequences (codes)

- Maximal length pseudorandom sequences
  - good auto and cross-correlation properties
  - small number of sequences
- Gold and Kasami codes. Generated from maximal length pseudorandom sequences, similar correlation properties, more sequences to use.
- Walsh and Hadamard codes
System capacity

assumption: noise - other users signals

\[ K \] - number of users (stations)
\[ R_b \] - data bit rate
\[ R_c \] - code bit rate
\[ C \] - carrier power
\[ (E_b/N_0)_w \] - required value of \((E_b/N_0)\) for specified BER

\[
E_b = \frac{C}{R_b} \quad N_0 = \frac{(K-1)C}{R_c}
\]

\[
\left( \frac{E_b}{N_0} \right)_w = \frac{R_c}{R_b} \frac{1}{(K-1)}
\]

\[
K_{max} = \left( \frac{R_c}{R_b} \frac{1}{(E_b/N_0)_w} + 1 \right)
\]