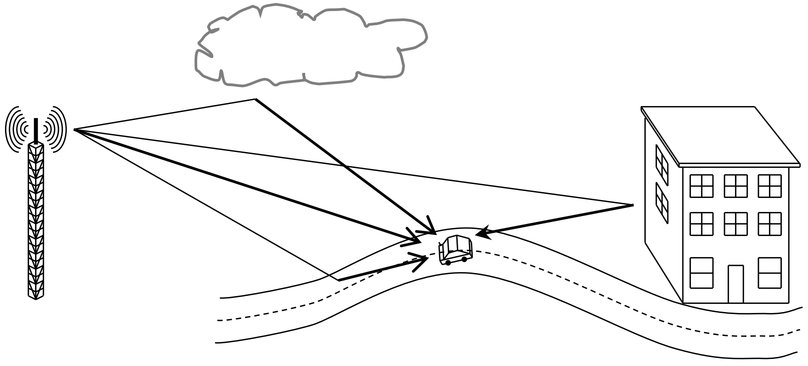
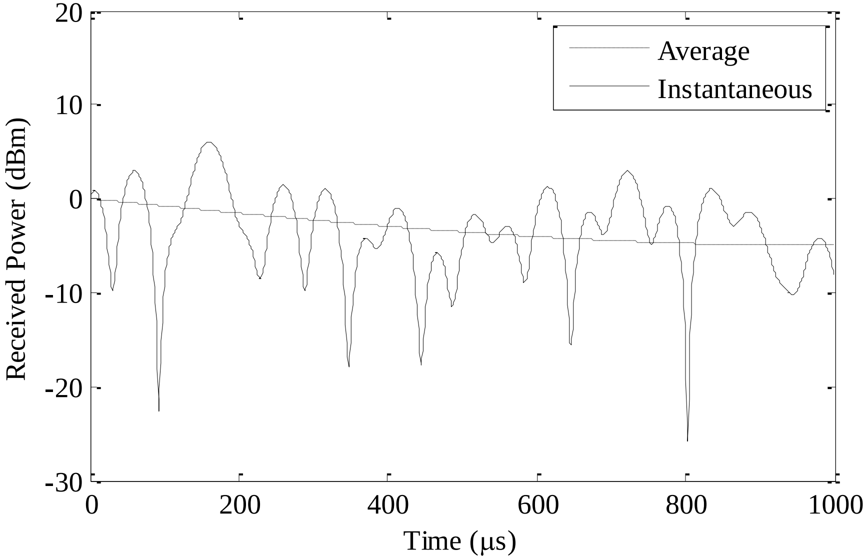
RF Systems Course: Advanced Modulation and Channel Issues II

Multipath Interference and Fading

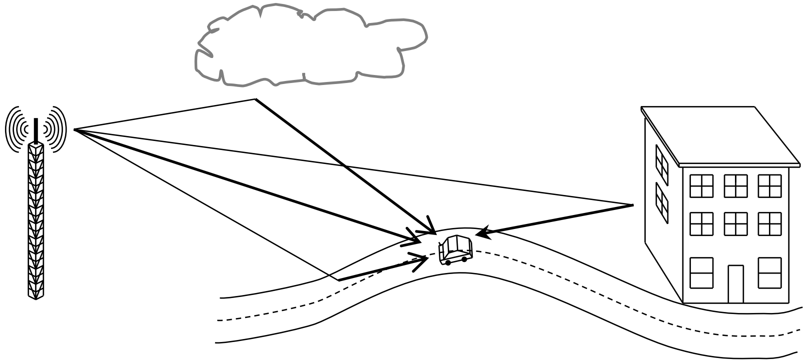
- signals transmitted wirelessly travel in all directions from antenna.
- They are reflected, diffracted, scattered by objects in the environment
- some of these replicas of Tx signal will inevitably arrive at Rx.
- there are multiple paths between Tx and Rx
- Each of these paths has its own attenuation and delay
- Some of these signals may arrive in anti phase and cancel each other.

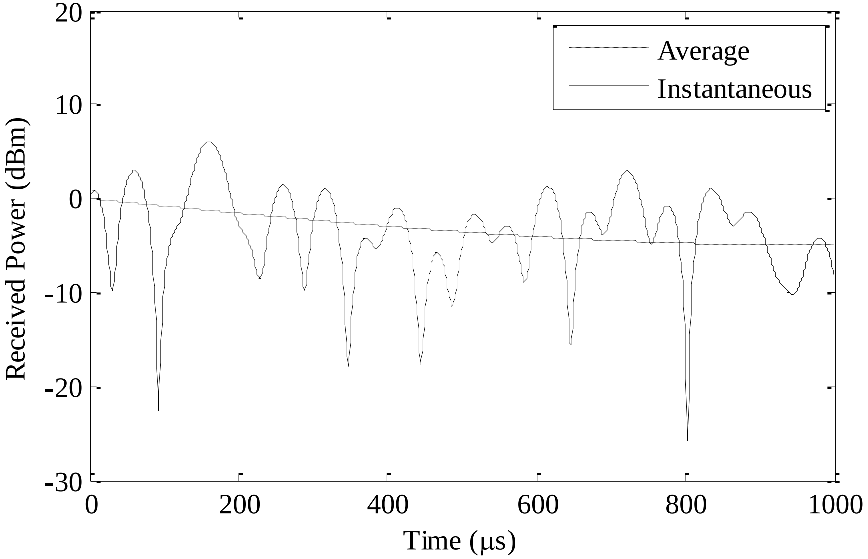




Multipath Interference and Fading

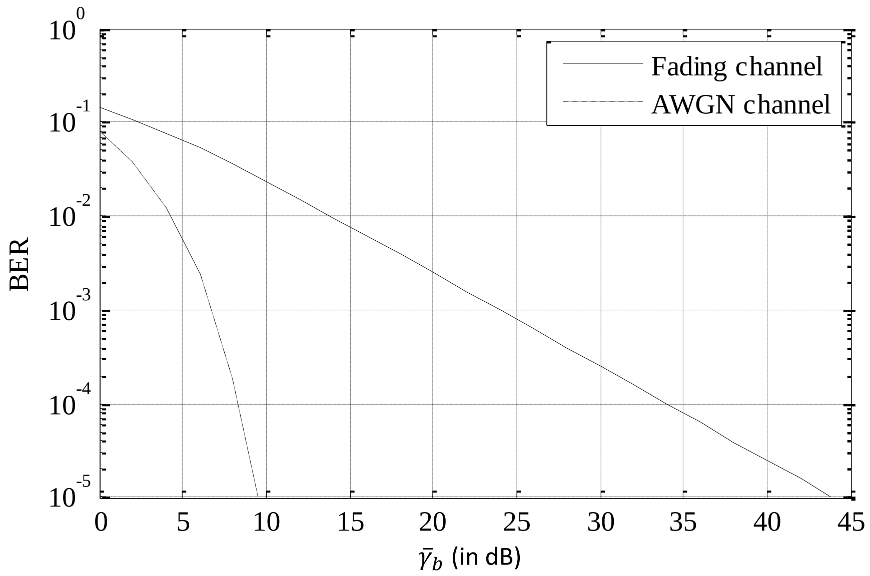
- Although path attenuations change over time happens slowly.
- phases can change quickly because movement of less than half a wavelength can cause change in propagation delay by enough to result in a 180° change in phase.
- motion of only a few centimeters can cause *signal strength* to change significantly.
- over time Rx signal power changes quickly about its mean due to multipath fading.
- mean power itself also changes over time because of changes to pathloss and shadowing, this occurs much more slowly.
- This phenomenon is referred to as *multipath fading* or *Rayleigh fading*.
- The instantaneous power often fades by up to 20 dB or more below the average.





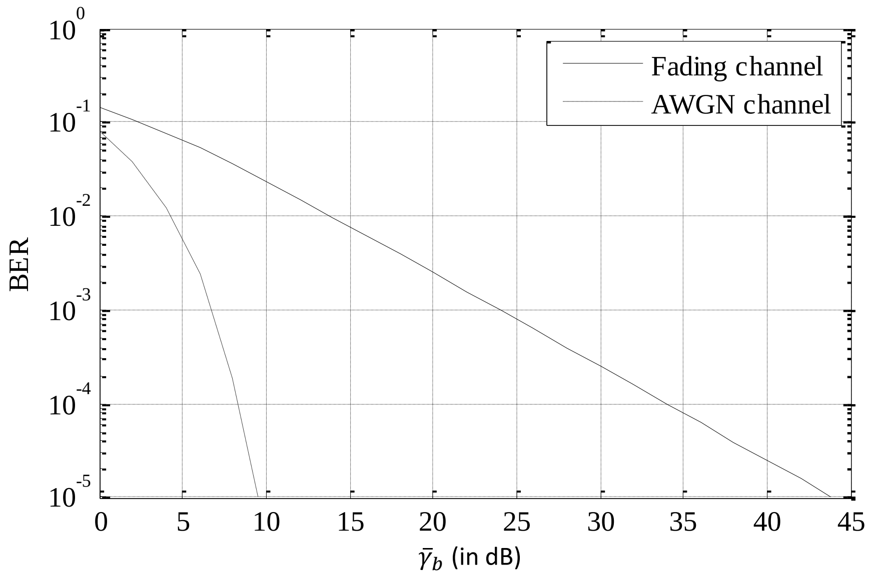
Multipath Interference and Fading

- Multipath fading is serious impediment to reliable wireless communication.
- without fading, BER depends on instantaneous SNR.
- In a fading environment, where instantaneous SNR is random, more interested in average BER than instantaneous SNR.
- to achieve a target BER, average SNR must be much larger for fading channels than for AWGN channel.
- BER only drops by one order of magnitude for each 10 dB increase in the SNR.



Multipath Interference and Fading

- In previous discussion, considered case when the signals along all paths arrive at essentially same time.
- usually some dispersion in propagation delays.
- *delay spread* of channel is time difference between shortest and longest delays.
- If delay spread is longer than a fraction of symbol duration, then each Tx symbol will be spread over more than one symbol interval, resulting in ISI.
- channel no longer has a flat freq response, as some freqs are attenuated more than others.
- Because freq response is also time-variant, this type of multipath interference is referred to as *frequency selective fading*.

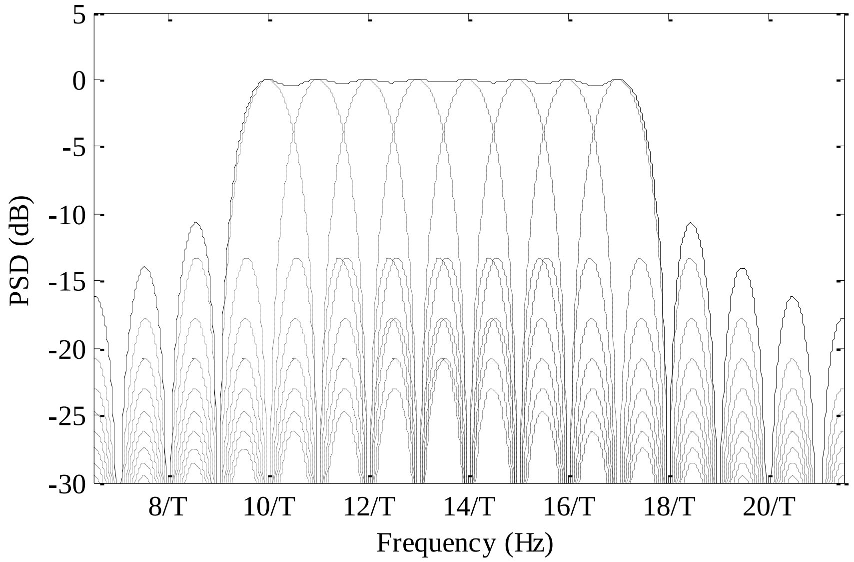


Advanced Techniques

- To provide better performance in wireless communication systems, many more advanced communication techniques have been developed and deployed in commercial systems.
- designed to help overcome difficulties caused by multipath fading, both freq flat and freq selective.
- use of orthogonal frequency division multiplexing (OFDM) allows for easy freq domain equalization of freq selective fading channels.
- Using multiple antennas at Tx and/or Rx allows for beamforming, spatial diversity against fading, spatial duplexing for higher throughput.
- Spread spectrum systems allow for better protection against interference and jamming, and easy multiuser spectrum sharing.
- Error control coding allows for detection and correction of transmission errors, significantly improving reliability of communication system.

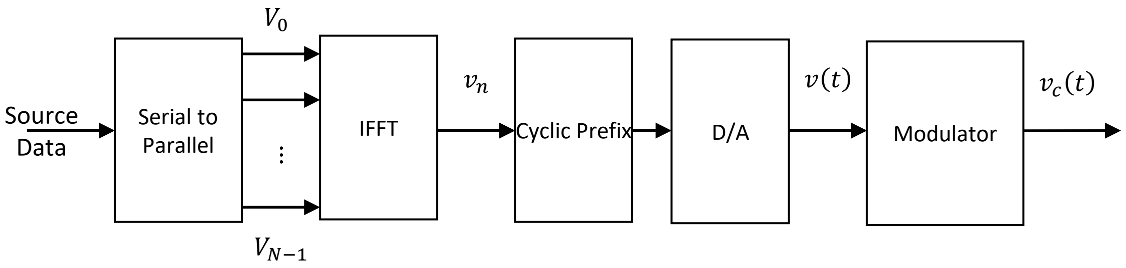
OFDM

- OFDM is a modulation scheme that is designed to improve performance from freq selective fading.
- replace single carrier with a wide BW with multiple carriers (called subcarriers) which individually have a narrow BW.
- instead of having one carrier with BW = 8 MHz, can be 8 subcarriers each with BW= 1 MHz.
- Typically, #subcarriers between 16 and 1024.
- During each OFDM symbol interval, *N* different PSK or QAM symbols are transmitted simultaneously, with each symbol transmitted on a separate subcarrier.
- separation between subcarriers is chosen to be $1/T$, -> signals orthogonal even though they overlap in freq
- no need for guard bands between subcarriers, allowing for tightest packing of subcarriers



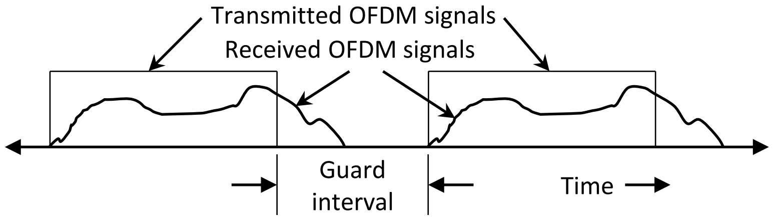
OFDM

- To avoid need for multiple RF signal chains, one for each subcarrier, OFDM signals are generated by using clever digital signal processing.
- Tx data first passed through a serial-to-parallel converter
- data in each stream mapped to points in signal constellation, typically QAM or PSK.
- not necessary to use same constellation for each subcarrier.
- Because each symbol is transmitted on a different subcarrier, can view these symbols, as a freq-domain representation of Tx signal.
- By applying inverse fast Fourier transform (IFFT) to symbols, can get a time-domain representation of signal.



OFDM

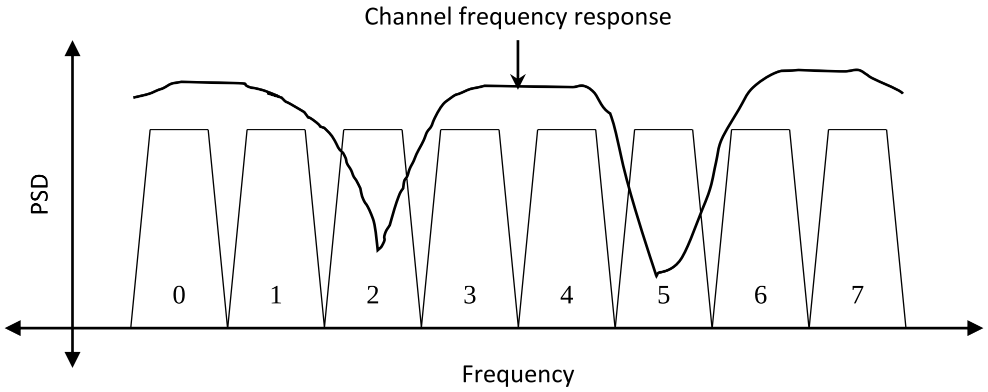
- OFDM signals usually intended for transmission over freq selective fading channels
- will cause OFDM signal to spread out over longer duration that *T* seconds when received.
- To prevent consecutive OFDM symbols from interfering with each other, it is a good idea to insert a guard interval between symbols
- duration of guard interval should be as long as max expected delay spread of channel.
- instead of not transmitting anything during guard interval, last few samples of following OFDM symbol are transmitted during guard interval.
- Doing so allows for simple equalization at receiver to counteract distortion.
- resulting sequence of samples are passed through the DAC and then up-converted by modulator to desired freq band.



OFDM

- After transmission, received signal is down-converted, filtered, and sampled.
- An FFT is applied to the received samples to recover transmitted symbols.

- If channel is not freq selective, BER for OFDM is same as single carrier case using same modulation
- in straight line-of-sight environments like satellite there is little advantage to using OFDM
- biggest benefits come with freq selective channels, where there is no need for complex time-domain equalizer (which is usually implemented with an adaptive tapped delay line), because each subcarrier essentially experiences freq flat fading.
- some subcarriers may have severe fading while others are very good.
- symbols transmitted on subcarriers 2 and 5 are severely attenuated and it may not be possible to reliably recover corresponding transmitted bits.
- If Tx knows channel freq response, it can avoid transmitted data on poor subcarriers.
- If not, Tx can use channel coding so Rx can recover data transmitted on weak subcarriers based on data received on other subcarriers.



OFDM

- OFDM also offers some BW advantages.
- If single carrier tone is used to transmit say 20 MB/s and a 25% guard band is used then total signal will occupy 25 MHz of spectrum.
- If same data is transmitted using 10 subcarriers, with 25% guard band on only first and last subcarriers then only 20.5MHz is needed.
- subcarriers don’t need guard bands from each other because they are orthogonal.
- by reducing power in subcarriers near edges, and by using an appropriate windowing function prior to DAC, possible to generate signals with very low sidelobes.
- OFDM can also be used as part of a multiple-access scheme to transmit different data streams to different receivers (users) simultaneously.
- known as orthogonal frequency division multiple access OFDMA
- set of subcarriers is divided into subsets, and each subset is assigned to a different user.
- Data for each user is transmitted only on subcarriers assigned to the user, while data for other users are transmitted on other subcarriers.
- very similar to regular FDMA, except OFDMA subcarriers are used instead of separate carriers.
- However has some important advantages over FDMA.
- Because each user receives entire OFDMA signal, it recovers the data on all the subcarriers and then discards unwanted data.
- very easy for system to dynamically allocate subcarriers to users without any need to tune the receivers to different freqs.
- with OFDMA some users can easily be assigned more subcarriers than others if they have different throughput requirements, whereas in a traditional FDMA system it is difficult to dynamically adjust signal BW.
- because each user experiences different channel conditions, some subcarriers may be severely faded for one user but very strong for another.
- Careful assignment of subcarriers to users can ensure that each user is served only with good subcarriers, while each subcarrier is likely to be good for at least one user.
- Although OFDM provides many advantages over single-carrier systems, Tx signal does not have a constant envelope, even when using constant envelope signals with PSK on each subcarrier.
- OFDM signals have a notoriously high peak-to-average power ratio (PAPR).

Multiple Antenna Systems

- By using multiple antennas at Tx and/or Rx possible to significantly improve system performance.
- Techniques that can be used include beamforming, receive and transmit diversity, spatial multiplexing.
- By using an array of antennas that are closely spaced with a fixed and carefully measured separation between antennas possible to exploit deterministic phase differences between signals on different antennas.
- If an antenna array is used at Tx, same signal can be sent over all antennas, but with slightly different delay.
- Resulting phase differences cause signals to combine constructively for signal propagating in some directions.
- possible to focus Tx power in any desired direction
- similar to using directional antenna, BUT possible to quickly change direction dynamically by changing phase of signal on each antenna element.
- known as *beamforming*, can also be used to simultaneously transmit 2 different signals to 2 different Rx, provided Rx in different directions.
- Beamforming can also be used at Rx.
- By adjusting phases of signals received on antennas, possible to dynamically adjust direction in which antenna array collects signals.
- It can lock onto signal from desired Tx while blocking signals arriving from Txs in other directions.
- In wireless systems where fading is a problem it can be beneficial to place antennas at Rx farther apart (usually at least a few wavelengths apart).
- signal fading on each antenna will be nearly independent, so it is unlikely that all the received signals will be weak at the same time.
- noise signals will be essentially independent
- simple Rx could just select the signal from “best” antenna at any given time -> *antenna selection*.
- better technique -> combine samples from all antennas, weighting them proportionally to their attenuation in a technique known as *maximal ratio combining* (MRC).

Multiple Antenna Systems

Example Using MRC to increase the SNR.

System with 2 receive antennas, first receives 0.1 mVrms, second one receives 0.13 mVrms.
noise present in BW of interest is 10 mVrms.
Use maximal ratio combining and determine the overall SNR.

Solution:

SNR from 1st antenna will be 20 dB
2nd antenna SNR = 22.3 dB.
If antenna selection used, only signal from 2nd antenna used and SNR = 22.3 dB
With MRC SNR will be

$$\text{SNR} = 10\log\frac{\alpha_1^2 P_S + \alpha_2^2 P_S,}{P_N}$$

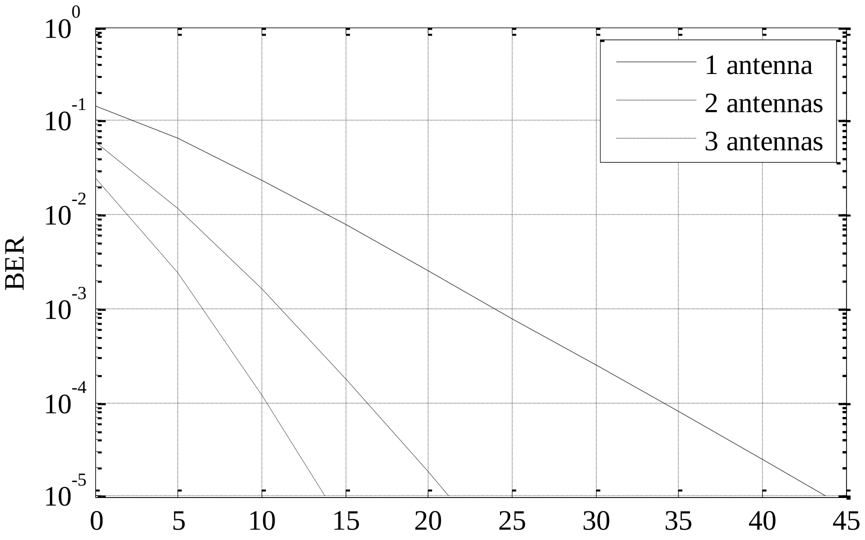
$$= 10\log\frac{(0.1\times 10^{-3})^2 + (0.13\times 10^{-3})^2}{(10\times 10^{-6})^2}$$

$$= 10\log 269 = 24.3\ \text{dB}$$

Multiple Antenna Systems

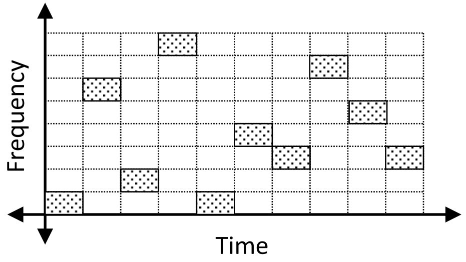
- multiple antennas at Rx to obtain multiple copies of Tx signal, each with different fading, is known as *antenna diversity*
- Increasing # of antennas leads to significant improvement in performance because BER drops more quickly as SNR increases.
- *diversity order* of a system is defined by the slope of BER curve.
- 2 antennas BER drops by 2 orders of magnitude for every 10 dB increase in SNR so diversity order is 2, whereas it drops by 3 orders of magnitude with 3 antennas, giving a diversity order of 3.

- not always possible to place multiple antennas sufficiently far apart in many mobile devices -> not possible to get receive antenna diversity when transmitting to such devices -> use multiple well-separated antennas at Tx
- but more difficult to get transmit antenna diversity.
- If complex channel gains are accurately known at Tx, Tx can adjust signal phases prior to transmission so that they will combine constructively at Rx, or Tx can just transmit over "best" antenna.
- If there are multiple antennas at both Tx and Rx, system is known as *multiple-input multiple-out (MIMO) system*.
- With MIMO systems possible to make use of *spatial multiplexing*, where multiple symbols are transmitted during each symbol period, thereby significantly improving the system throughput.
- If channel knowledge is available at Tx, possible to use precoding at Tx to generate multiple virtual channels between Tx and Rx that also provide additional diversity.



Spread Spectrum Systems

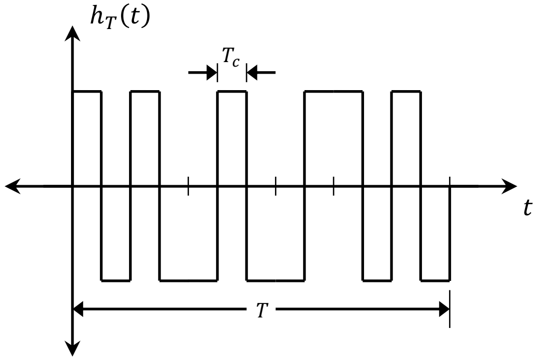
- Another way to avoid poor performance caused by freq flat fading is to employ a *spread spectrum* technique.
- a spread spectrum system, a narrowband signal is intentionally spread over a much wider BW than is required.
- narrowband signal, which may have been subjected to freq flat fading, is more likely to experience freq selective fading, which is less detrimental because only a portion of signal is lost during deep fades.
- Spread spectrum systems are also more robust against narrowband interference such as intentional jamming.
- Because signal power spectral density is very low it is difficult for an observer to detect whether or not communication is taking place
- 2 most common spread spectrum systems in use are freq hopping spread spectrum (FHSS) and direct sequence spread spectrum (DSSS).
- With freq hopping narrowband signal is transmitted using a rapidly changing carrier freq.
- hopping sequence which determines which freq band to use next is determined in a pseudo random fashion that is known to both Tx and Rx.
- An eavesdropper that does not know hopping pattern will not be able to track signal because it will not know which band to tune to at any given time.
- With slow freq hopping, carrier freq changes more slowly than symbol duration
- With fast freq hopping, each symbol is transmitted at many different freqs, so it is unlikely that an entire symbol will be lost due to fading.
- However RF system design is more complicated because hopping occurs so rapidly.
- With slow hopping it is possible that whole symbols will be lost, but because other symbols are received reliably, an error correcting coding scheme can be used to recover lost symbols.
- It is worth noting that even with slow hopping it is difficult to acquire a carrier reference phase, so QAM and PSK are difficult to implement.
- FHSS is better used with FSK or ASK.



Spread Spectrum Systems

- Direct sequence spread spectrum provides an alternative method for spreading signal.
- It involves using a pulse shape with a very wide BW.
- impulse response of filter usually made up of large # very short rectangular pulses called chips.
- E.g. pulse shape composed of $\eta=13$ chips, each with duration T_c seconds.
- Because resulting signal has BW $\propto 1 T_c=\eta T$ instead of $1T$, this is a spread spectrum signal, with BW expansion factor of η.
- Recovery of Tx signal at Rx can be performed with matched filter, matched to spread pulse shape.

- much of pulse shaping performed digitally.
- Tx constellation point is repeated and multiplied by spreading code, which is sequence of ±1's reflecting amps of pulse shape.
- For pulse shape shown, spreading code is $+1,-1,+1,-1,-1,+1,-1,-1,+1,+1,-1,+1,-1$, so instead of just transmitting an amp of, A, for T secs, sequence of amps $A,-A,A,-A,-A,A,-A,-A,A,A,-A,A,-A$ is transmitted, with each segment lasting only T_c seconds.
- By spreading each symbol over a wide freq band whole symbol is less likely to be lost because of fading.



Error Coding

- Error control coding useful for reducing required SNR.
- An encoder at Tx can add redundancy to data prior to transmission, and corresponding decoder at Rx can detect and/or correct transmission errors.
- an error control coding scheme involves taking a *message word*, and mapping it to a *codeword*, prior to transmission.
- extra bits are appended to message word to give the codeword called *parity bits*, these bits depend only on the message word.
- most simple error control coding scheme is single parity bit.
- E.g. sequence 1011 will be encoded as 10111, final bit is the parity bit.
- Rx can count # of 1s, and if this # is odd then an error occurred.
- With this coding scheme, Rx can detect occurrence of any single bit error.
- can also detect whenever an odd # of bit errors occurs, but if probability of a bit error is low then it is much less likely that multiple bits will be in error
- if an even # of bit errors occur then Rx will not be able to detect that errors have occurred.
- If error are detected the receiver can ask for a retransmission of the message, and it can continue doing so until the message is received correctly (or at least until no errors are detected).
- This type of retransmission scheme, known as *automatic repeat request* (ARQ), is widely used in wireless systems (and in the Internet).
- Although it can give a much, much lower probability of error, it does lead to a reduction in throughput -> there is overhead involved in transmitting parity bits
- In some wireless communication systems not possible to perform retransmissions.
- With an error correcting code Tx adds a much high fraction of redundancy to transmitted message, allowing for error correction as well as detection at Rx.
- This is useful not only for cases where retransmissions are impossible, but also for cases where it is desirable to reduce probability that retransmissions are required.
- Most modern communication systems use error correcting codes.

Error Coding

- E.g. of error correcting code is the (6,3) shortened Hamming code, where message words of $k=3$ bits are mapped to codewords of $n=6$ bits at Tx, according to mapping rule shown in Table 2.3.
- E.g. message 100 is mapped to codeword 100011, which is transmitted.
- If received codeword is not in table then Rx knows that transmission errors have occurred.
- It can either request a retransmission, or it can attempt to correct.
- Because it is not likely that many errors occurred, optimal decoding strategy is to find codeword that is "closest" to received word, where closeness is measured in terms of the *Hamming distance*.

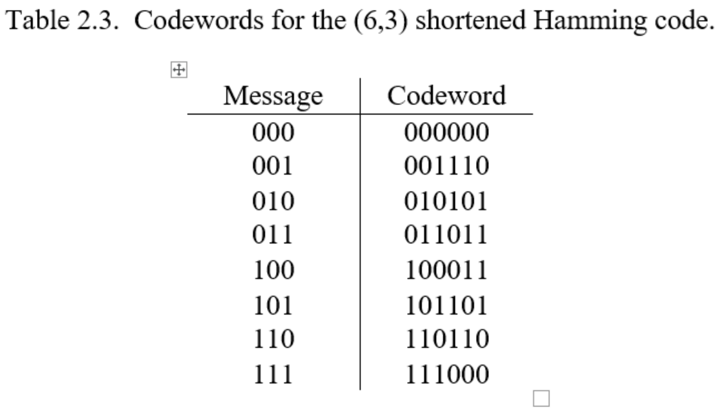


Table 2.3. Codewords for the (6,3) shortened Hamming code.

Message	Codeword
000	000000
001	001110
010	010101
011	011011
100	100011
101	101101
110	110110
111	111000

- Although this simple Hamming code is useful for illustration much better codes available.
- With any error correcting code, still possible that errors will remain after error correction has been attempted.
- One important factor affecting performance of a code is *code rate*, which is defined as the fraction of message bits per code bit, the smaller the rate, the lower the BER.
- But this comes with a corresponding reduction in the throughput, so in most applications only codes with rates greater than 1/3 are used.