UNIT – I WIRELESS TRANSMISSION FUNDAMENTALS

Introduction to wireless transmission – signal propagation – Multiplexing-Modulation-Spread Spectrum-Fading-Coding and Error control.

Applications of Wireless Networks and Mobile Communications

- Vehicles
  - transmission of news, road condition, weather, music via DAB
  - personal communication using GSM
  - position via GPS
  - local ad-hoc network with vehicles close-by to prevent accidents, guidance system, redundancy
  - vehicle data (e.g., from busses, high-speed trains) can be transmitted in advance for maintenance

- Emergencies
  - early transmission of patient data to the hospital, current status, first diagnosis
  - replacement of a fixed infrastructure in case of earthquakes, hurricanes, fire etc.
  - crisis, war, ...

- Business - Travelling salesmen
  - direct access to customer files stored in a central location
  - consistent databases for all agents
  - mobile office

- Replacement of fixed networks
  - remote sensors, e.g., weather, earth activities
  - flexibility for trade shows
  - LANs in historic buildings

- Entertainment, education, ...
  - outdoor Internet access
  - intelligent travel guide with up-to-date location dependent information
  - ad-hoc networks for multi user games

- Location dependent services
  - Location aware services
    - what services, e.g., printer, fax, phone, server etc. exist in the local environment
  - Follow-on services
    - automatic call-forwarding, transmission of the actual workspace to the current location
  - Information services
    - „push“: e.g., current special offers in the supermarket
    - „pull“: e.g., where is the Black Forrest Cherry Cake?
  - Support services
    - caches, intermediate results, state information etc.
  - Privacy
    - who should gain knowledge about the location

Effects of device portability

- Power consumption
  - limited computing power, low quality displays, small disks due to limited battery capacity
  - CPU: power consumption \( \sim CV^2f \)
    - C: internal capacity, reduced by integration
    - V: supply voltage, can be reduced to a certain limit
    - f: clock frequency, can be reduced temporarily

- Loss of data
  - higher probability, has to be included in advance into the design (e.g., defects, theft)

- Limited user interfaces
  - compromise between size of fingers and portability
  - integration of character/voice recognition, abstract symbols

- Limited memory
  - limited value of mass memories with moving parts, flash-memory or as alternative
Wireless networks in comparison to fixed networks

- Higher loss-rates due to interference
  - emissions of, e.g., engines, lightning
- Restrictive regulations of frequencies
  - frequencies have to be coordinated, useful frequencies are almost all occupied
- Low transmission rates
  - local some Mbit/s, regional currently, e.g., 9.6kbit/s with GSM
- Higher delays, higher jitter
  - connection setup time with GSM in the second range,
  - several hundred milliseconds for other wireless systems
- Lower security, simpler active attacking
  - radio interface accessible for everyone, base station can be simulated
- Always shared medium
  - secure access mechanisms important

A SIMPLIFIED REFERENCE MODEL

<table>
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<th>Layer</th>
<th>Functions</th>
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<td>Application</td>
<td>service location</td>
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<td></td>
<td>new applications, multimedia</td>
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<td>adaptive applications</td>
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<td>Transport</td>
<td>congestion and flow control</td>
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<td></td>
<td>quality of service</td>
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<tr>
<td>Network</td>
<td>addressing, routing, device location</td>
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<td>hand-over</td>
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<td>Datalink</td>
<td>authentication, media access</td>
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<td>multiplexing, media access control</td>
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<tr>
<td>Physical</td>
<td>encryption, modulation, interference</td>
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<td></td>
<td>attenuation, frequency</td>
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Introduction to wireless transmission

Frequencies for radio transmission

- Radio transmission can take place using many different frequency bands.
- Each frequency band exhibits certain advantages and disadvantages

Frequency spectrum

- Frequency and wave length: \( \lambda = \frac{c}{f} \)
  - where wave length \( \lambda \), speed of light \( c \approx 3 \times 10^8 \text{m/s} \), frequency \( f \)
- VHF-/UHF-ranges for mobile radio
  - simple, small antenna for cars
  - deterministic propagation characteristics, reliable connections
- SHF and higher for directed radio links, satellite communication
  - small antenna, focusing
  - large bandwidth available
- Wireless LANs use frequencies in UHF to SHF spectrum
  - some systems planned up to EHF
  - limitations due to absorption by water and oxygen molecules (resonance frequencies)
    - weather dependent fading, signal loss caused by heavy rainfall etc

Frequencies and regulations

<table>
<thead>
<tr>
<th>Mobile phones</th>
<th>Europe</th>
<th>USA</th>
<th>Japan</th>
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<tbody>
<tr>
<td></td>
<td>NMT 453-457MHz, 463-467 MHz;</td>
<td>AMPS, TDMA, CDMA 824-849 MHz, 869-894 MHz;</td>
<td>PDC 810-826 MHz, 940-956 MHz;</td>
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<tr>
<td></td>
<td>GSM 890-915 MHz, 935-960 MHz;</td>
<td>TDMA, CDMA, GSM 1850-1910 MHz, 1930-1990 MHz;</td>
<td>1429-1465 MHz, 1477-1513 MHz</td>
</tr>
<tr>
<td></td>
<td>1710-1785 MHz, 1805-1880 MHz</td>
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<tr>
<td>Cordless</td>
<td>CT1+ 885-887 MHz, 930-932 MHz;</td>
<td>PACS 1850-1910 MHz, 1930-1990 MHz;</td>
<td>PHS 1895-1918 MHz</td>
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<tr>
<td>telephones</td>
<td>CT2 864-868 MHz;</td>
<td>PACS-UB 1910-1930 MHz</td>
<td>JCT 254-380 MHz</td>
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<tr>
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<td>DECT 1880-1900 MHz</td>
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<td>Wireless</td>
<td>IEEE 802.11 2400-2483 MHz</td>
<td>IEEE 802.11 2400-2483 MHz</td>
<td>IEEE 802.11</td>
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<td>LANs</td>
<td>HIPERLAN 1 5176-5270 MHz</td>
<td></td>
<td>2471-2497 MHz</td>
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Signals

- physical representation of data
- function of time and location
- signal parameters: parameters representing the value of data
- classification
  - continuous time/discrete time
• continuous values/discrete values
• analog signal = continuous time and continuous values
• digital signal = discrete time and discrete values

• signal parameters of periodic signals:
  o period T,
  o frequency f=1/T,
  o amplitude A,
  o phase shift φ

• sine wave as special periodic signal for a carrier: \( g(t) = A_t \sin(2\pi f t + \phi) \)

• it is possible to construct every periodic signal g by using only sine and cosine functions according to a fundamental equation of Fourier

\[
g(t) = \frac{1}{2} c + \sum_{n=1}^{\infty} a_n \sin(2\pi nft) + \sum_{n=1}^{\infty} b_n \cos(2\pi nft)
\]

• parameter c determines the Direct Current (DC) component of the signal,
• the coefficients \( a_n \) and \( b_n \) are the amplitudes of the \( n^{th} \) sine and cosine function.

**Different representations of signals**

• amplitude (amplitude domain)
• frequency spectrum (frequency domain)
• phase state diagram (amplitude M and phase ϕ in polar coordinates)

<table>
<thead>
<tr>
<th>Time domain</th>
<th>Frequency domain</th>
<th>Phase domain</th>
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<tbody>
<tr>
<td><img src="image1.png" alt="Time domain" /></td>
<td><img src="image2.png" alt="Frequency domain" /></td>
<td><img src="image3.png" alt="Phase domain" /></td>
</tr>
</tbody>
</table>

• Composed signals transferred into frequency domain using Fourier transformation
• Digital signals need
  o infinite frequencies for perfect transmission
  o modulation with a carrier frequency for transmission (analog signal!)
Antennas

- Radiation and reception of electromagnetic waves, coupling of wires to space for radio transmission
- Isotropic radiator equal radiation in all directions (three dimensional) - only a theoretical reference antenna
- Real antennas always have directive effects (vertically and/or horizontally)
- Radiation pattern: measurement of radiation around an antenna

Radiation pattern of an isotropic radiator

Simple Dipoles

- Real antennas are not isotropic radiators
- dipoles with lengths $\lambda/4$ on car roofs or $\lambda/2$ as Hertzian dipole
- shape of antenna proportional to wavelength
- thin, center-fed dipole, also called Hertzian dipole,
- The dipole consists of two collinear conductors of equal length, separated by a small feeding gap.
- The length of the dipole is not arbitrary, example,
  - half the wavelength $\lambda$ of the signal to transmit results in a very efficient radiation of the energy
  - If mounted on the roof of a car, the length of $\lambda/4$ is efficient.
- This is also known as Marconi antenna

Radiation pattern of a simple dipole

- A $\lambda/2$ dipole has a uniform or omni-directional radiation pattern in one plane and a figure eight pattern in the other two planes
- Gain: maximum power in the direction of the main lobe compared to the power of an isotropic radiator (with the same average power)
- can only overcome environmental challenges by boosting the power level of the signal.
- Challenges could be mountains, valleys, buildings etc.
- If an antenna is positioned, in a valley or between buildings, an omnidirectional radiation pattern is not very useful
Directional antennas

- Certain fixed preferential transmission and reception directions can be used.
- Main lobe in the direction of the x-axis
- Often used for microwave connections or base stations for mobile phones (e.g., radio coverage of a valley)

Radiation pattern of a directed antenna

- Main lobe in the direction of the x-axis

Sectorized antenna

- Several directed antennas can be combined on a single pole
- A cell can be sectorized into, for example, three or six sectors, thus enabling frequency reuse

Radiation patterns of sectorized antennas

- Top view, 3 sector
- Top view, 6 sector

Multi-element antenna arrays

- Two or more antennas can also be combined to improve reception by counteracting the negative effects of multi-path propagation
- Allow different diversity schemes
  - Switched diversity, selection diversity
    - Receiver chooses antenna with largest output
  - Diversity combining
    - Combine output power to produce gain
    - Cophasing needed to avoid cancellation

Smart Antennas

- Combine multiple antenna elements (also called antenna array) with signal processing to optimize the radiation/reception pattern in response to the signal environment.
- These antennas can adapt to changes in reception power, transmission conditions and many signal propagation effects
Signal propagation

Signal propagation ranges

- Transmission range
  - communication possible
  - low error rate
- Detection range
  - detection of the signal possible
  - no communication possible
- Interference range
  - signal may not be detected
  - signal adds to the background noise

Signal Propagation Behaviors

- Radio waves can exhibit three fundamental propagation behaviors
- Ground wave (<2 MHz)
  - Waves with low frequencies follow the earth’s surface and can propagate long distances.
  - These waves are used for, e.g., submarine communication or AM radio.
- Sky wave (2–30 MHz)
  - Many international broadcasts and amateur radio use these short waves that are reflected at the ionosphere
  - This way the waves can bounce back and forth between the ionosphere and the earth’s surface, travelling around the world.
- Line-of-sight (>30 MHz)
  - Mobile phone systems, satellite systems, cordless telephones etc. use even higher frequencies.
  - The emitted waves follow a (more or less) straight line of sight.

Path loss of radio signals

- If a straight line exists between a sender and a receiver it is called line-of-sight (LOS).
- Even if no matter exists between the sender and the receiver (i.e., if there is a vacuum), the signal still experiences the free space loss.
- Propagation in free space always like light (straight line)
- Receiving power proportional to $1/d^2$  
  ($d =$ distance between sender and receiver, inverse square law)

Additional signal propagation effects

- Rx power additionally influenced by
  - fading (frequency dependent)
  - shadowing
  - reflection at large obstacles
  - scattering at small obstacles
  - diffraction at edges

Scattering  Diffraction  Refraction  Reflection  Shadowing
Multi-path propagation

- Signal can take many different paths between sender and receiver due to reflection, scattering, diffraction
- Due to the finite speed of light, signals travelling along different paths with different lengths arrive at the receiver at different times.
- This effect (caused by multi-path propagation) is called delay spread: the original signal is spread due to different delays of parts of the signal.
- Typical values for delay spread are approximately 3 μs in cities, up to 12 μs can be observed. GSM, for example, can tolerate up to 16 μs of delay spread, i.e., almost a 5 km path difference

Multi-path propagation and intersymbol interference

Intersymbol interference (ISI)

- an effect, where the energy intended for one symbol now spills over to the adjacent symbol
- sender may first transmit a training sequence known by the receiver.
- The receiver then compares the received signal to the original training sequence and programs an equalizer that compensates for the distortion

Effects of mobility: Fading

Short-term fading

- receivers, or senders, or both, move.
- channel characteristics change over time
- quick changes in the received power

Long-term fading

- average power over time
- caused by, for example, varying distance to the sender or more remote obstacles
- senders can compensate for long-term fading by increasing/decreasing sending power

Doppler shift

- caused by a moving sender or receiver.
Multiplexing

- Multiplexing describes how several users can share a medium with minimum or no interference
- Important: guard spaces needed
- Multiplexing in 4 dimensions
  - space ($s_1$)
  - time ($t$)
  - frequency ($f$)
  - code ($c$)

Space Division Multiplexing

- separate sender for each communication channel with a wide enough distance between senders
- The channels $k_1$ to $k_3$ can be mapped onto the three ‘spaces’ $s_1$ to $s_3$ which clearly separate the channels and prevent the interference ranges from overlapping.
- The space between the interference ranges is sometimes called guard space
- For the remaining channels ($k_4$ to $k_6$) three additional spaces would be needed
- FM radio stations where the transmission range is limited to a certain region
- problems arise if two or more channels were established within the same space

Frequency Division Multiplexing

- Separation of the whole spectrum into smaller frequency bands
- A channel gets a certain band of the spectrum for the whole time
- Advantages:
  - no dynamic coordination necessary
  - works also for analog signals
- Disadvantages:
  - waste of bandwidth if the traffic is distributed unevenly
  - inflexible
  - guard spaces

Time Division Multiplexing

- A channel gets the whole spectrum for a certain amount of time
- Advantages:
  - only one carrier in the medium at any time
  - throughput high even for many users
- Disadvantages:
  - precise synchronization necessary
Time and Frequency Multiplexing

- Combination of both methods
- A channel gets a certain frequency band for a certain amount of time
- Example: GSM
- Advantages:
  - better protection against tapping
  - protection against frequency selective interference
  - higher data rates compared to code multiplex
- but: precise coordination required

Code Division Multiplexing

- Each channel has a unique code
- All channels use the same spectrum at the same time
- Advantages:
  - bandwidth efficient
  - no coordination and synchronization necessary
  - good protection against interference and tapping
- Disadvantages:
  - lower user data rates
  - more complex signal regeneration
  - Implemented using spread spectrum technology

Modulation

- Digital modulation
  - digital data is translated into an analog signal (baseband)
  - ASK, FSK, PSK
  - differences in spectral efficiency, power efficiency, robustness
- Analog modulation
  - shifts center frequency of baseband signal up to the radio carrier
- Motivation
  - smaller antennas (e.g., λ/4)
  - Frequency Division Multiplexing
  - medium characteristics
- Basic schemes
  - Amplitude Modulation (AM)
  - Frequency Modulation (FM)
  - Phase Modulation (PM)

Modulation and Demodulation

Modulation in a transmitter
Amplitude shift keying
- The two binary values, 1 and 0, are represented by two different amplitudes
- very simple
- low bandwidth requirements
- very susceptible to interference

Frequency shift keying
- The simplest form of FSK, also called binary FSK (BFSK)
- assigns one frequency $f_1$ to the binary 1 and another frequency $f_2$ to the binary 0.
- needs larger bandwidth
- To avoid sudden changes in phase, special frequency modulators with continuous phase modulation, (CPM) can be used
- demodulation is by using two bandpass filters
- A comparator can then compare the signal levels of the filter outputs to decide which of them is stronger

Phase shift keying
- uses shifts in the phase of a signal to represent data.
- phase shift of 180° or $\pi$ as the 0 follows the 1 (the same happens as the 1 follows the 0).
- Binary PSK (BPSK).
  - shifting the phase by 180° each time the value of data changes
- receiver must synchronize in frequency and phase with the transmitter using a phase lock loop (PLL).

Advanced frequency shift keying
Minimum shift keying (MSK)
- MSK is basically BFSK without abrupt phase changes
- Steps
  - bit separated into even and odd bits,
  - the duration of each bit is doubled
  - depending on the bit values (even, odd) the higher or lower frequency, original or inverted is chosen
- Detailed
  - data bits are separated into even and odd bits,
the duration of each bit being doubled.

- uses two frequencies: \( f_1 \), the lower frequency, and \( f_2 \), the higher frequency, with \( f_2 = 2f_1 \).
- if the even and the odd bit are both 0, then the higher frequency \( f_2 \) is inverted (i.e., \( f_2 \) is used with a phase shift of 180°);
- if the even bit is 1, the odd bit 0, then the lower frequency \( f_1 \) is inverted.

**Gaussian MSK (GMSK),**

- Adding a Gaussian lowpass filter to the MSK scheme
- digital modulation scheme for many European wireless standards
- The filter reduces the large spectrum needed by MSK

**Advanced phase shift keying**

**BPSK (Binary Phase Shift Keying):**

- bit value 0: sine wave
- bit value 1: inverted sine wave
- very simple PSK
- low spectral efficiency
- robust, used e.g. in satellite systems

**Quadrature PSK (QPSK)**

- also called Quaternary PSK
- 2 bits coded as one symbol
- symbol determines shift of sine wave
- needs less bandwidth compared to BPSK
- more complex
- higher bit rates can be achieved for the same bandwidth by coding two bits into one phase shift
- can reduce the bandwidth and still achieve the same bit rates as for BPSK.
- The phase shift can always be relative to a reference signal (with the same frequency)
**Differential QPSK (DQPSK)**
- the phase shift is not relative to a reference signal but to the phase of the previous two bits
- the receiver does not need the reference signal but only compares two signals to reconstruct data.
- DQPSK is used in US wireless technologies IS-136 and PACS and in Japanese PHS

**Quadrature amplitude modulation (QAM)**
- PSK scheme could be combined with ASK
- three different amplitudes and 12 angles are combined coding 4 bits per phase/amplitude change
- it is possible to code n bits using one symbol
- $2^n$ discrete levels, n=2 identical to QPSK
- bit error rate increases with n, but less errors compared to comparable PSK schemes
- 16 quadrature amplitude modulation (4 bits = 1 symbol)
  - Symbols 0011 and 0001 have the same phase, but different amplitude
  - 0000 and 1000 have different phase, but same amplitude.
  - used in standard 9600 bit/s modems

**Special modulation schemes**

**Multi-carrier modulation (MCM)**
- good ISI mitigation property
- MCM splits the high bit rate stream into many lower bit rate streams
- each stream being sent using an independent carrier frequency
- physical layer of HiperLAN2 and IEEE 802.11a uses 48 subcarriers for data

**Parallel data transmission on several subcarriers with lower rate**

**Orthogonal frequency division multiplexing (OFDM)**
- Max of one subcarrier frequency appears exactly at a frequency where all other subcarriers equal zero
- method of implementing MCM using orthogonal carriers
- based on fast Fourier transform (FFT) for modulation / demodulation

**Coded OFDM (COFDM)**
- Additional error-control coding across the symbols in different subcarriers is applied
Spread spectrum

- techniques involve spreading the bandwidth needed to transmit data
- Problem of radio transmission
  - frequency dependent fading can wipe out narrow band signals for duration of the interference
- Solution
  - spread the narrow band signal into a broad band signal using a special code
  - protection against narrow band interference
- Adv
  - resistance to narrowband interference

Spread spectrum: spreading and dispreading for single channel

- idealized narrowband signal from a sender of user data (here power density $dP/df$ versus frequency $f$).
- The sender now spreads the signal i.e., converts the narrowband signal into a broadband signal in step ii)
- During transmission, narrowband and broadband interference add to the signal in step iii).
- The sum of interference and user signal is received in iv)
- the receiver applies a bandpass filter to cut off frequencies left and right of the narrowband signal

Spread Spectrum for Multiple Channels

- Narrowband interference without spread spectrum
- Six different channels use FDM for multiplexing
- Between each frequency band a guard space is needed to avoid adjacent channel interference.
- Depending on receiver characteristics, channels 1, 2, 5, and 6 could be received while the quality of channels 3 and 4 is too bad to reconstruct transmitted data.
- Narrowband interference destroys the transmission of channels 3 and 4.

Solution

- All narrowband signals are now spread into broadband signals using the same frequency range.
- To separate different channels, CDM is now used instead of FDM
Direct Sequence Spread Spectrum (DSSS)

- XOR of the signal with pseudo-random number (chipping sequence)
- many chips per bit (e.g., 128) result in higher bandwidth of the signal
- Barker code
- Advantages
  - reduces frequency selective fading
  - in cellular networks
  - base stations can use the same frequency range
  - several base stations can detect and recover the signal
  - soft handover
- Disadvantages
  - precise power control necessary

DSSS transmitter

- a user signal with a bandwidth of 1 MHz.
- Spreading with the above 11-chip Barker code would result in a signal with 11 MHz bandwidth.
- The radio carrier then shifts this signal to the carrier frequency (e.g., 2.4 GHz in the ISM band).
- This signal is then transmitted
DSSS receiver

- first step in the receiver involves demodulating the received signal
- an integrator adds all these products.
- Calculating the products of chips and signal, and adding the products in an integrator is also called correlation, the device a correlator.
- decision unit samples the sums by the integrator and decides if this sum represents a binary 1 or a 0
- A rake receiver uses n correlators for the n strongest paths

**Frequency Hopping Spread Spectrum (FHSS)**

- Total available bandwidth is split into many channels of smaller bandwidth plus guard spaces
- Transmitter and receiver stay on one of these channels for a certain time and then hop to another channel.
- Implements FDM and TDM.
- Pattern of channel usage is called the hopping sequence
- Time spend on a channel with a certain frequency is called the dwell time.
- Discrete changes of carrier frequency
  - sequence of frequency changes determined via pseudo random number sequence
- Two variants
  - Slow: one frequency for several bit periods
  - Fast: changes the frequency several times during the transmission of a single bit.
- Advantages
  - frequency selective fading and interference limited to short period
  - simple implementation
  - uses only small portion of spectrum at any time
- Disadvantages
  - not as robust as DSSS
  - simpler to detect
**FHSS Transmitter**
- Modulation of user data according to one of the digital-to-analog modulation schemes, e.g., FSK or BPSK
- if FSK is used with a frequency $f_0$ for a binary 0 and $f_1$ for a binary
- frequency hopping is performed, based on a hopping sequence
- The hopping sequence is fed into a frequency synthesizer generating the carrier frequencies $f_i$
- A second modulation uses the modulated narrowband signal and the carrier frequency to generate a new spread signal with frequency of $f_i+f_0$ for a 0 and $f_i+f_1$ for a 1 respectively.

![FHSS Transmitter Diagram](image)

**FHSS receiver**
- has to know the hopping sequence and must stay synchronized.
- It then performs the inverse operations of the modulation to reconstruct user data.
- Several filters are also needed

![FHSS Receiver Diagram](image)

**Comparison**
- **DSSS**
  - always use the total bandwidth available
  - more resistant to fading and multi-path effects
  - much harder to detect – without knowing the spreading code, detection is virtually impossible
- **FHSS**
  - spreading is simpler
  - only use a portion of the total band at any time
Cellular systems

- Implements Space Division Multiplexing - SDM
- Each transmitter, typically called a base station, covers a certain area, a cell.
- Mobile stations communicate only via the base station
- Cell sizes from some 100 m in cities to, e.g., 35 km on the country side (GSM) - even less for higher frequencies
- To reduce interference even further sectorized antennas can be used

Frequency Planning

- Frequency reuse only with a certain distance between the base stations
- Standard model using 7 frequencies
- Fixed frequency assignment:
  o certain frequencies are assigned to a certain cell
  o problem: different traffic load in different cells
- Dynamic frequency assignment:
  o base station chooses frequencies depending on the frequencies already used in neighbor cells
  o more capacity in cells with more traffic
  o assignment can also be based on interference measurements

Cellular system with three and seven cell clusters

- Borrowing channel allocation (BCA)
  o Cells with more traffic are dynamically allotted more frequencies
- Fixed channel allocation (FCA)
  o fixed assignment of frequencies to cell clusters and cells respectively
  o FCA is used in the GSM system as it is much simpler to use, but it requires careful traffic analysis before installation.
- Dynamic channel allocation (DCA)
  o Frequencies can only be borrowed, but it is also possible to freely assign frequencies to cells.

Advantages of cell structures:

- higher capacity, higher number of users
- less transmission power needed
- more robust, decentralized
- base station deals with interference, transmission area etc. locally

Problems:

- fixed network needed for the base stations
- handover (changing from one cell to another) necessary
- interference with other cells
  o Frequency planning
Fading

- Fading refers to the time variation of received signal power caused by changes in the medium or path(s)
- In a fixed environment, fading is affected by changes in atmospheric conditions, such as rainfall.
- But in a mobile environment, where one of the two antennas is moving relative to the other, the relative location of various obstacles changes over time, creating complex transmission effects.

Multipath Propagation

- Reflection
  - occurs when a signal is transmitted, some of the signal power may be reflected back to its origin rather than being carried all the way.
- Diffraction
  - The apparent bending of waves around small obstacles and the spreading out of waves past small openings.
- Scattering
  - Is a general physical process where light, sound, or moving particles, are forced to deviate from a straight trajectory, by one or more localized non-uniformities, in the medium through which they pass.

The Effects of Multi path Propagation

- multiple copies of a signal may arrive at different phases
  - If these phases add destructively, the signal level relative to noise declines, making signal detection at the receiver more difficult.
- Inter Symbol Interference (ISI)
  - Consider that we are sending a narrow pulse at a given frequency across a link between a fixed antenna and a mobile unit
  - one or more delayed copies of a pulse may arrive at the same time as the primary pulse for a subsequent bit
  - These delayed pulses act as a form of noise to the subsequent primary pulse, making recovery of the bit information more difficult.
Types of Fading

- Fast Fading
  - rapidly changing fading phenomenon
  - rapid variations in signal strength occur over distances of about one-half a wavelength
  - changes of amplitude can be as much as 20 or 30 dB over a short distance
  - affects not only mobile phones in automobiles, but even a mobile phone user walking down an urban street
- Slow Fading
  - Over longer distances, there is a change in the average received power level about which the rapid fluctuations occur

Fading effects

- Flat fading, or nonselective fading
  - type of fading in which all frequency components of the received signal fluctuate in the same proportions simultaneously.
- Selective fading
  - affects unequally the different spectral components of a radio signal.
  - If attenuation occurs over a portion of the bandwidth of the signal, the fading is considered to be selective

Fading Channels

Additive White Gaussian Noise (AWGN) Channel

- Desired signal is degraded by thermal noise associated with the physical channel itself as well as electronics at the transmitter and receiver

Rayleigh fading

- multiple indirect paths between transmitter and receiver and
- no distinct dominant path, such as an LOS path

Rician fading

- where there is a direct LOS path in addition to a number of indirect multi path signals
Coding and Error control

Error Detection

- Additional bits added by transmitter for error detection code
- $P_b$: Probability of a single bit error; also known as the bit error rate (BER)
- $P_i$: Probability that a frame arrives with no bit errors
- $P_2$: Probability that, with an error detection algorithm in use, a frame arrives with one or more undetected errors - residual error rate
- $P_3$: Probability that, with an error detection algorithm in use, a frame arrives with one or more detected bit errors but no undetected bit errors

![Error Detection Process](image)

Error Detection Methods

Parity Check

- The simplest error detection scheme is to append a parity bit to the end of a block of data.
- A typical example is character transmission, in which a parity bit is attached to each 7-bit character.
- The value of this bit is selected so that the character has an even number of 1s (even parity) or an odd number of 1s (odd parity).
- if two (or any even number) of bits are inverted due to error, an undetected error occurs

Cyclic Redundancy Check

Given a k bit block of bits, or message, the transmitter generates an $(n - k)$-bit sequence, known as a frame check sequence (FCS), such that the resulting frame, consisting of n bits, is exactly divisible by some predetermined number.

The receiver then divides the incoming frame by that number and, if there is no remainder, assumes there was no error.
Modulo 2 arithmetic

- Uses binary addition with no carries, which is just the exclusive-OR (XOR) operation.
- Binary subtraction with no carries is also interpreted as the XOR operation:

\[
\begin{array}{c}
1111 \\
+1010 \\
\hline
0101
\end{array} \quad \begin{array}{c}
1111 \\
-0101 \\
\hline
1010
\end{array}
\]

Now define,

\[
T = n\text{-bit frame to be transmitted} \\
D = k\text{-bit block of data, or message, the first } k \text{ bits of } T \\
F = (n - k)\text{-bit FCS, the last } (n - k) \text{ bits of } T \\
P = \text{pattern of } n - k + 1 \text{ bits; this is the predetermined divisor}
\]

We would like \( T/P \) to have no remainder. It should be clear that

\[
T = 2^{n-k}D + F
\]

That is, by multiplying \( D \) by \( 2^{n-k} \), we have in effect shifted it to the left by \( n - k \) bits and padded out the result with zeroes. Adding \( F \) yields the concatenation of \( D \) and \( F \), which is \( T \). We want \( T \) to be exactly divisible by \( P \). Suppose that we divide \( 2^{n-k}D \) by \( P \):

\[
\frac{2^{n-k}D}{P} = Q + \frac{R}{P}
\]

(6.1)

There is a quotient and a remainder. Because division is modulo 2, the remainder is always at least one bit shorter than the divisor. We will use this remainder as our FCS.

Then

\[
T = 2^{n-k}D + R
\]

(6.2)

Consider,

\[
\frac{T}{P} = \frac{2^{n-k}D + R}{P} = \frac{2^{n-k}D}{P} + \frac{R}{P}
\]

Substituting Equation (6.1), we have

\[
\frac{T}{P} = Q + \frac{R}{P} + \frac{R}{P}
\]

However, any binary number added to itself modulo 2 yields zero. Thus

\[
\frac{T}{P} = Q + \frac{R + R}{P} = Q
\]

There is no remainder, and therefore \( T \) is exactly divisible by \( P \). Thus, the FCS is easily generated: Simply divide \( 2^{n-k}D \) by \( P \) and use the \( (n - k) \)-bit remainder as the FCS. On reception, the receiver will divide \( T \) by \( P \) and will get no remainder if there have been no errors.
Example

1. Given
Message D = 1010011011 (10 bits)
Pattern P = 110101 (6 bits)
FCS R = to be calculated (5 bits)
Thus, n = 15, k = 10, and (n - k) = 5

2. The message is multiplied by 25, yielding 101000110100000

3. This product is divided by P:

4. The remainder is added to $2^5 D$ to give T = 101000110101110 which is transmitted.

5. If there are no errors, the receiver receives T intact. The received frame is divided by P:

Because there is no remainder, it is assumed that there have been no errors.
### Polynomials

A second way of viewing the CRC process is to express all values as polynomials in a dummy variable $X$, with binary coefficients.

The coefficients correspond to the bits in the binary number. Thus, for $D = 110011$, we have

$$D(X) = X^5 + X^4 + X + 1,$$  
and for $P = 11001$, we have $P(X) = X^4 + X^3 + 1$.

Arithmetic operations are again modulo 2. The CRC process can now be described as

$$\frac{X^{n-k}D(X)}{P(X)} = Q(X) + \frac{R(X)}{P(X)}$$

$$T(X) = X^{n-k}D(X) + R(X)$$

#### Example 6.7

Using the preceding example, for $D = 1010001011$, we have $D(X) = X^9 + X^7 + X^3 + X^2 + 1$, and for $P = 110101$, we have $P(X) = X^5 + X^4 + X^2 + 1$. We should end up with $R = 01110$, which corresponds to $R(X) = X^3 + X^2 + X$. Figure 6.4 shows the polynomial division that corresponds to the binary division in the preceding example.

![Polynomial Division Diagram](image)

Four versions of $P(X)$ are widely used

- **CRC-12** = $X^{12} + X^{11} + X^3 + X^2 + X + 1$
- **CRC-16** = $X^{16} + X^{15} + X^2 + 1$
- **CRC-CCITT** = $X^{16} + X^{12} + X^5 + 1$
- **CRC-32** = $X^{32} + X^{26} + X^{23} + X^{22} + X^{16} + X^{12} + X^{11} + X^{10} + X^8 + X^7 + X^5 + X^4 + X^2 + X + 1$

### Digital Logic

The CRC process can be represented by, and indeed implemented as, a dividing circuit consisting of XOR gates and a shift register.

The shift register is a string of 1-bit storage devices.

Each device has an output line, which indicates the value currently stored, and an input line.

At discrete time instants, known as clock times, the value in the storage device is replaced by the value indicated by its input line.

The entire register is clocked simultaneously, causing a 1-bit shift along the entire register.
The circuit is implemented as follows:

1. The register contains $n - k$ bits, equal to the length of the FCS.
2. There are up to $n - k$ XOR gates.
3. The presence or absence of a gate corresponds to the presence or absence of a term in the divisor polynomial, $P(X)$, excluding the terms $1$ and $X^{n-k}$.

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**Figure 6.5** Circuit with Shift Registers for Dividing by the Polynomial $X^5 + X^4 + X^2 + 1$

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**Figure 6.6** General CRC Architecture to Implement Divisor $(1 + A_1X + A_2X^2 + \cdots + A_{n-1}X^{n-k-1} + X^{n-k})$
Block Error Correction Codes

- Correction of detected errors usually requires data block to be retransmitted
- Not appropriate for wireless applications
  - Bit error rate is high
    - Lots of retransmissions
  - Propagation delay can be long (satellite) compared with frame transmission time
- Would result in retransmission of frame in error plus many subsequent frames
- Need to correct errors on basis of bits received

![Diagram of Error Correction Process](image)

**Figure 6.7 Error Correction Process**

**Error Correction Process**

- Each k bit block mapped to an n bit block (n>k)
- Codeword
- Forward error correction (FEC) encoder
- Codeword sent
- Received bit string similar to transmitted but may contain errors
- Received code word passed to FEC decoder
  - If no errors, original data block output
  - Some error patterns can be detected and corrected
  - Some error patterns can be detected but not corrected
  - Some (rare) error patterns are not detected
- Results in incorrect data output from FEC

**Working of Error Correction**

- Add redundancy to transmitted message
- Can deduce original in face of certain level of error rate
- E.g. block error correction code
- In general, add (n – k ) bits to end of block
- Gives n bit block (codeword)
- All of original k bits included in codeword
- Some FEC map k bit input onto n bit codeword such that original k bits do not appear

Comments & Feedback

Thanks to my family members who supported me while I spent hours and hours to prepare this.
Your feedback is welcome at GHCRajan@gmail.com