EELE 5414 Wireless Communications

Chapter 9: Multiple Access Techniques for Wireless Communications

Multiple access are used to support many users in the system.

Outline

- Duplexing.
  - Time division duplexing (TDD).
  - Frequency division duplexing (FDD).
- Narrow-band and Wide-band systems.
- Frequency division multiple access (FDMA).
- Time division multiple access (TDMA).
- Spread spectrum multiple access (SSMA).
  - Frequency hopped multiple access (FHMA).
  - Code division multiple access (CDMA).
- Hybrid spread spectrum techniques.
- Space division multiple access.

Communication Direction

- If the communication between two parties is one way, it is called simplex communication.
- If the communication between two parties is two-way, then it is called duplex communication.
- Simplex communication is achieved by default by using a single wireless channel (frequency band) to transmit from sender to receiver.

Duplexing

- Enable the subscriber to send and receive information simultaneously to/from the base station.
- May be done in frequency or time domain techniques.
- Frequency division duplexing (FDD): provides two distinct bands of frequencies for every user.
- Time division duplexing (TDD): use time instead of the frequency to provide the bi-directional transmission.
Duplexing - FDD
- A duplex channel consists of two simplex channels with different carrier frequencies.
  - **Forward band**: carries traffic from base to mobile.
  - **Reverse band**: carries traffic from mobile to base.
- Frequency separation should be carefully decided, frequency separation is constant.

Duplexing - TDD
- A single radio channel (carrier frequency) is shared in time in a deterministic manner.
  - The time is slotted with fixed slot length (sec).
  - Some slots are used for **forward channel** (traffic from base to mobile).
  - Some slots are used for **reverse channel** (traffic from mobile to base).

Motivation
- **Why multiple Access?**
  - To allow many users to share simultaneously a finite amount of radio spectrum.
- **Why the spectrum sharing?**
  - To achieve high capacity using the available bandwidth.
  - The sharing should be performed without severe degradation of in the system performance.
  - Multiple access techniques divide up the total signaling dimensions into channels and then assign these channels to different users.

Duplexing – TDD versus FDD
- **FDD**
  - FDD is used in radio systems that can allocate individual radio frequencies for each user.
  - More suitable for wide-area cellular networks: GSM, AMPS all use FDD.
- **TDD**
  - Can only be used in digital wireless systems (digital modulation).
  - Requires rigid timing and synchronization.
  - Mostly used in short-range and fixed wireless systems so that propagation delay between base and mobile do not change much with respect to location of the mobile.
    - Such as cordless phones...
Multiple Access

- Three major multiple access schemes
  - Time Division Multiple Access (TDMA)
    - Could be used in narrowband or wideband systems
  - Frequency Division Multiple Access (FDMA)
    - Usually used narrowband systems
  - Code Division Multiple Access
    - Used in wideband systems.
- All multiple access techniques that divide the signal space orthogonally have the same channel capacity in AWGN.
- Flat and frequency-selective fading affect these techniques in different ways, which lead to different channel capacities and different performance in practice.

Narrow- and Wideband Systems

- Classified based on how the available B.W is allocated to the users.
- Relates the B.W of a single channel w.r.t the coherence B.W of the channel.

Narrowband System
- The channel bandwidth is large compared to the coherence bandwidth of the channel
- Achieved by dividing the B.W into many small B.W channels.
- To minimize interference between FWO and REV, the frequency separation is made as great as possible → increase in the cost of the duplexer and the antenna.
- Usually operated using FDD.
- AMPS is a narrowband system (channel bandwidth is 30kHz in one-way).

Narrow- and Wideband Systems (2)

- Wideband Systems
  - The channel bandwidth is large
    - More precisely, the channel bandwidth is much larger than the coherence bandwidth of the multipath channel.
  - A large number of users can access the same channel (frequency band) at the same time.
- Narrowband Systems
  - Could be employing one of the following multiple access and duplexing schemes
    - FDMA/FDD or TDMA/FDD or TDMA/TDD
- Wideband systems
  - Could be employing one of the following multiple access and duplexing schemes
    - TDMA/FDD or TDMA/TDD or CDMA/FDD or CDMA/TDD

Frequency Division Multiple Access (FDMA)

diagram showing frequency and time axes with channel allocation and frequency separation.
FDMA

- Individual radio channels are assigned to individual users.
- Each user is allocated a frequency band (channel).
  - During the call time, no other user can share the channel.
- Base station allocates channels to the users.
- In FDMA/FDD systems: the users are assigned a channel as a pair of frequencies (FWD and Rev.)

Features of FDMA:

- If channel allocated to a user is idle, then it is not used by someone else: waste of resource.
- Mobile and base can transmit and receive simultaneously and continuously.
- Bandwidth of FDMA channels are relatively narrow.
- Symbol time is usually larger (low data rate) than the delay spread of the multipath channel (implies that inter-symbol interference is low).
- Lower complexity systems than TDMA systems.
- Continuous transmission → fewer bits are needed for overhead purposes.
- Higher Cost than TDMA, (duplexer, Antenna, and filters).
  \[ \text{Not found in TDMA} \]

FDMA

Frequency spectrum allocated for FDMA system

\[ \text{Number of channel in FDMA system} = \frac{B_s - 2B_{\text{guard}}}{B_c} \]

- \( B_s \): Total spectrum allocation
- \( B_{\text{guard}} \): Guard band allocated at the edge of the spectrum band
- \( B_c \): Bandwidth of a channel

AMPS has 12 MHz simplex spectrum band, 10 kHz guard band, 30 kHz channel bandwidth (simplex), Number of channels is 416.

FDMA → usable BW is small → Narrow Band system
FDMA → cannot be wide Band

Time Division Multiple Access (TDMA)

- to increase the number of users in the system:

The allocated radio spectrum for the system is divided into time slots:

- In each slot a user can have access to the entire B.W.
- A user occupies a cyclically repeating slots.
- A channel is logically defined as a particular time slot that repeats with some period.
TDMA

- TDMA systems buffer the data, until its turn (time slot) comes to transmit (called buffer-and-burst method).
- The transmission for each user is not continues.
- Requires digital modulation
- In TDMA/TDD: half of the time slots are used for forward and the other half for the reverse.
- In TDMA/FDD: the bands is divided into two parts, each one has several time slots.

TDMA Frames

- Multiple, fixed number of slots are put together into a frame.
- Every frame has preamble contains address and synchronization info to identify base station and mobiles to each other.
- Guard times are used to allow synchronization of the receivers between different slots and frames
  - Different mobiles may have different propagation delays to a base station because of different distances.

TDMA Frame

- Enables the sharing of a single radio channel among $N$ users
- Transmission occurs in bursts (not continues)
  - Enables power saving by going to sleep modes in unrelated slots
  - Discontinues transmission also enables mobile assisted handoff
- Requires synchronization of the receivers.
  - Need guard bits, sync bits. $\rightarrow$ large overhead per slot.
- Allocation of slots to mobile users should not be uniform.
  - It may depend on the traffic requirement of mobiles.
  - This brings extra flexibility and efficiency compared to FDMA systems
Example 9.3

Consider the GSM system, which uses a TDMA/TDMA system that uses six carriers, allowing for 576 voice channels. The GMSK modulation is used for the forward link, and 200 kHz of spectrum is allocated for each carrier. Calculate the number of simultaneous users that can be accommodated in the GSM system.

Solution

N = \frac{25 MHz}{200 kHz} = 100

Thus, GSM can accommodate 100 simultaneous users.

Example 9.4

Each GSM frame consists of 156.25 bits, and data is transmitted at 270.833 kbps in each time slot. The time duration of a frame is T_f = 156.25 ms, and the time duration of a slot is T_s = 66.67 ms.

Efficiency of frame is defined as the percentage of data bits to the total frame size in bits.

- Each frame contains header bits and data bits.
- Efficiency of frame is defined as the percentage of data bits to the total frame size in bits.

\[ \eta = \frac{n_d}{T_f R} \times 100\% \]

where n_d is the number of data bits in a frame, and R is the total number of bits in a frame.

Example 9.5

A frame has 8 x 156.25 = 1250 bits/frame.

The number of overhead bits per frame, 26 training bits, and 2 traffic bursts of 88 bits of data, find the frame efficiency.

\[ \eta = \left[ 1 - \left( \frac{26 + 88}{1250} \right) \right] \times 100 = 74.24\% \]
Spread Spectrum Multiple Access (SSMA)

- Uses signals which have a B.W that is several orders of magnitude greater than the minimum required RF B.W.
- Pseudo-noise sequence converts narrowband signal into a wideband noise-like signal.
- Not very bandwidth efficient when used by a single user, but many users can share the channel.
- Two main types: frequency hopped multiple access (FH) and direct sequence multiple access (also called CDMA).

Frequency hopped multiple access (FHMA)

Frequency hopped multiple access

- Allow multiple users to occupy the same spectrum at the same time.
- Each user has a different PN code.
- In the FH receiver, a locally generated PN code is used to synchronize the receiver frequency with that of the transmitter.
- Provides a good level of security.
- Example: Bluetooth.

Code division multiple access (CDMA)

- The narrow band message signal is multiplied by a very large bandwidth signal called spreading signal.
- Each user has a sequence which is approximately orthogonal to the other users.
- The receiver perform a time correlation with the received signal.
- All the other signals appear as a noise.
- Near-far problem in CDMA → power control is needed.
CDMA Features

- Many users share the same frequency, TDD or FDD can be used.
- Unlike FDMA and TDMA, there is no absolute limit on the number of users. → CDMA has soft capacity
- The multipath fading is reduced due to the large B.W.
- Soft handoff is supported as the frequency reuse is 1.

Hybrid Spread Spectrum Techniques

- Hybrid FDMA/CDMA (FCDMA): The available spectrum is divided into a number of subspectrums with smaller B.W. Each one is a narrowband CDMA.

Hybrid Spread Spectrum Techniques (2)

- Hybrid Direct sequence/frequency hopped multiple access (DS/FHMA): the center frequency is made to hop periodically.
  - They avoid near-far effect.
  - Not adaptable to the soft handoff due to synchronization difficulty.

Hybrid Spread Spectrum Techniques (3)

- Time Division CDMA (TCDMA):
  - Different spreading codes are assigned to different cells.
  - In the cell, only one user can transmit at a given time slot using the assigned code.
  - The spreading code should be changed after the handoff.
  - Avoid near-far effect as only one user transmit to the BS.
Hybrid Spread Spectrum Techniques (4)

- Time division frequency hopping (TDFH): the subscriber can hop to a new frequency at the start of new TDMA frame.
  - Avoid severe fade in a particular channel.
  - Avoid co-channel interference as two adjacent base stations are transmitting at different frequencies at different times.
  - Used in GSM.

Space Division Multiple Access (SDMA)

- Uses direction (angle) as another dimension in signal space, which can be channelized and assigned to different users.
- Generally done with directional antennas.
- Orthogonal channels can only be assigned if the angular separation between users exceeds the angular resolution of the directional antenna.
- In practice SDMA is often implemented using sectorized antenna arrays.
  - The 360° angular range is divided into \( N \) sectors.
  - High directional gain in each sector and little interference between sectors.
  - TDMA or FDMA is used to channelize users within a sector.

Space Division Multiple Access (SDMA)

In the next lecture

- We will cover Random Access techniques.
Wireless Communications

Chapter 9: Multiple Access Techniques for Wireless Communications

Outline

- Random Access
  - Pure ALOHA.
  - Slotted ALOHA.
- Carrier Sense Multiple Access.
- Scheduling.
- Packet Reservation Multiple Access (PRMA).

Random Access

- Most of data users do not require continuous transmission (bursty transmission).
- Most of the systems have many more total users (active plus idle users) than what can be accommodated simultaneously.
- Random access strategies are used in such systems to efficiently assign channels to the active users.
- All random access techniques are based on the packetized data or packet radio.

Packet Radio

- In packet radio user data is collected into packets of $N$ bits, and once a packet is formed it is transmitted over the channel.
- The transmission time of a packet is $T = \frac{N}{R}$ where $R$ is channel data rate (bps).
- All users transmit their packets over the entire bandwidth.
- No additional coding to allow separation of simultaneously transmitted packets if packets from different users overlap in time a collision occurs.

$T \rightarrow $ packet time
$N \rightarrow $ number of packets in one
Modeling of random access

- **Typical Assumption**: the users accessing the channel generate packets according to a Poisson process at a rate of $\lambda$ packets per unit time.
- **I.o.w.**, $\lambda$ is the average number of packets that arrive in any time interval [0, $t$] divided by $t$ (Arrival rate).
- Equivalently: $\lambda N$ is the average number of bits generated in any time interval [0, $t$] divided by $t$.

**Poisson process**

- For a Poisson process, the probability that the number of packet arrivals in a time period [0, $t$], denoted as $X(t)$, is equal to some integer $k$ is given by:

$$P(X(t) = k) = \frac{(\lambda t)^k e^{-\lambda t}}{k!}$$

- Poisson processes are memoryless.
- The number of packet arrivals during any given time period does not affect the distribution of packet arrivals in any other time period.

**Performance of random access**

- Typically characterized by the **throughput** $T$ of the system.
- The throughput (unitless): the ratio of the average number of packets successfully transmitted in any given time interval divided by the number of attempted transmissions in that interval.
- The throughput thus equals the offered load multiplied by the probability of successful packet reception.
- The probability is a function of the random access protocol in use as well as the channel characteristics.
- In stable systems, $T \leq L \leq 1$. 

**Poisson process (2)**

- The traffic load is defined as $L = \lambda t = \lambda / R_p$. Where $R_p$ is the number of sent packets per second and $t$ is the time required to send one packet.
- $L$ is unitless → relates the packets arrival rate with the transmission rate.
- If $L > 1 \rightarrow$ then on average more packets (or bits) arrive in the system over a given time period than can be transmitted in that period.
- If $L > 1 \rightarrow$ system is unstable.
- If the packets received in error and retransmission is require → $L$ referred to total offered load (new arrival + packets that require retransmission). 

**Packet arrival**

- User can access the system at any time
- User generate packet according to Poisson process with rate of $\lambda$
Performance of random access (2)

- For a packet radio with a link data rate of $R$ bps, the effective data rate of the system is $RT$.
- $T$ is the fraction of packets or bits successfully transmitted at rate $R$.
- The goal of a random access method is to make $T$ as large as possible.
- In some circumstances overlapping packets do not cause a collision (capture effect):
  - short periods of overlap between colliding packets.
  - different channel gains on the received packets.
  - error correction coding can allow one or more packets to be successfully received even with a collision.

Pure (unslotted) ALOHA

- Users transmit data packets as soon as they are formed.
- Neglect the capture effect, then packets that overlap in time are assumed to be received in error, and must be retransmitted.
- Assume packets that do not collide are successfully received.
- The throughput equals the offered load times the probability of no collisions: $T = Lp$ (no collisions).

Pure (unslotted) ALOHA (2)

- Suppose a given user transmits a packet of duration $\tau$ during time $[0, \tau]$.
- Then if any other user generates a packet during time $[-\tau, \tau]$, that packet, of duration $\tau$, will overlap with the transmitted packet, causing a collision.
- The probability that no packets are generated during the time $[-\tau, \tau]$ with $t = 2\tau$ is given by:
  \[ P(X(t) = 0) = e^{-2\lambda t} = e^{-2L} \]
  with corresponding throughput
  \[ T = Le^{-2L} \]
Slotted ALOHA

In pure ALOHA, users can start their packet transmissions at any time → any partial overlap of two or more packets destroys the successful reception of all packets.

- The partial overlap of packet transmissions can be avoided by synchronizing the users.
- In slotted ALOHA, time is assumed to be slotted in timeslots of duration $\tau$.
- Users can only start their packet transmissions at the beginning of the next timeslot after the packet has formed.

A packet transmitted over the time period $[0, \tau]$ is successfully received if no other packets are transmitted during this period.

- The probability that no packets are generated during the time $[0, \tau]$ with $t = \tau$ is given by:
  \[ P(X(\tau) = 0) = e^{-\lambda \tau} = e^{-L} \]
- with corresponding throughput
  \[ T = L e^{-L} \]

Carrier Sense Multiple Access (CSMA)

- Users sense the channel and delay the transmission if they detect that another user is currently transmitting.
- To be effective, detection time and propagation delays in the system must be small.
- **Random backoff**: a user waits to transmit a random time period after sensing a busy channel.
- This avoids multiple users simultaneously transmitting as soon as the channel is free.
- CSMA is part of the Ethernet protocol (all users can detect each other's transmissions and the propagation delays are small).
CSMA (2)

- The nature of the wireless channel may prevent a given user from detecting the signals transmitted by all other users.
- **Hidden terminal problem**: where each node can hear its immediate neighbor but no other nodes in the network.
- **Hidden terminal problem** can be solved by several techniques (handshaking, busy tone, hybrid of both).

Hidden terminal problem (2)

- **Solution (1-collision avoidance)**
  - A node that wants to send a data packet will first wait for the channel to become available and then transmit a short RTS (Request To Send) packet.
  - The potential receiver, assuming it perceives an available channel, will immediately respond with a CTS (Clear To Send) packet that authorizes the initiating node to transmit.
  - Also informs neighboring hidden nodes (i.e., nodes that are outside the communication range of the transmitter but within the communication range of the receiver) that they will have to remain silent for the duration of the transmission.
  - The RTS/CTS handshake is typically coupled with random backoff to avoid all nodes transmitting as soon as the channel becomes available.
  - The receiver could send an ACK packet back to verify when it has correctly received the packet.

Hidden terminal problem (3)

- **Solution (2-busy tone transmission)**
  - Users first check to see whether the transmit channel is busy by listening for a “busy tone” on a separate control channel (bit is set in a predetermined field on the control channel).
  - This scheme works well in preventing collisions when a centralized controller can be “heard” by users throughout the network.
packet reservation multiple access (PRMA)

- Assumes a slotted system with both continuous and bursty users (e.g., voice and data users).
- Multiple users compete for a given timeslot under a random access strategy.
- A successful transmission by one user in a given timeslot reserves that timeslot for all subsequent transmissions by the same user.
- If the user has a continuous or long transmission then after successfully capturing the channel he has a dedicated channel for the remainder of his transmission.
- When this user has no more packets to transmit, the slot is returned to the pool of available slots.

Next lecture

- Capacity of Cellular Systems.
Introduction

- What is the basic idea of multicarrier modulation?
  - Divide the transmitted bitstream into many different substreams and send these over many different subchannels.
  - Typically the subchannels are orthogonal.
  - The data rate on each of the subchannels is much less than the total data rate, and the corresponding subchannel bandwidth is much less than the total system bandwidth.

Wireless Communications

Multicarrier Modulation

Outline

- Introduction
- Data Transmission using Multiple Carriers.
- Multicarrier Modulation with Overlapping Subchannels.
- Mitigation of Subcarrier Fading
  - Coding with Interleaving over Time and Frequency.
  - Frequency Equalization.
  - Precoding
  - Adaptive Loading
- Discrete Implementation of Multicarrier
  - The Cyclic Prefix,
  - Orthogonal Frequency Division Multiplexing (OFDM).
- Challenges in Multicarrier Systems
  - Peak to Average Power Ratio.
  - Frequency Offset.
- Case Study: The IEEE 802.11a Wireless LAN Standard.

Introduction (2)

- How the number of streams is chosen?
  - Should ensure that each subchannel has a bandwidth less than the coherence bandwidth of the channel (Flat Fading → Small ISI).
- Subchannels not contiguous → no need for large continuous block of spectrum (High rate)
- Multicarrier modulation is efficiently implemented digitally → Spread reason (not new tech. since 1950-1960).
Introduction (3)

- Digital Television
  - European and Australian standard.
- Wireless Local Area Networks (LANs)
  - IEEE 802.11 and Hiperlan/2.
- ADSL (asymmetric digital subscriber loop)
- UWB.
- 4G cellular standards (Wimax and LTE).

Introduction (4)

- Problems:
  - frequency offset degrades the orthogonally of the subchannels.
  - The peak-to-average power ratio (PAPR) which is a serious problem when nonlinear amplifiers are used.
- Most emerging high rate wireless systems use either multicarrier modulation or spread spectrum instead of equalization to compensate for ISI.

Data Transmission using Multiple Carriers

- Coherence bandwidth (Bc)
- a statistical measurement of the range of frequencies over which the channel can be considered "flat".
- Delay Spread (Tm):
  - the difference between the time of arrival of the earliest significant multipath component (typically the line-of-sight component) and the time of arrival of the latest multipath component.

Data Transmission using Multiple Carriers (2)

- Stream with Rate R and bandwidth B.
- Bc < B → Frequency selective.
- Divide into N channels \( Bn = B/N \ll Bc \) and \( Rn = R/N \).
- In time domain, symbol time \( Tn = 1/Bn \) \( Tm = 1/Bc \) ISI is reduced with N sufficiently large.
- \( Tn \): Symbol time in each subchannel.
Data Transmission using Multiple Carriers

- Disadvantages of this scheme:
  - The roll off of the raised cosine filter will increase the total BW (spectrally inefficient).
  - This scheme requires N independent modulators and demodulators, which entails significant expense, size, and power consumption.

Example: Consider a multicarrier system with a total passband bandwidth of 1 MHz. Suppose the system operates in a city with channel delay spread $T_d = 200\mu s$. How many subchannels are needed to achieve approximately flat-fading in each subchannel.

Solution: The channel coherence bandwidth is $B_c = 1/T_d = 1/0.2 = 5$ kHz. To insure flat-fading on each subchannel, we take $B_s = B_c/N < 1/2$. Thus, $N = (700000)/5000 = 200$ subchannels are needed to insure flat-fading on each subchannel. In discrete implementations of multicarriers, $N$ must be a power of two for the DFT and IDFT operations, in which case $N = 256$ for this set of parameters.
Multicarrier Modulation with Overlapping Subchannels

- The following set:
  \[ \{ g(t) \cos(2\pi(f_n + i/T_N) t - \phi_i), i = 0, 1, \ldots, N - 1 \} \]

- form a set of orthogonal basis functions on the interval \([0, T_N]\) for any set of subcarrier phase offsets.
- \(g(t)\): the family of raised cosine pulses are a common choice for this pulse shape.
- Given this orthonormal basis set, even if the subchannels overlap, the modulated signals transmitted in each subchannel can be separated out in the receiver.

Multicarrier Modulation with Overlapping Subchannels (2)

Mitigation of Subcarrier Fading

- Each subchannel experiences flat-fading, which can cause large BERs on some of the subchannels.
- The received SNR \( \gamma = \frac{\alpha^2 P_t}{(N_0 B_N)} \)
- Quite low SNR \(\rightarrow\) High BER on that channel.
- Flat fading can seriously degrade performance in each subchannel.
- It is important to compensate for flat fading in the subchannels.
Mitigation of Subcarrier Fading (2)

- Coding with Interleaving over Time and Frequency
  - encode data bits into codewords.
  - interleave the resulting coded bits over both time and frequency.
  - transmit the coded bits over different subchannels.
  - coded bits within a given codeword all experience independent fading.
  - if most of the subchannels have a high SNR, the codeword will have most coded bits received correctly, and the errors associated with the few bad subchannels can be corrected.

Mitigation of Subcarrier Fading (3)

- Frequency Equalization:
  - flat fading \( a_i^2 \) on the \( i \)th subchannel is basically inverted in the receiver.
  - the received signal is multiplied by \( 1/a_i^2 \), which gives a resultant signal power \( a_i^2 Pi/a_i^2 = Pi \).
  - removes the impact of flat fading on the signal.
  - it enhances the noise.
  - frequency equalization does not really change the performance degradation associated with subcarrier flat fading.

Mitigation of Subcarrier Fading (4)

- Precoding: 
  - uses the same idea as frequency equalization.
  - fading is inverted at the transmitter instead of the receiver.
  - the power transmitted in the \( i \)th subchannel is \( Pi/a_i^2 \).
  - needs correct information and requires infinite power.

Adaptive Loading

- The basic idea is to vary the data rate and power assigned to each subchannel relative to that subchannel gain.

Discrete Implementation of Multicarrier (1)

The Cyclic Prefix:

- input sequence \( x[n] = x[0], \ldots, x[N-1] \) of length \( N \).
- discrete-time channel with (FIR) \( h[n] = h[0], \ldots, h[\mu] \) of length \( \mu + 1 = T_m/T_s \).

\[ x[n] = [x[n-M], x[n-M+1], \ldots, x[n-1], x[0], \ldots, x[N-1]] \]

Append last \( M \) symbols to beginning.

Cyclic Prefix of Length \( \mu \).
Discrete Implementation of Multicarrier (2)

- The cyclic prefix eliminates ISI between the data blocks since the first \( \mu \) samples of the channel output affected by this ISI can be discarded without any loss relative to the original information sequence.

- Equivalent to using a guard band of duration \( T_m \) (the channel delay spread) after every block of \( N \) symbols of duration \( NT_s \) to eliminate the ISI between these data blocks.

Discrete Implementation of Multicarrier (3)

[Diagram of cyclic prefix and data block]

ISI Between Data Blocks in Channel Output.

- \( \mu \) symbols are added to the input data blocks \( \rightarrow \) there is an overhead.
  
  Waste of the transmitted power.

- In zero-Prefix, no power is used in transmitting the prefix, \( C_P = \frac{\mu P}{T_s} \).

Discrete Implementation of Multicarrier (4)

Example: Consider an OFDM system with total pass-bandwidth \( B = 1 \) MHz assuming \( \sigma = \sigma_t \).
A single-carrier system would have symbol time \( T_s = 1 \) ns, \( T_{m} = 10 \) ns, the channel delay spread.

Solution: The subchannel bandwidth \( B_N = \frac{B}{N} \) kHz, so \( B_N < \frac{B}{N} \) kHz assuming negligible ISI. The total transmission time for each OFDM symbol is \( T_X = \frac{T_s}{N} \) which is roughly \( 1.5 \) ns. The overhead associated with the cyclic prefix is \( 5 \) symbols, which is roughly \( 7.5 \)%. The system transmits \( \frac{N-\mu}{N} = 4 \) bits/symbol every \( f \) seconds, so the data rate is \( \frac{N-\mu}{N} \times 10^{11} = 3.5 \) Mbps, which is slightly less than \( 3.5 \) Mbps due to the cyclic prefix overhead.

Orthogonal Frequency Division Multiplexing (OFDM)

[Diagram of OFDM system]
Challenges in Multicarrier Systems

- **Peak to Average Power Ratio:**
  - in the time domain, a multicarrier signal is the sum of many narrowband signals. At some time instances, this sum is large and at other times is small, which means that the peak value of the signal is substantially larger than the average value.
  - This high PAPR is one of the most important implementation challenges that face OFDM, because it reduces the efficiency and hence increases the cost of the RF power amplifier, which is one of the most expensive components in the radio.

- The maximum PAPR is $N$ for $N$ subcarriers.
- PAPR increases approximately linearly with the number of subcarriers.
- a large PAPR is an important penalty that must be paid for large $N$.
- There are several techniques to reduce PAPR.
Challenges in Multicarrier Systems (4)

- Frequency Offset
- Imperfect Frequency Separation: mismatched oscillators, Doppler frequency shifts, or timing synchronization

Challenges in Multicarrier Systems (5)

- The total ICI power on subcarrier $i$ is
  \[ ICI_i = \sum_{n \neq n_i} |h_{ni}|^2 \approx C_n(T_N \delta)^2. \]
- Direct relation between $T_n$ and ICI and also $\delta$.
- Relation with $N$?
- Considering ICI and PAR, $N$ should be as low as possible.

Case Study: The IEEE 802.11a Wireless LAN Standard

- $BW=20\text{MHz}$,
- Samples=$64(48\text{symbols} + 12\text{zeros} + 4\text{pilots}) + 16\text{CP}$,
- $P=80$.
- The error correction code is a convolutional code with one of three possible coding rates: $r=1/2, 2/3, 3/4$.
- Modulation types: BPSK, QPSK, 16QAM, or 64QAM.

WLAN (2)

- the subcarrier bandwidth
  \[ B_N = \frac{20\text{MHz}}{64} = 312.5\text{KHz}. \]
- the maximum delay spread
  \[ T_m = \mu T_s = \frac{16}{20\text{MHz}} = 0.8\ \mu\text{sec}. \]
- the symbol time per subchannel
  \[ T_N = \frac{80}{20 \times 10^6} = 0.4 \mu\text{s}. \]

The rest are used as pilots

The symbol rate is

- $B_{min} = 6\text{subcarriers} \times \frac{1}{2}\text{bit} = 3\text{bit/sec}$
- $B_{max} = 18\text{subcarriers} \times \frac{3}{4}\text{bit} = 12\text{bit/sec}$
- 1 subcarrier symbol $= 1 \times 10^{-6}\text{seconds}$
- 1 subcarrier symbol $= 2.1\text{Mbits}$