CS 480: MOBILE NETWORKS

Lecture PowerPoints

Lecture 5

Wireless Transmission II

Topics Covered

- Modulation
  - Amplitude Shift Keying
  - Frequency Shift Keying
  - Phase Shift Keying
  - Advanced Frequency Shift Keying
  - Advanced Phase Shift Keying
- Spread Spectrum
  - Direct Sequence Spread Spectrum
  - Frequency Hopping Spread Spectrum
- Cellular Systems

Modulation

- For *digital modulation*, digital data (0 and 1) is translated into an analog signal (baseband signal).
- Digital modulation is required if digital data has to be transmitted over a medium that only allows for analog transmission.
  - E.g. the old analog telephone system in wired networks – to connect a computer to this system a modem is needed.
  - The modem translates digital data Into analog signals and vice versa.
- In wireless networks, digital transmission cannot be used
- The binary bit-stream has to be transmitted into the analog signal first.

Modulation (2)

- The three basic methods for this translation are
  - *amplitude shift keying* (ASK),
  - *frequency shift keying* (FSK),
  - *phase shift keyi*ng (PSK).
- Modulation of digital signals is known as *shift keying*.
- Apart from translation of digital data into analog signals,
  - wireless transmission requires *analog modulation* that shifts the center frequency of the baseband signal generated by digital modulation up to the radio carrier.
- For example, digital modulation translates a 1 Mbit/s bit-stream into a baseband signal with a bandwidth of 1 MHz.

Modulation (3)

- Reasons why the baseband signal cannot be directly transmitted in a wireless system
  - *Antennas*: an antenna must be the order of magnitude of the signal's wavelength in size to be effective.
    - A1 MHz signal, this requires an antenna several hundred meters high. With 1 GHz, antennas should be a few centimeters in length.
  - *Frequency division multiplexing*: using only baseband transmission, FDM could not be applied.
    - Analog modulation shifts the baseband signals to different carrier frequencies.
  - *Medium characteristics:* path loss, penetration of obstacles, reflection, scattering and diffraction depend heavily on the wavelength of the signal.
    - The right carrier frequency with has to be chosen: long waves for submarines, short waves for handheld devices,.

Modulation (4)

- Similar to digital modulation, three different basic schemes for analog modulation are
  - *amplitude modulation* (AM),
  - *frequency modulation* (FM),
  - *phase modulation* (PM).
- Figure 1 shows a (simplified) block diagram of a radio transmitter for digital data.
  - The first step is the digital modulation of data into the analog baseband signal
  - The analog modulation then shifts the center frequency of the analog signal up to the radio carrier
  - The signal is then transmitted via the antenna

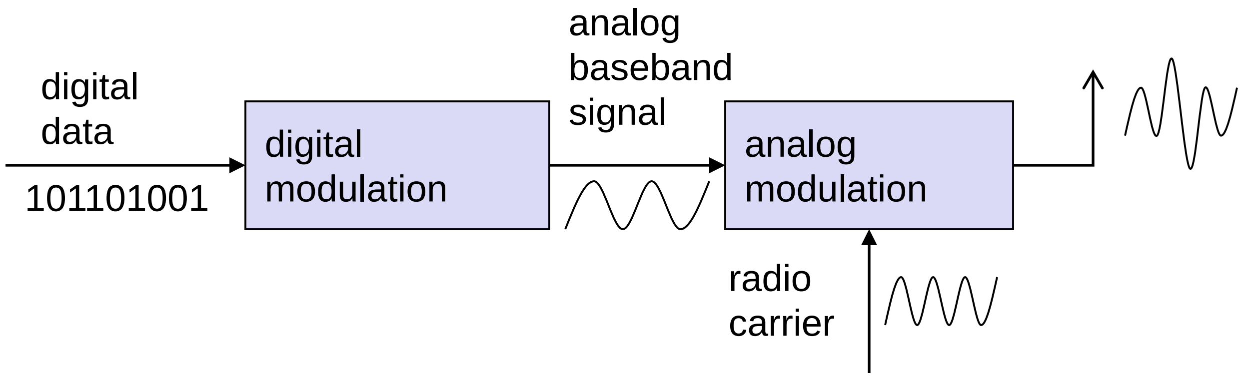


Figure 1: Modulation in a transmitter.

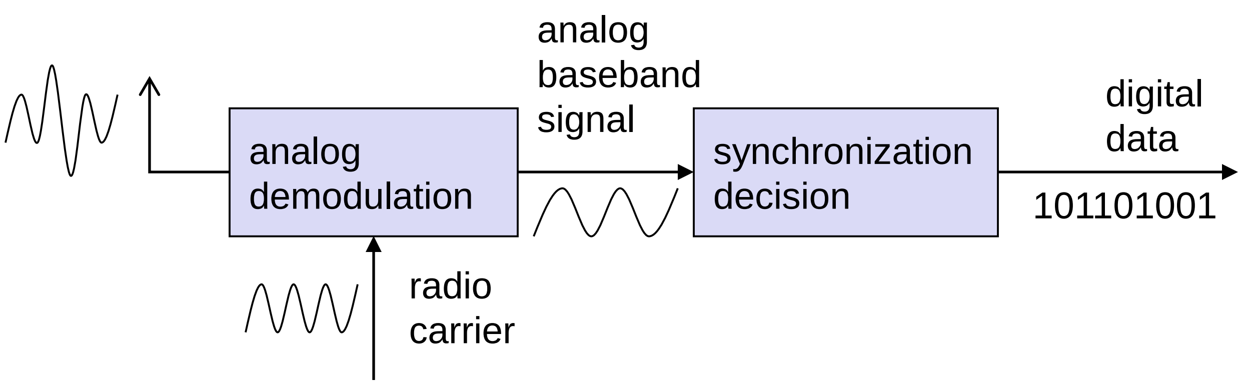


Figure 2: Demodulation and data reconstruction in a receiver.

Modulation (5)

- In Figure 2, the receiver receives the analog radio signal via its antenna and demodulates the signal into the analog baseband signal with the help of the known carrier.
- For analog radio tuned in to a station this is all that is needed
- For digital data, another step is required, bits or frames have to be detected, i.e. the receiver must synchronize with the sender.
  - After synchronization, the receiver has to decide if the signal represents a digital 1 or a 0.

Amplitude shift keying (ASK)

- Figure 3 illustrates ASK, the simplest digital modulation scheme.
- Two binary values, 1 and 0, are represented by two different amplitudes.
- This simple scheme only requires low bandwidth, but is very susceptible to interference.
  - Effects like multi-path propagation, noise, or path loss heavily influence the amplitude.
- In a wireless environment, a constant amplitude cannot be guaranteed, so ASK is typically not used for wireless radio transmission.
- Wired transmission scheme with highest performance, namely optical transmission, uses ASK.

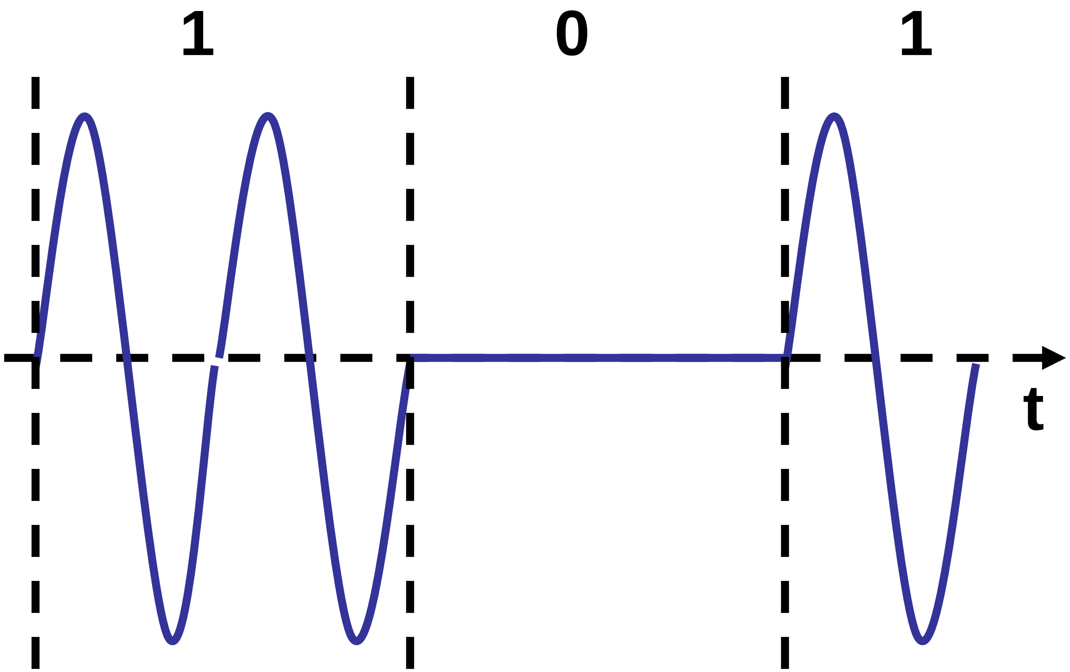


Figure 3: Amplitude shift keying (ASK).

Frequency shift keying (FSK)

- FSK is a modulation scheme often used for wireless transmission (see Figure 4).
- 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.

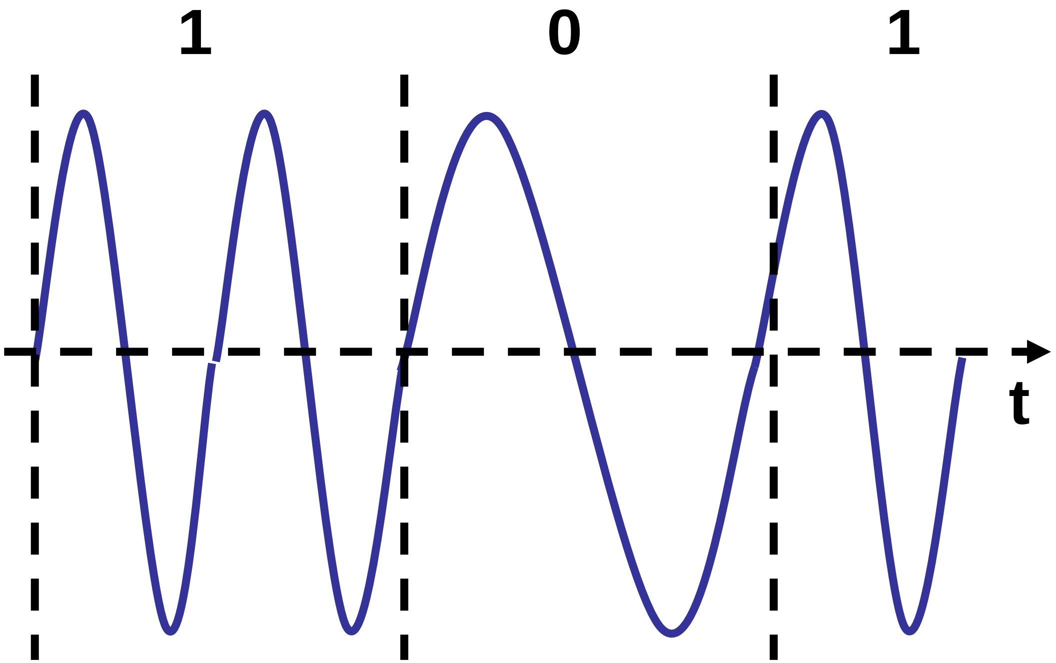


Figure 4: Frequency shift keying (FSK).

Phase shift keying (PSK)

- PSK uses shifts in a phase of a signal to represent data
- Figure 5 shows a phase shift of 180^o or π as the 0 follows a 1.
- This simple scheme, shifting the phase by 180^o each time the data value changes, is also referred to as binary PSK (BPSK).
- To receive the signal correctly, the receiver must synchronize in frequency and phase with the transmitter.

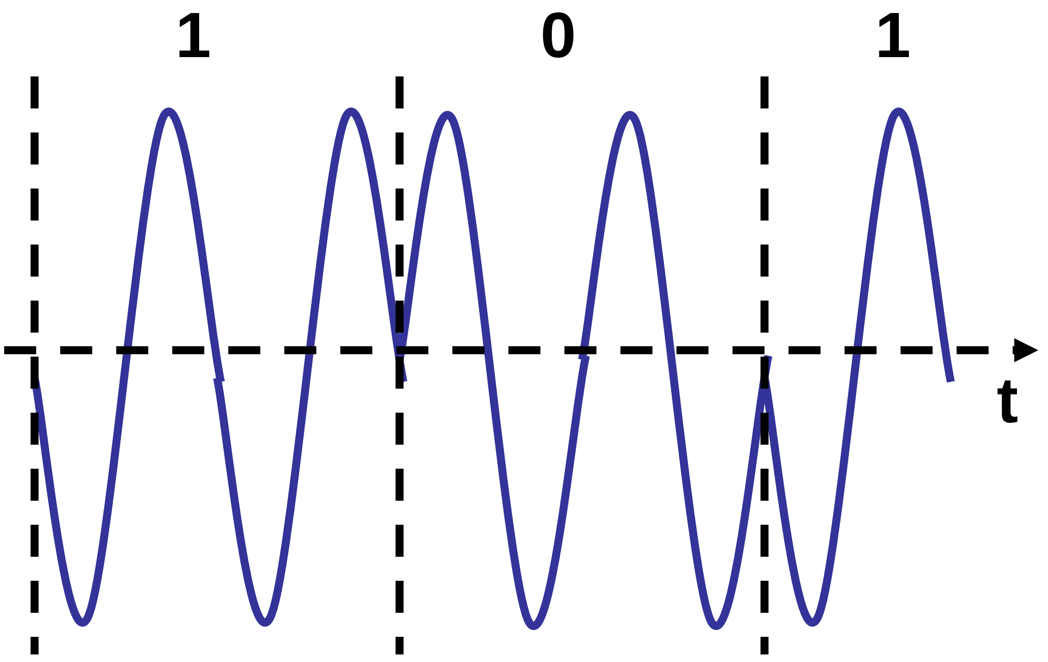


Figure 5: Phase shift keying (PSK).

Advanced frequency shift keying

- A famous FSK used in many wireless systems is *minimum shift keying* (MSK).
- MSK is basically BFSK without abrupt phase changes.
- Figure 6 shows an example implementation of MSK.
- In the first step, data bits are separated into even and odd bits, the duration of each bit doubled.
- The scheme uses two frequencies: f_1, the lower frequency, and f_2, the higher frequency: $f_2=2f_1$
- According to the following scheme, the lower or higher frequency is chosen to generate the MSK signal:
  - If the even and the odd bit are both 0, then the higher frequency f_2 is inverted

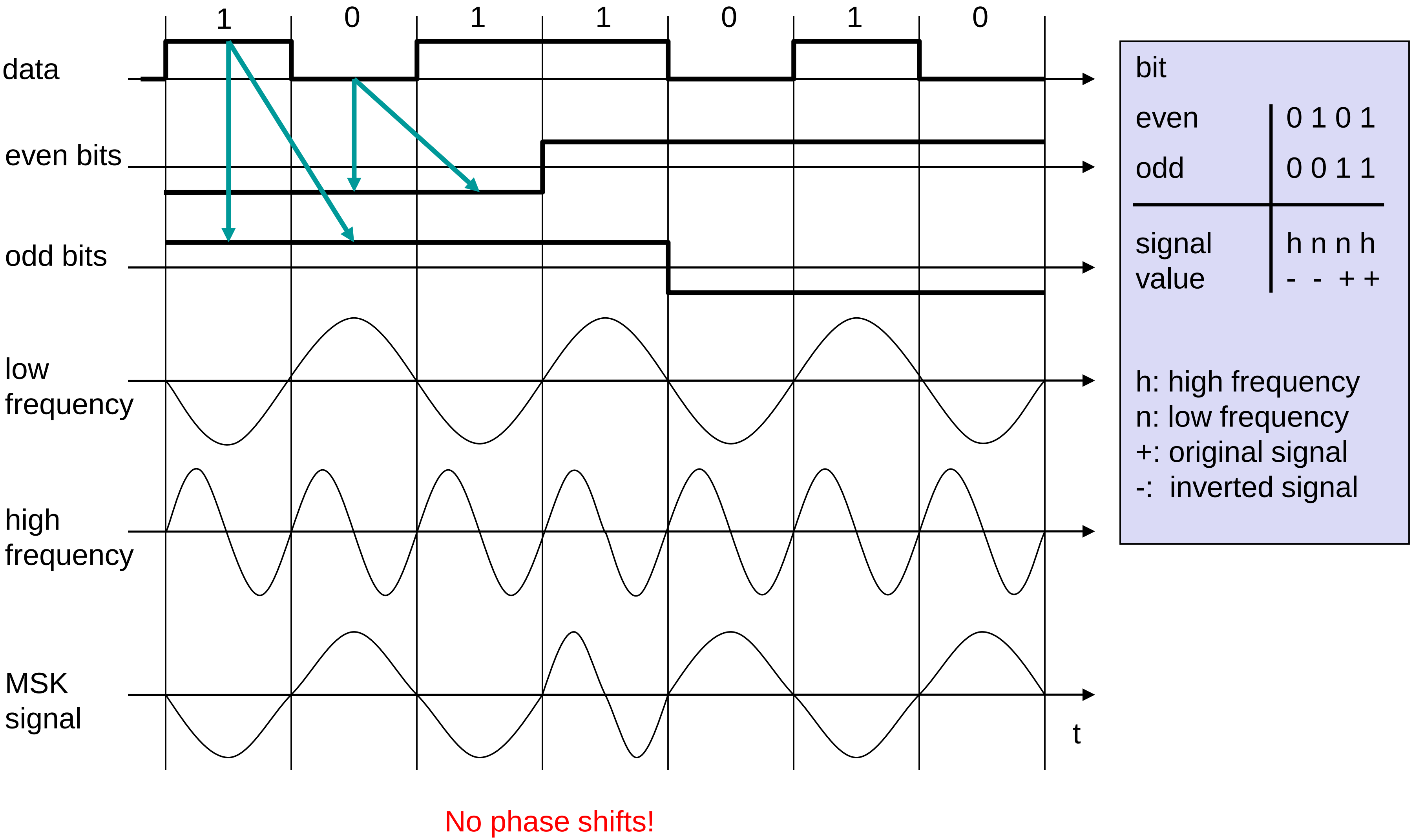


Figure 6: Minimum shift keying (MSK).

Advanced frequency shift keying (2)

  - If the even bit is 1, the odd bit 0, then the lower frequency f_1 is inverted. This is the case in fifth to seventh columns of Figure 6.
  - If the even bit is 0 and the odd bit is 1, as in columns 1 to 3, f_1 is taken without changing the phase.
  - If both bits are 1 then the original f_2 is taken.
- High frequency is chosen if even and odd bits are equal
- The signal is inverted if the odd bit equals 0.
- This avoids all phase shifts in the resulting MSK signal.
- Adding a Gaussian lowpass filter to the MSK results in Gaussian MSK (GMSK).
- This is a digital modulation scheme for many European wireless standards e.g. GSM, DECT.
  - The filter reduces the large spectrum needed by MSK.

Advanced phase shift keying

- The basic BPSK scheme only uses one possible phase shift of 180^o. This can be improved in many ways
- The left side of Figure 7 shows BPSK in the phase domain. The right side shows *quadrature PSK* (QPSK).
- In QPSK, higher bit rates can be achieved for the same bandwidth by encoding two bits into one phase shift.
- If the phase shift is relative to reference signal (same frequency)
  – A phase shift of 0 means that the signal is in phase with the reference signal.
  – A QPSK signal exhibits a phase shift of 45^o for the data 11, 135^o for 10, 225^o for 00, and 315^o for 01.
  – The transmitter “selects” part of the signal as shown in Figure 8 and concatenates them.

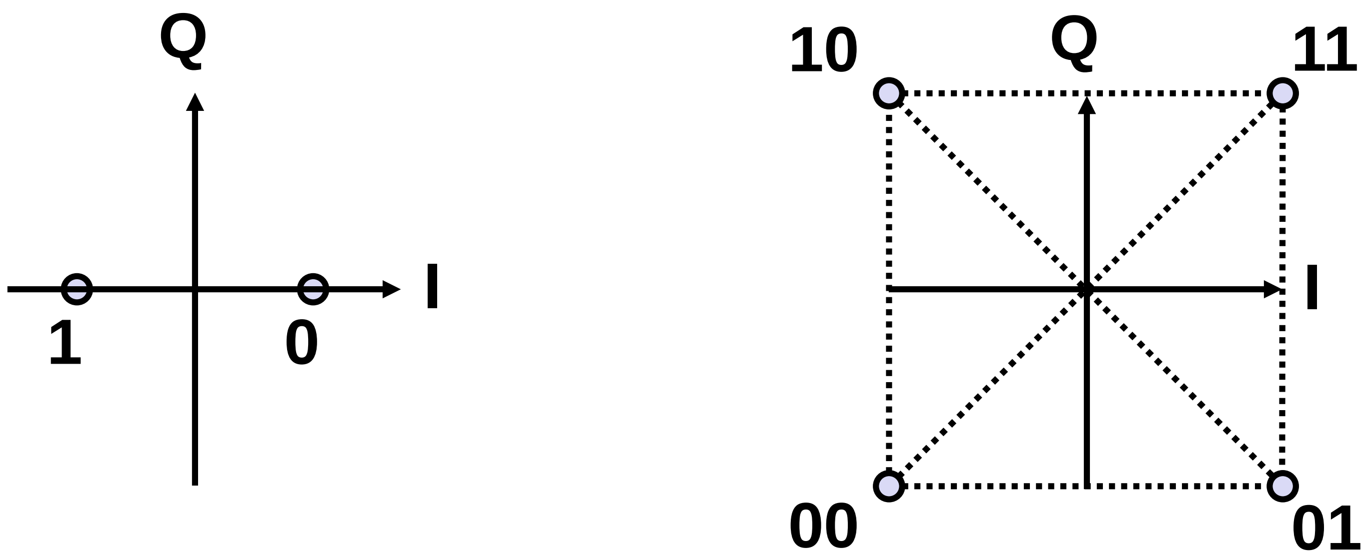


Figure 7: BPSK and QPSK in the phase domain.

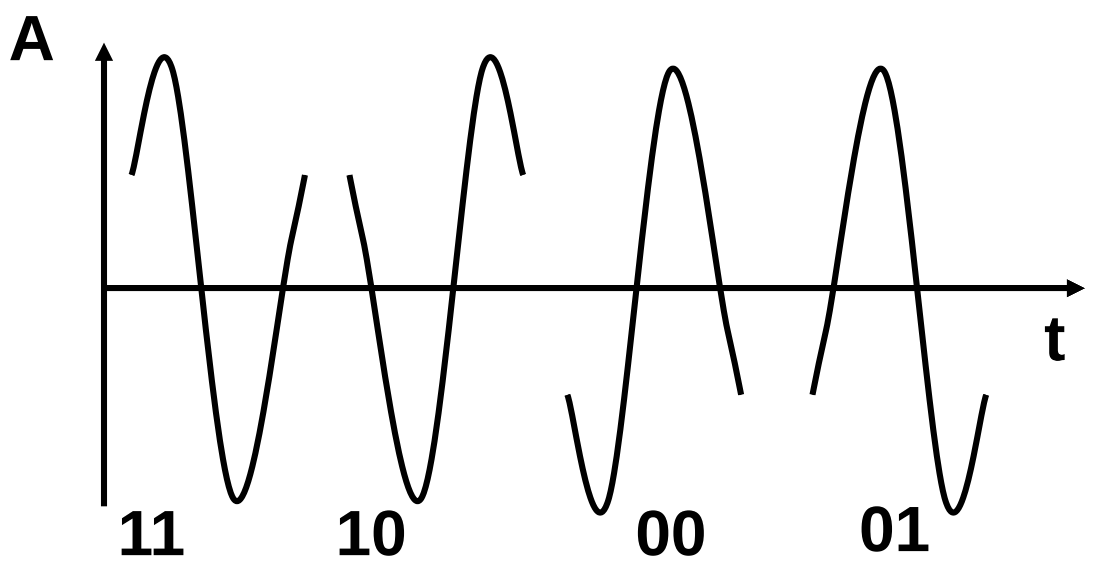


Figure 8: QPSK in the time domain.

Advanced phase shift keying (2)

  - To reconstruct data, the receiver compares the incoming signal with the reference signal.
  - Transmitter and receiver have to be synchronized very often.
- In differential QPSK (DQPSK), the phase shift is relative to the phase of the previous two bits.
  - The receiver does not need the reference signal
  - DQPSK is used in US wireless technologies IS (Interim Standard)-136 and PACS (Personal Access Communication System) and in Japanese PHS (Personal Handyphone System).
- The PSK scheme could be combined with ASK leading to *quadrature amplitude modulation* (QAM)
  - Used in standard 9,600 bit/s modems (see Figure 9 (left)).
  - Here three different amplitudes and 12 angles are combined coding 4 bits per phase/amplitude change.
  - The more "points" used in the phase domain, the harder it is to separate them.

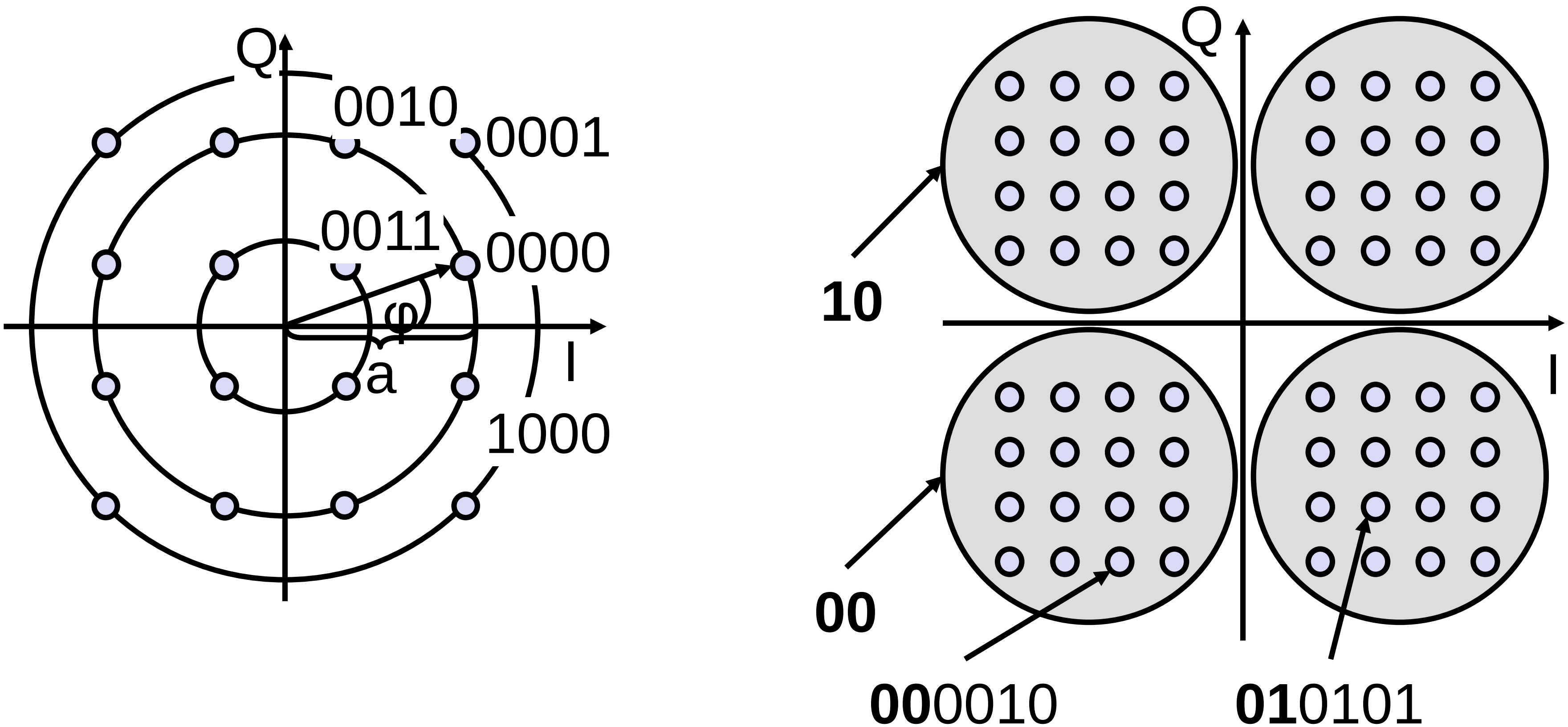


Figure 9: 16 quadrature amplitude modulation (left) and hierarchical 64 QAM (right).

Hierarchical modulation

- A more advanced scheme is a hierarchical modulation
  - as used in the digital TV standard DVB-T.
- Figure 9 (right) shows a 64 QAM that has a QPSK modulation
  - here two most significant bits are used for the QPSK signal embedded in the QAM signal
  - Under good signal reception conditions, the entire QAM constellation can be resolved
  - Under poor reception conditions, e.g. moving receivers, only the QPSK portion can be resolved
- A high priority data stream in DVB-T is coded with QPSK using two most significant bits
  - The remaining 4 bits represent low priority data.
  - For TV, standard resolution data stream to be coded with high priority, high resolution information with low priority.

Spread Spectrum (1)

- *Spread spectrum* techniques involve spreading the bandwidth needed to transmit data
- Spreading the bandwidth has several advantages, the main one being resistance to *narrowband interference.*
- Figure 10 (i) shows an idealized narrowband signal from a sender of user data (power density vs. frequency)
- The sender now spreads the signal in step (ii), i.e. converts the narrowband signal into a broadband signal
  - The energy needed to transmit the signal (area) is the same in (i) and (ii), but is now spread over a larger frequency range
- The power level of the user signal can even be as low as the background noise, making it hard to detect
- During transmission, the narrowband and broadband interference add to the signal in step (iii).

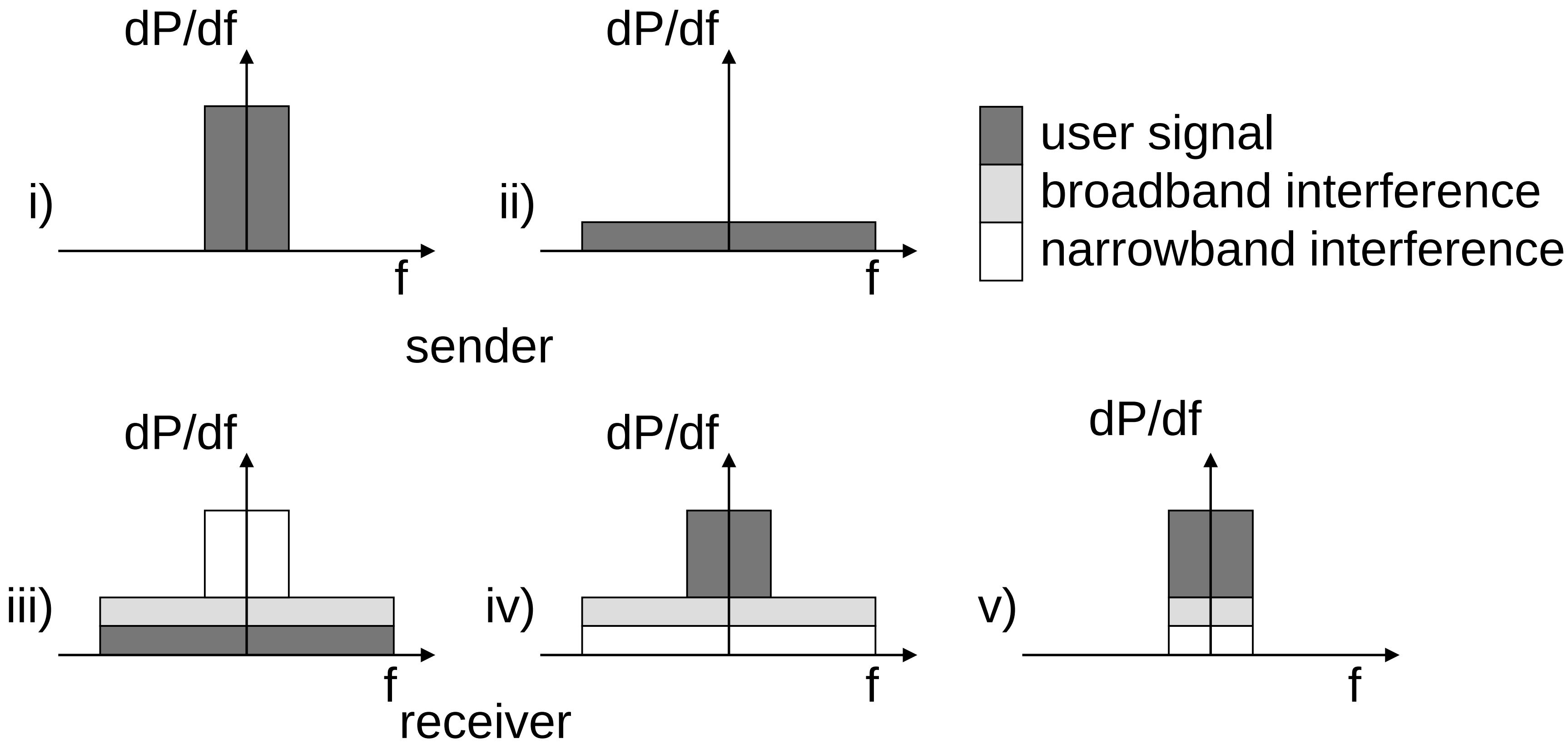


Figure 10: Spread spectrum: spreading and despreading.

Spread Spectrum (2)

- The sum of interference and user signal is received.
- The receiver despread the signal, converting spread user signal into a narrowband signal
  - while spreading narrowband interference and leaving broadband interference.
- In step v) the receiver applies a bandpass filter to cut off frequencies to the left and right of the narrowband signal.
- Finally, the receiver can reconstruct the original data since the power level of the user signal is high enough.

Spread Spectrum (3)

- Spread spectrum can also be used for several channels.
- Consider the situation in Figure 11
- Six different channels use FDM for multiplexing:
  - each channel has a narrow frequency band for transmission
- Each frequency band has its guard space to avoid adjacent channel interference.
- Also shown in Figure 11 is the channel quality which is frequency dependent (measure of interference)
- Channels 1, 2, 5 and 6 could be received while quality of channels 3 and 4 is bad to reconstruct transmitted data
- Here narrowband interference destroys transmission of channels 3 and 4.

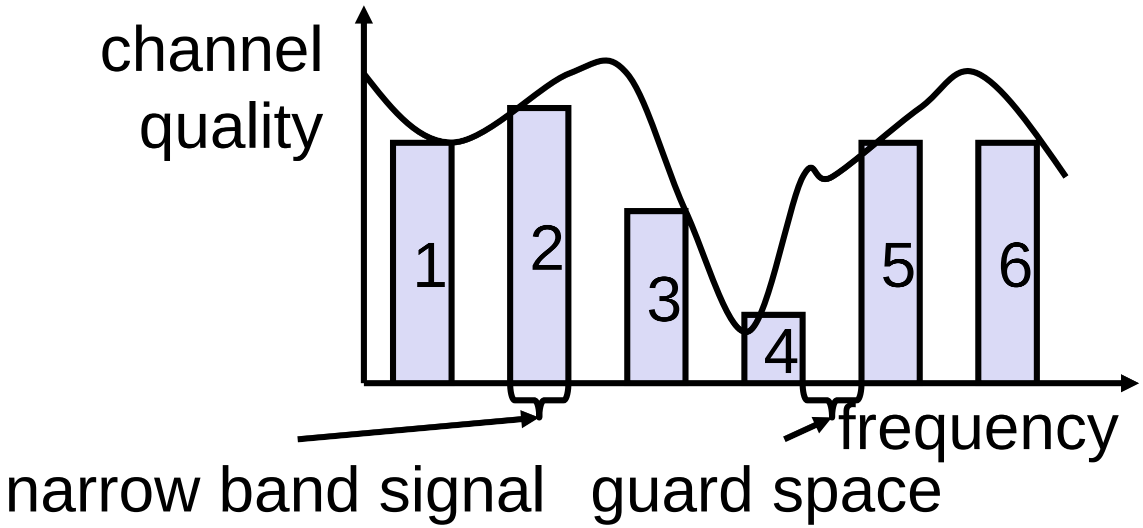


Figure 11: Narrowband interference without spread spectrum.

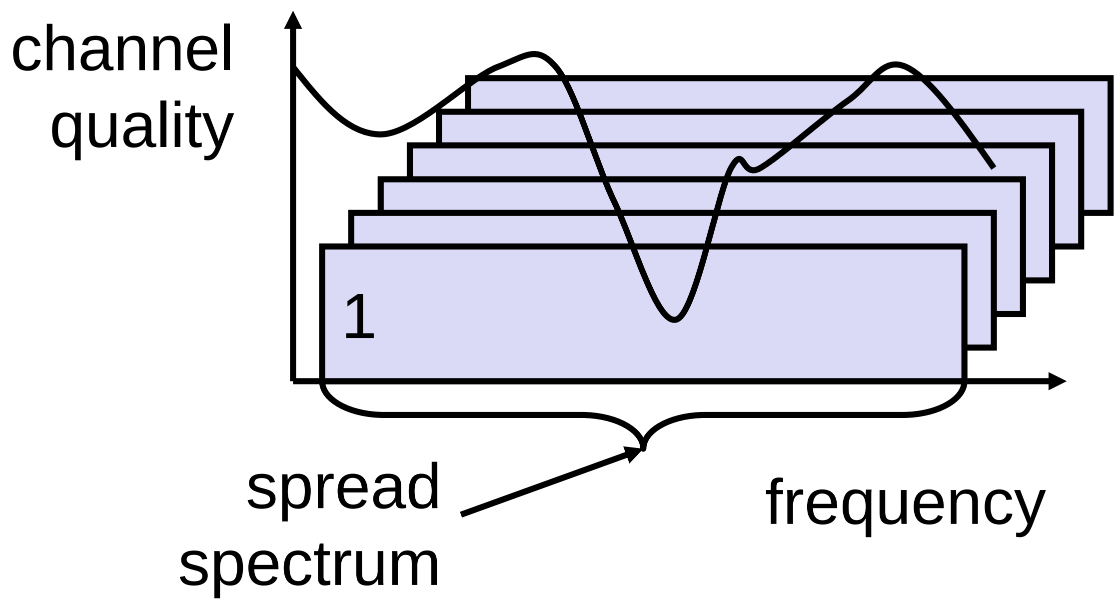


Figure 12: Spread spectrum to avoid narrowband interference.

Spread Spectrum (4)

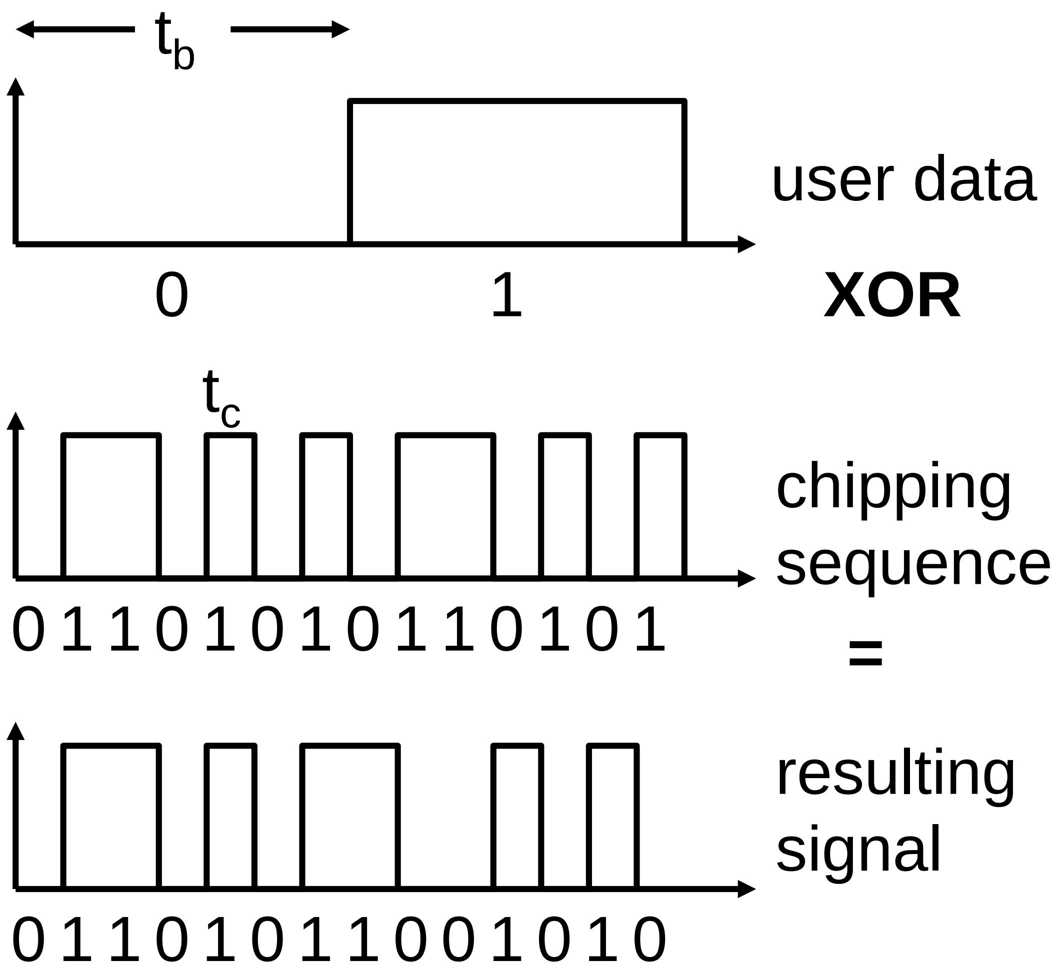
- Spread spectrum can increase resistance to narrowband interference.
  - Here same technique is now applied to all narrow band signals.
- In Figure 12, all narrowband signals are now spread into broadband signals using the same frequency range.
- No frequency planning is needed.
- To separate different channels, CDM is now used.
- Spreading of a narrowband signal is achieved using a special code.
  - Each channel is allotted its own code for receivers to apply in order to recover the signal.

Spread Spectrum (5)

- Without the code, the signal behaves like background noise.
- Spread spectrum technologies are used by US mobile phone systems.
- One of the disadvantages of spread spectrum techniques is the increased complexity of receivers that have to despread a signal.
- Another problem is the large frequency band required to spread the signal
- Spreading the spectrum can be achieved in two different ways:
  - *direct sequence spread spectrum* and
  - *frequency hopping spread spectrum*.

Direct sequence spread spectrum (DSSS)

- DSSS systems take a user bit stream and perform an exclusive OR (XOR) with a chipping sequence as shown in Figure 13.
- While each user bit has a duration t_b, the chipping sequence consists of smaller pulses, called *chips*, with a duration t_c.
- If generated properly, the chipping sequence appears as random noise.
- The spreading factor $s = t_b/t_c$ determines the bandwidth of the resulting signal.
- If the original signal needs a bandwidth w, the resulting signal needs s·w after spreading.



t_b: bit period
t_c: chip period

Figure 13: Spreading with DSSS.

Direct sequence spread spectrum (DSSS) (2)

- Wireless LANs complying with IEEE 802.11 standard, for example use the chipping sequence 10110111000 also known as the Barker code if implemented using DSSS.
- Transmitters and receivers using DSSS require additional components shown in Figure 14.
- The first step in a DSSS transmitter is the spreading of user data with the chipping sequence (digital modulation)
- The spread signal is then modulated with a radio carrier (radio modulation).
- Assuming for example a user signal with a bandwidth of 1 MHz, spreading with the above 11-chip Barker code results in a signal with 11 MHz bandwidth.

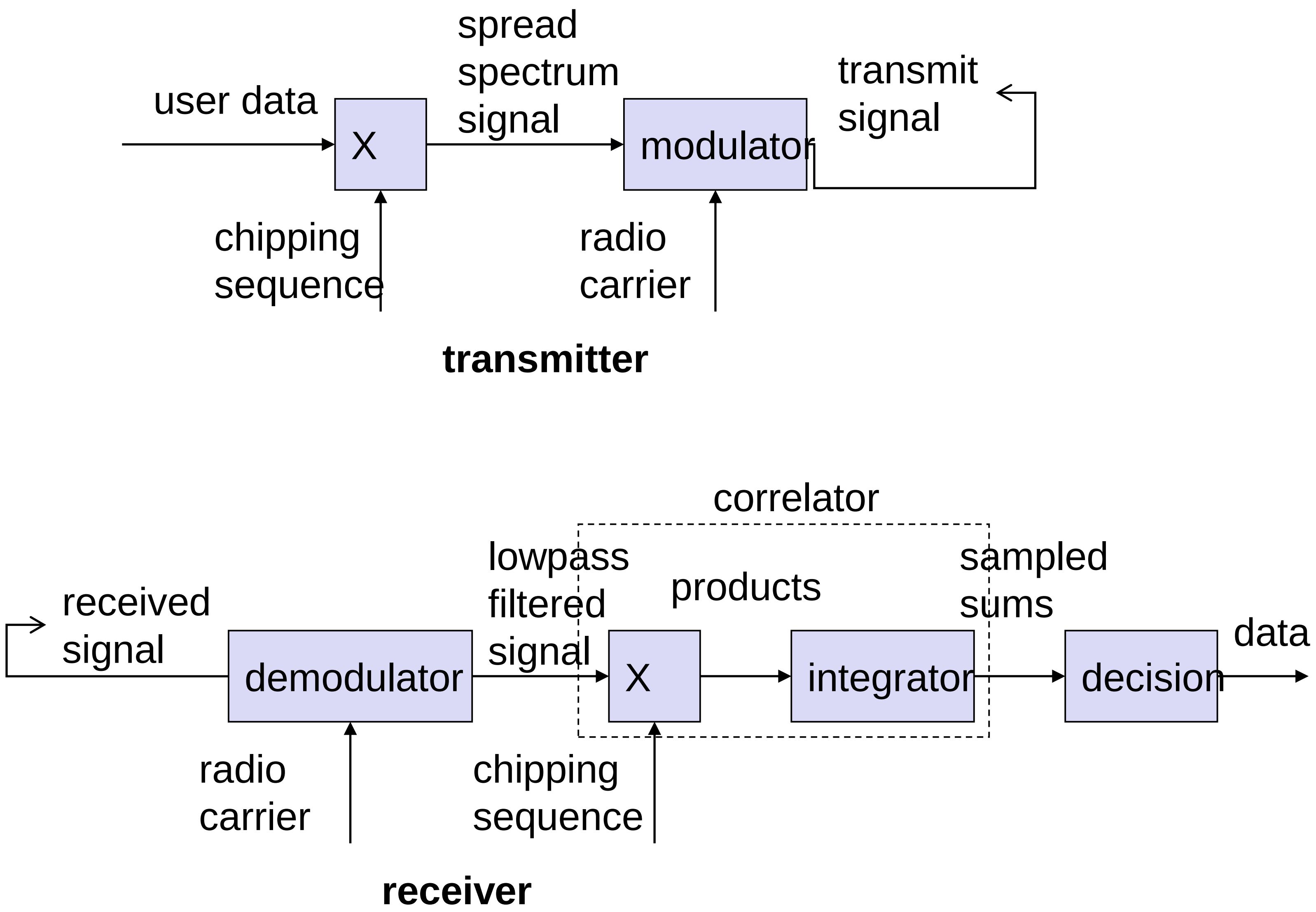


Figure 14: DSSS transmitter (top) and DSSS receiver (bottom).

Direct sequence spread spectrum (DSSS) (3)

- The radio carrier shifts this signal to the carrier frequency (e.g. 2.4 GHz in the ISM band). This signal is then transmitted.
- The receiver only has to perform the inverse functions of the two transmitter modulation steps.
- Noise and multi-path propagation require additional mechanisms to reconstruct the original data
- First step involves demodulating the received signal followed by additional filtering
  - The receiver should know the original chipping sequence

Direct sequence spread spectrum (DSSS) (4)

- Sequences at the sender and receiver needs to be precisely synchronized since the receiver calculates the product of the chip with incoming signal.
- An integrator adds all these products.
- Calculating products of chips and signal and adding the products in an integrator is called correlation.
- In each bit period, a decision unit samples the sums generated by the integrator and decides if the sum represents a binary 1 or a 0.

Frequency hopping spread spectrum (FHSS)

- In FHSS systems, the total available bandwidth is split into many channels of smaller bandwidth plus guard spaces between the channels.
- Transmitter and receiver stay on one of these channels for a certain time and then hop to another channel.
- This system implements FDM and TDM.
- The pattern of channel usage is called the *hopping sequence*.
- The time spent on a channel with a certain frequency is called *dwell time*.
- FHSS comes in two variants, slow and fast hopping (see Figure 15)

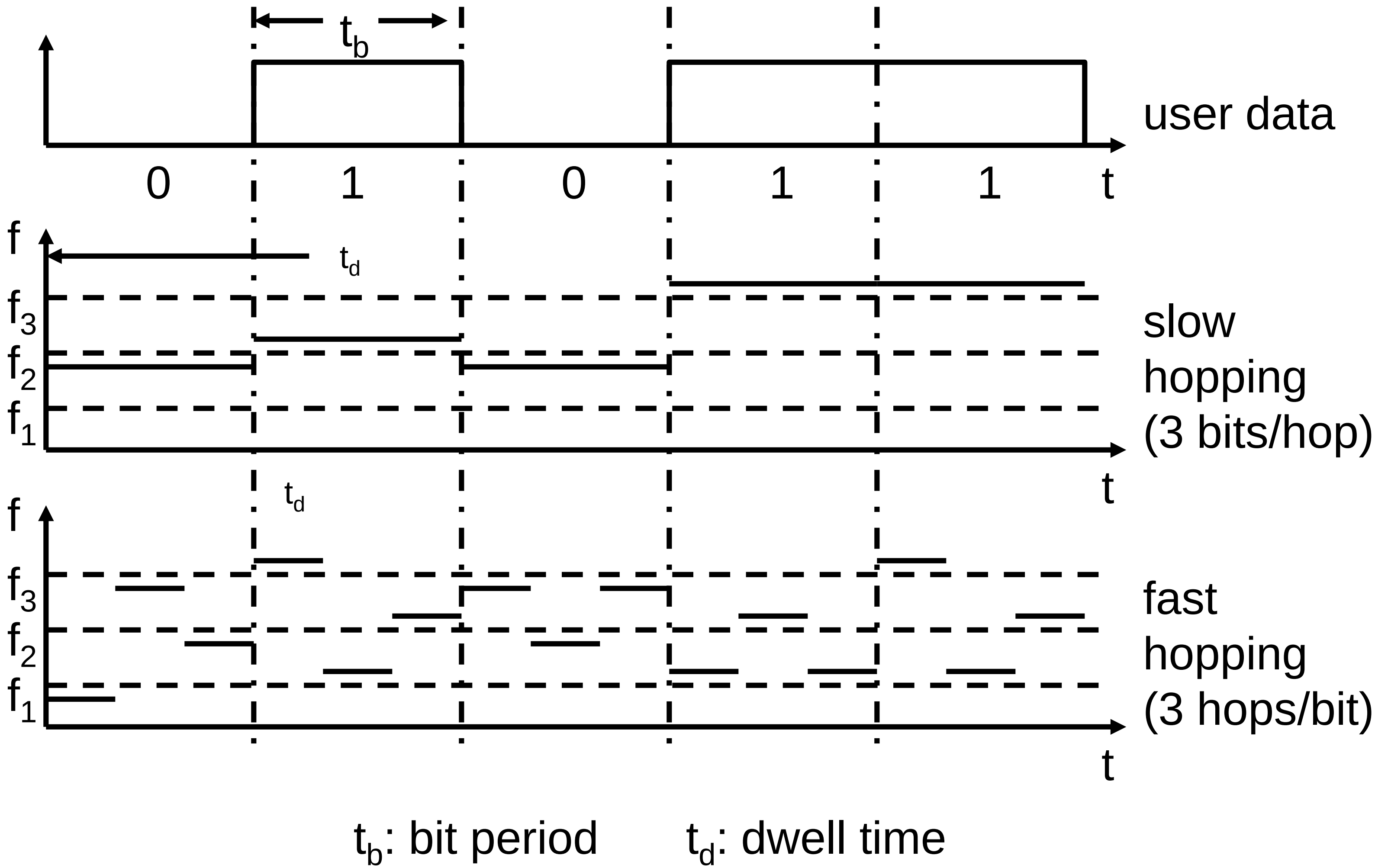


Figure 15: Slow and fast frequency hopping.

Frequency hopping spread spectrum (FHSS) (2)

- In *slow hopping*, the transmitter uses one frequency for several bit periods.
  - Figure 15 shows five user bits with bit period t_b.
- In performing slow hopping, the transmitter uses frequency f_2 for transmitting the first three bits during dwell time t_d.
  - Then the transmitter hops to the next frequency f_3
- Slow frequency hopping is an option for GSM.
- For *fast hopping* systems, the transmitter changes the frequency several times during the transmission of a single bit.
  - In Figure 15, the transmitter hops three times during a single bit period

Frequency hopping spread spectrum (FHSS) (3)

- Fast hopping systems are more complex to implement
  - since transmitter and receiver must be synchronized within smaller tolerances to perform hopping at same points in time.
  - These systems are better at overcoming effects of narrowband interference and frequency selective fading since they stick to one frequency for a very short time.
- Bluetooth is an example FHSS system
  - Bluetooth performs 1,600 hops per second and uses 79 hop carriers equally spaced with 1 MHz in the 2.4 GHz ISM band
- Figure 16 shows simplified block diagrams for FHSS transmitters and receivers.
- The first step in a transmitter is the modulation of user data using one of digital-to-analog modulation schemes.

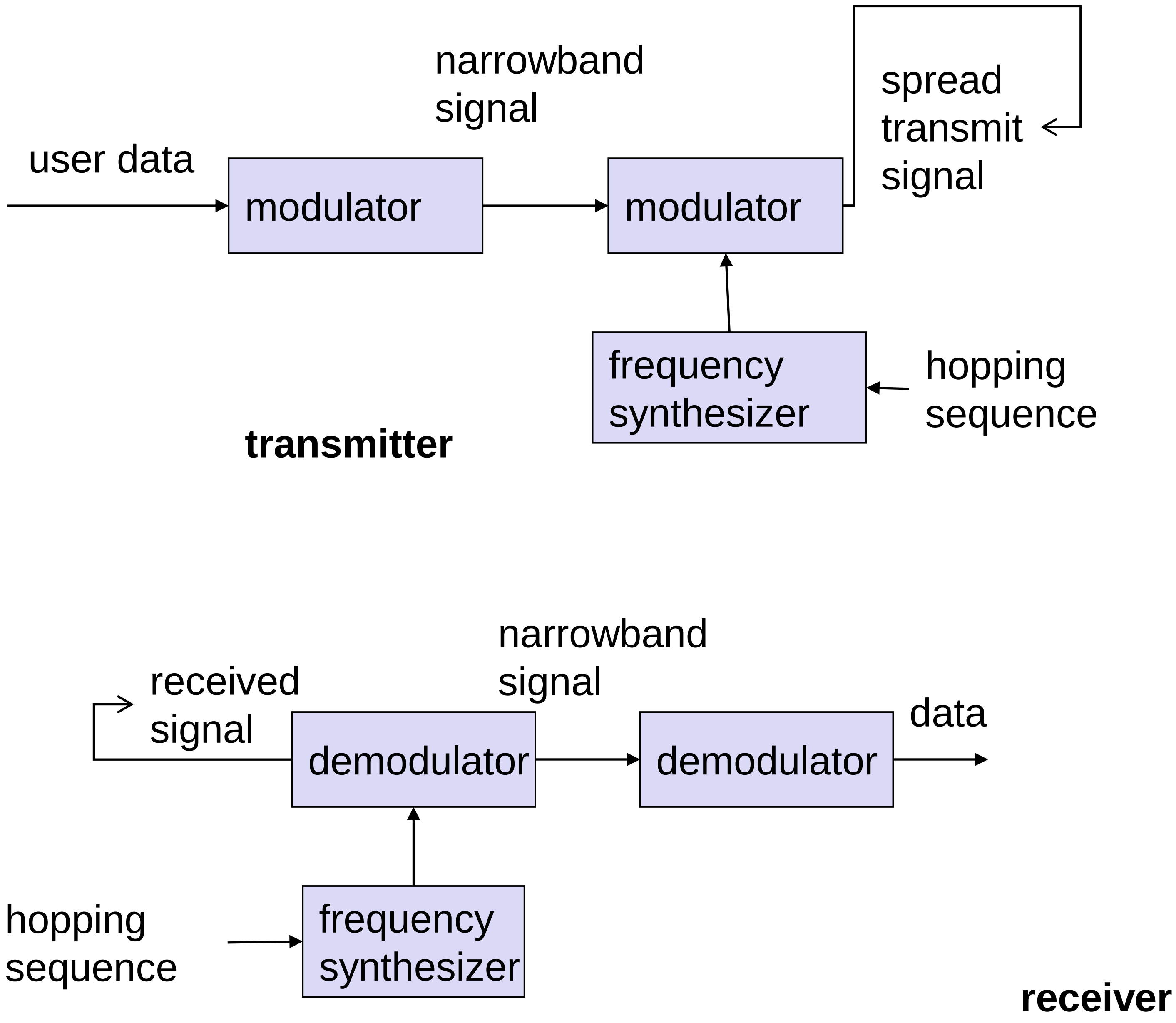


Figure 16: FHSS transmitter (top) and FHSS receiver (bottom).

Frequency hopping spread spectrum (FHSS) (4)

  - This results in a narrowband signal, if FSK is used with a frequency f_0 for a binary 0 and f_1 for a binary 1.
- In the next step 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 carrier frequency to generate a new spread signal with frequency $f_i + f_0$ for a 0 and $f_i + f_1$ for a 1 respectively.
  - The receiver needs to know the hopping sequence and must stay synchronized
  - It then performs inverse operations of the modulation to reconstruct user data. Several filters are also needed.

Frequency hopping spread spectrum (FHSS) (5)

- Compared to DSSS, spreading is simpler using FHSS systems.
- FHSS systems use only a small portion of the total band at any time,

  while DSSS systems always use the total bandwidth available.
- DSSS signals on the other hand are more resistant to fading and multi-path effects.
- DSSS signals are much harder to detect
  - without knowing the spreading code, detection is virtually impossible.
- If each sender has its own pseudo-random number sequence for spreading the signal (DSSS or FHSS), the system implements CDM.

Cellular Systems (1)

- Cellular systems for mobile communications implement space division multiplexing (SDM).
- Each transmitter, typically called a *base station*, covers a certain area, a *cell*.
- Cell radii can vary from tens of meters in buildings and hundreds of meters in cities, up to tens of kilometers in the country side.
- The shape of cells are never perfect circles or hexagons, but depend on the environment (buildings, mountains, valleys) and weather conditions
- Typical systems using this approach are mobile telecommunication systems, where a mobile station within a cell around a base station communicates with this base station and vice versa

Cellular Systems (2)

- Why do mobile network providers install several thousands of base stations throughout the country (which is quite expensive) and do not use powerful transmitters with huge cells like radio stations?
- *Advantag*es of cellular systems with small cells are
  - *Higher capacity*: implementing SDM allows frequency reuse. If one transmitter is far away from another (outside the interference range), it can reuse the same frequencies.
    - Frequencies are a scarce resource and the number of concurrent users per cell is limited. Huge cells do not allow for more users.
  - *Less transmission power*: a receiver far away from a base station would need much more transmit power than the current few Watts.
    - But energy is a serious problem for mobile handheld devices.

Cellular Systems (3)

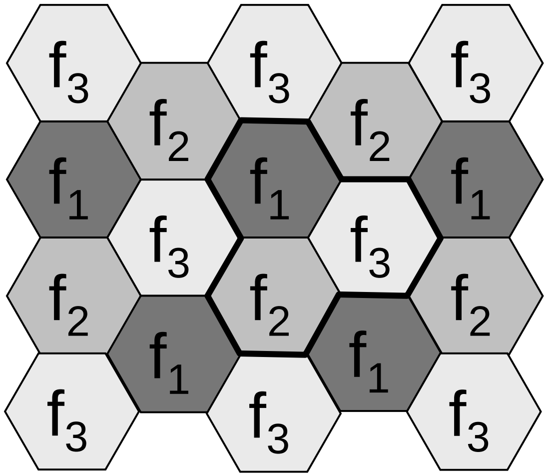
- *Local interference only*: having long distances between sender and receiver results in even more interference problems. With small cells, mobile stations and base stations only deal with local interference.
- *Robustness*: cellular systems are decentralized and so more robust against the failure of single components. If one antenna fails, this only influences communication within a small area.

- *Disadvantages* of cellular systems with small cells are
  - *Infrastructure needed:* cellular systems need a complex infrastructure to connect all base stations. This includes many antennas, switches for call forwarding, location registers to find mobile station
  - *Handover needed:* the mobile station has to perform a handover when changing from one cell to another. Depending on the cell size and the speed of movement, this can happen quite often.

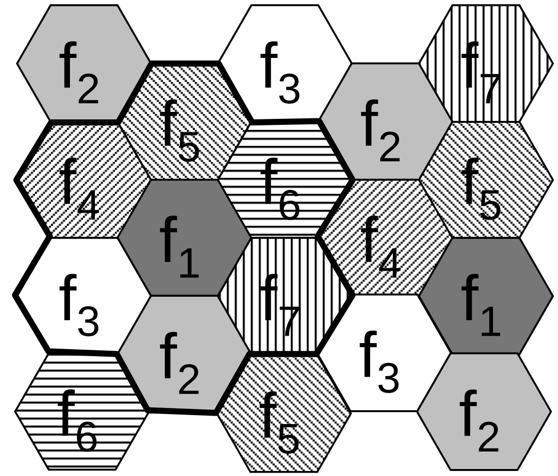
Cellular Systems (4)

- *Frequency planning:* to avoid interference between transmitters using the same frequencies, frequencies have to be distributed carefully. On the one hand, interference should be avoided, on the other, only a limited number of frequencies is available.

- Two possible models to create cell patterns with minimal interference are shown in Figure 17
- Cells are combined in *clusters*. Figure 17 left shows three cells that form a cluster, on the right, seven cells form a cluster
- All cells in a cluster use disjointed sets of frequencies.
- Figure 17 left shows one cell in the cluster that uses set f_1, another cell f_2 and the third cell f_3.
- In real life transmission, the pattern will look somewhat different.



3 cell cluster

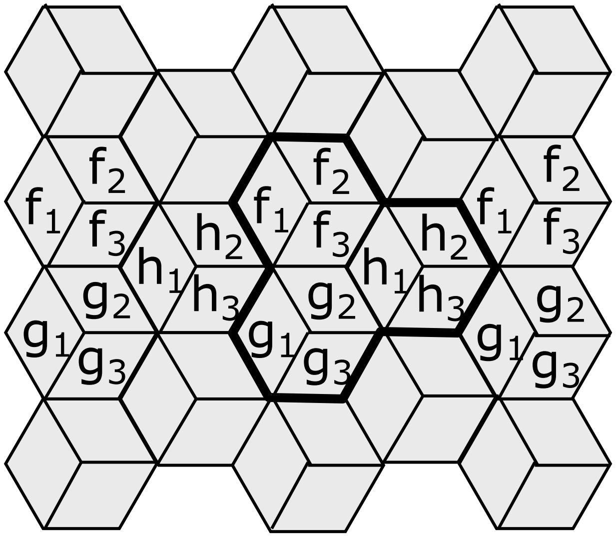


7 cell cluster

Figure 17: Cellular system with three and seven cell clusters

Cellular Systems (5)

- The pattern also shows the repetition of the same frequency sets
- To reduce interference even further, *sectorized antennas* can be used.
- Figure 18 shows the use of three sectors per cell in a cluster with three cells
- The fixed assignment of frequencies to cell clusters and cells respectively, is known as *fixed channel allocation* (FCA). This scheme is not very efficient if traffic load varies.
  - E.g. if there is heavy load in one cell and light load in a neighboring cell. It could make sense to borrow frequencies



3 cell cluster
with 3 sector antennas

Figure 18: Cellular system with three cell clusters and three sectors per cell.

Cellular Systems (6)

- FCA is used in the GSM system since it is much simpler to use but requires careful analysis before installation.
- A *dynamic channel allocation* (DCA) scheme has been implemented in DECT.
- In this scheme, frequencies can only be borrowed, but it is also possible to freely assign frequencies to cells.
  - With dynamic assignment of frequencies to cells, the danger of interference with cells using the same frequency exists. The "borrowed" frequency can be blocked in the surrounding cells.
- Cellular systems using CDM instead of FDM do not need such elaborate channel allocation schemes and complex frequency planning.
  - Users are separated through the code they use, not through frequency.

Cellular Systems (7)

- Cell planning faces another problem, the cell size depends on the current load.
- CDM cells are commonly said to “breathe”.
- While a cell can cover a larger area under a light load, it shrinks if the load increases.
  - This is due to the growing noise level if more users are in a cell.
  - Recall if you don’t know the code, other signals appear as noise.
- The higher the noise, the higher the path loss and higher transmission errors.
- Mobile stations further away from base station drop out of cell.
- Figure 19 illustrates this phenomenon with a user transmitting a high bit rate stream within a CDM cell.

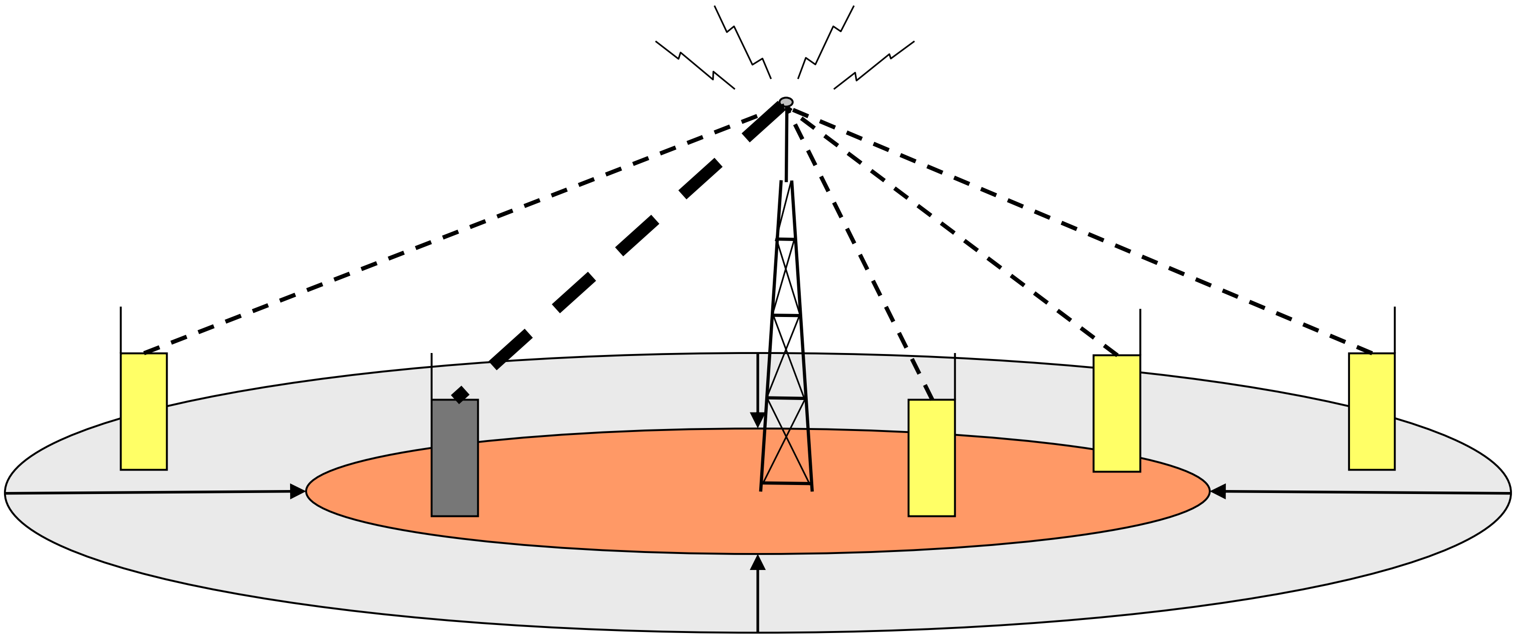


Figure 19: Cell breathing depending on the current load

Cellular Systems (8)

- This additional user lets the cell shrink with the result that two users drop out of the cell.
- In real life, this additional user could request a video stream (high bit rate) while the others use standard voice communication (low bit rate).