There are a number of tradeoffs to be made in the design of a wireless digital data communication system. With analog voice communication, we can use the speech recognition capabilities of our brains to compensate for signal degradation in the transmission channel. For digital communication, the processing power of a computer must be used. This requires making tradeoffs to minimize both the amount of energy that must be radiated by the transmitter and the complexity of the signal processing required at the receiver. These tradeoffs tend to fall into four categories:

1. Power versus Bandwidth
2. Transmission Channel Limitations
3. Frequency Selection
4. Limited Spectrum Availability

Claude Shannon enumerated the power versus bandwidth tradeoff in 1948. For a given bandwidth, using more power can increase the rate of information transmission. Conversely, for a given information rate, using a wider bandwidth can decrease the amount of power required. Figure 1 shows the theoretical signal to noise ratio (SNR) required with a perfect demodulator for various forms of modulation for a $10^{-5}$ symbol error rate in an additive white Gaussian noise (AWGN) channel. This is a channel where the only source of interference is the thermal noise generated by the random motions of charged particles in atoms and molecules when they are at a temperature above 0 K. The amount of electromagnetic energy radiated is proportional to the temperature and has constant power spectral density over a wide frequency range. Thus, when it is viewed at optical frequencies, it appears white.

| **Symbol States** | | 2 | 4 | 8 | 16 | 32 | 64 | 256 |
|---|---|---|---|---|---|---|---|---|
| **Bits per Hertz** | | 1 | 2 | 3 | 4 | 5 | 6 | 8 |
| **SNR (dB)** | **ASK** | 10 | 17 | 24 | 30 | 36 | - | - |
| | **PSK** | 10 | 13 | 18 | 24 | 30 | 36 | 47 |
| | **DPSK** | 11 | 15 | 21 | 27 | 33 | 39 | 51 |
| | **QAM** | - | 13 | - | 20 | - | 26 | 32 |
| | **DQAM** | - | 15 | - | 23 | - | 29 | 35 |

Table 1. Required SNR for Data Rates Greater than the Signaling Rate

As the data rate (in Bits/Hz) increases, the amount of power required increases dramatically. Doubling the data rate from 1 to 2 bits per Hertz requires doubling the transmitter power. However, doubling the data rate gets progressively harder -- going from 4 to 8 bits per Hertz requires increasing transmitter power by a factor of sixteen. This is because the power required increases with the number of states of the symbol (the signal constellation size) rather than the number of bits transmitted. Increasing the number of states in a phase shift keyed (PSK) or amplitude modulated (AM) signal uses only one dimension and ultimately requires 4 times more power for each doubling. If both phase and amplitude information can be utilized, the power increase can be limited to a factor of 2, as 2 dimensions are utilized as shown in figure 1.

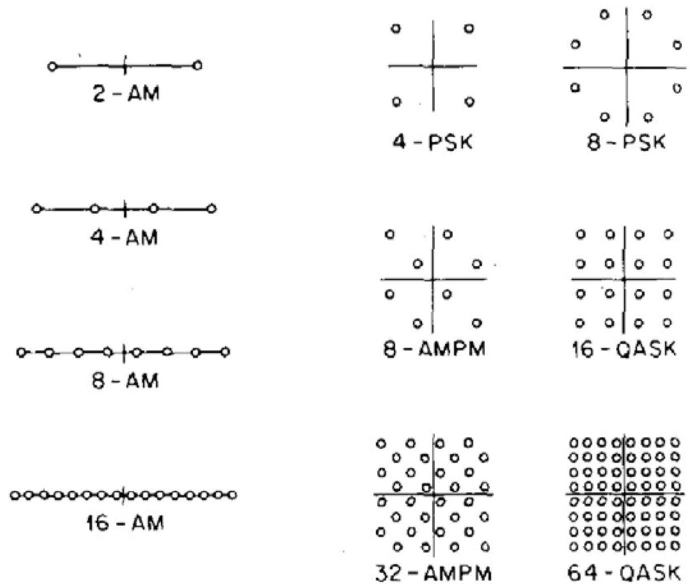

Figure 1. Signal Constellations

Adding redundancy to the transmitted signal can decrease the amount of power required at the transmitter. The information-bearing signal is spread out over time. Multiple copies of the signal will correlate but the noise will not correlate so the signal to noise ratio is increased. This is performed most efficiently by using an error correcting code. A rate ½ code doubles the bandwidth occupied by the transmitted signal but decreases the power required by a factor of 2 to 4 at a $10^{-5}$ symbol error rate. The amount of reduction depends on the complexity of the decoder. A bandwidth expansion of 16 can reduce the power level by a factor of 25. The effect is similar to analog FM modulation – increasing signal redundancy increases the error rate at low SNRs and decreases it at high SNRs. Large signal constellations and coding can be combined to produce high data rates at reasonable power levels.

In outer space, this is all that we need to contend with. The thermal noise level is 2.7 K between 2 GHz and 50 GHz and signals need to be a certain level above that noise. Below 2 GHz the noise level increases at 6 dB per octave due to the black hole at the center of our galaxy. Above 50 GHz, the noise level increases at 6 dB per octave due to quantitization noise because the energy required per photon increases with frequency.

On Earth, the situation is more complex. First, the average temperature is 290 K so the thermal noise level is about 100 times higher and transmitter power must be 100 times higher for the same path loss. Second, there are lots of objects that absorb, diffract and reflect electromagnetic radiation as shown in figure 2. This includes solid objects, such as mountains and buildings, and gasses, such as the atmosphere and the ionosphere. These do two things to the signal. They cause the received signal to arrive via multiple paths, spreading the energy out over time. In addition, these objects move, causing Doppler shift that spreads the energy over a band of frequencies.  There are two general cases.

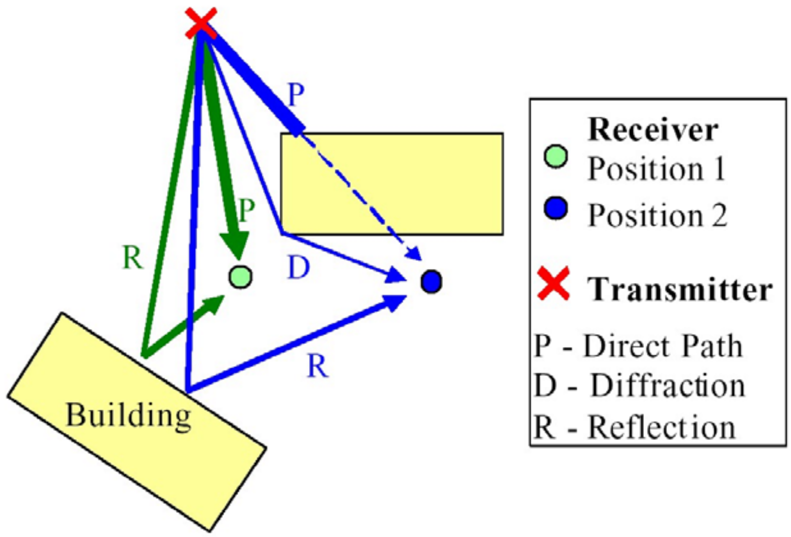


Figure 2. Signal Propagation with Obstacles

Between 3 kHz and 30 MHz, the electric charge density of the ionosphere is high enough to reflect signals back to Earth by continuous refraction. Not only are desired signals reflected, but also the energy from all of the thunderstorms throughout the world. This raises the ambient noise level by 20 to 40 dB over the thermal noise level so transmitter power must be increased to compensate. Below 3 MHz, the properties of the ionosphere are fairly stable, except for a diurnal variation that causes instability at sunrise and sunset. However, between 3 and 30 MHz, its characteristics are extremely variable. The Doppler shift varies between 0.1 and 1 Hz and the multi-path spread varies between 1 and 10 ms. Propagation via auroral paths is even worse.

Between 30 MHz and 300 GHz, propagation conditions are more stable. Figure 3 shows the multi-path spread for a 2.3-km long path in an urban area at 910 MHz.

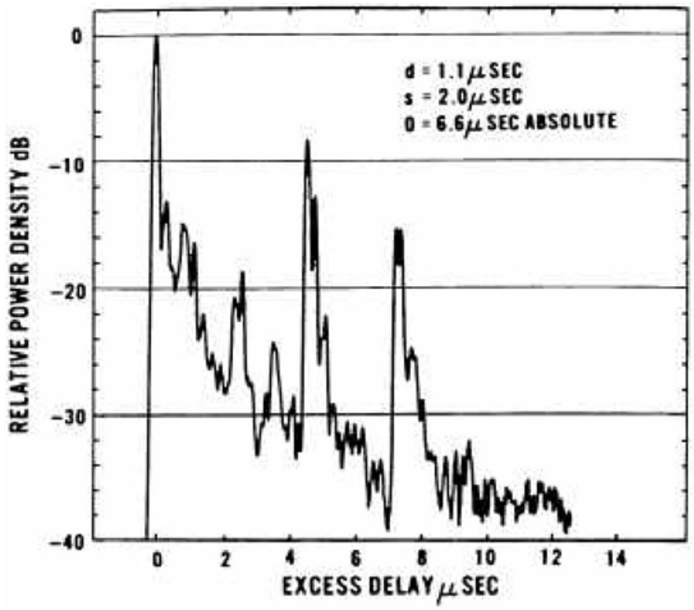

Figure 3. Multi-path Spread for 2.4 km Path at 910 MHz.

The Doppler shift is generally less than 10 Hz up to 30 GHz and the multi-path spread is usually between 0.4 and 20 μs. Rural areas have less multi-path propagation and urban areas have more multi-path propagation. Shorter paths have shorter spreads and longer paths have longer spreads. There are two approaches to alleviate this problem and the effectiveness depends on the environment.

When information is transmitted serially, the effect is to smear one transmitted symbol into the next transmitted symbol, causing inter-symbol interference (ISI) and a much higher error rate. If the spread is a small fraction of the symbol period, the receiver can perform equalization. An algorithm that determines the delays of the two or three highest amplitude rays and inserts a compensating delay at the receiver accomplishes this. The energy from all rays is then combined to increase the SNR. This can work well until the spread becomes larger than ½ of the symbol period. Thus, the symbol rates accommodated could extend to between 25 and 1,250 kBaud, depending on the local environment. The D-Star system uses this approach with GMSK modulation at 128 kBaud for a throughput of 128 KBPS. The advantage is that the RF amplifier can be non-linear so that a PA module made for an analog FM transceiver can be re-used.

An approach that works at higher data rates is orthogonal frequency division multiplexing or OFDM. This method divides the communications channel into smaller and smaller frequency bands until the multi-path spread is a fraction of the symbol rate. Multiple carriers are then transmitted with many bits in parallel. If the carrier spacing is the inverse of the symbol period the sidebands of each carrier do not interfere with each other and orthogonality is maintained. A gap between received symbols is inserted that is longer than the expected multi-path spread. At the transmitter, this is filled with a copy of the end of the next transmitted symbol. The receiver never sees the multi-path interference. The cost of this is the extra energy transmitted to fill the gap. If the gap is less than 25% of the symbol rate, the loss is less than 1 dB. For example, a symbol rate of 4800 Baud allows a gap of 41.7-μs, which removes most ISI in the 30 MHz to 30 GHz range. For 3-30 MHz, the optimum symbol rate is near 12 Baud. OFDM required linear power amplifiers, so they are somewhat less efficient. However the overall power efficiency is improved.

In either case, there is a limit on the length of the received symbol if two-dimensional modulation is to be used. The Doppler spread rotates the received signal constellation at a rate of 360° per second per Hz, causing errors. The amount of rotation in one symbol period should be less than ¼ of the distance between symbol states. Thus, for a 10 Hz Doppler spread, received symbols should be less than 12.5 ms in width for BPSK and less than 1.56 ms in width for 256QAM. This puts a lower limit on the symbol rate of about 500-Baud for the 30 MHz to 30 GHz range. For HF, the 1 Hz Doppler spread and 12-Baud symbol rate limits the complexity of the signal constellation to DQPSK.

The path loss varies as the incoming rays enforce each other or cancel. For fixed stations, this is a slow variation, but for mobile stations the rate increases with velocity. Signal redundancy over time is used to combat fading. Codes that combat thermal noise are not the best for fading. Generally an additional error correcting code that is optimized for correcting bursts of errors, such as a Reed-Solomon code, is used to combat fading. These codes generally have a rate of 80-95% and can decrease the required power level by a factor of ten by allowing the bits received during a null to be lost. Two rays will generally cancel completely for only a short period of time as shown in figure 4.

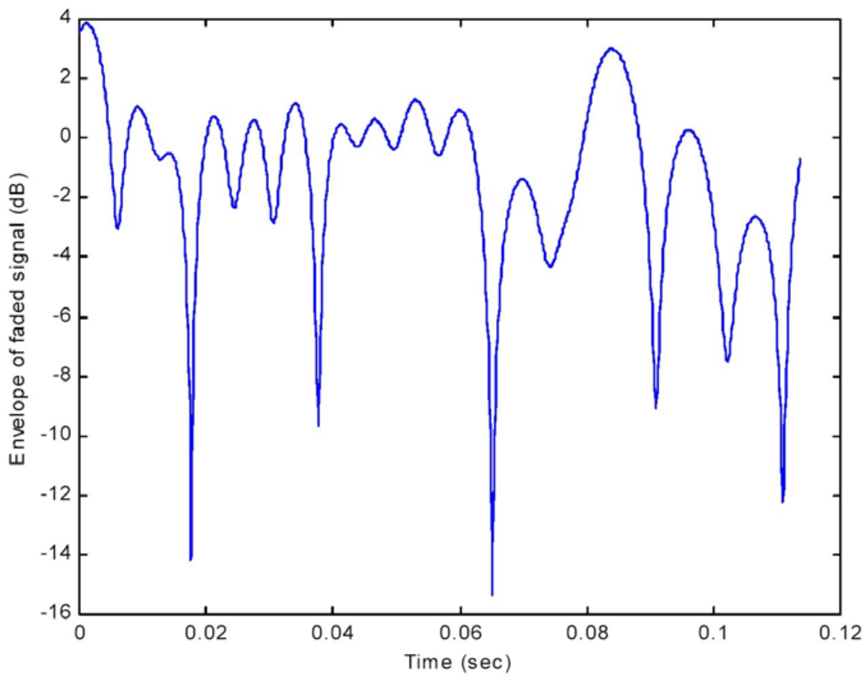


Figure 4. Amplitude of Fading Signal over Time

OFDM increases the effectiveness of error correction during fading as the fading channel has a narrow bandwidth. This ensures that the fade is flat and not frequency selective. When a signal occupies a wide bandwidth the fading can generate a notch in the frequency spectrum that sweeps across the signal. This results in extreme levels of distortion and high error rates that persist over an extended period of time.

For moving vehicles, the maximum frequency that can be used with phase modulation is determined by the Doppler shift. In part 2, the proposed UHF-RMAN OFDM modem standard uses a carrier spacing of 1.5 kHz up to 450 MHz and 6 kHz up to 2.4 GHz. The reason is as follows. For automobiles operating at 75 MPH the Doppler shift is 0.112 PPM or 270 Hz at 2.4 GHz and 51 Hz at 450 MHz. This causes the signal constellation to rotate by 16° per symbol period at 2.4 GHz and 12° per symbol period at 450 MHz. Since the minimum difference between symbols is 45° for 8DPSK modulation, these are near the maximum frequencies that should be utilized with the specified carrier spacing. Fixed stations could use more complex signal constellations.

When Doppler shift cannot be avoided and cannot be compensated for, amplitude shift keying must be used and the amount of power required increases dramatically.

Path loss, for antennas of a given gain, varies with the square of the frequency. When omnidirectional coverage is desired, there are limits on the range of frequencies that can be used. To achieve high data rates, we need to operate above 30 MHz and avoid ionospheric propagation. The minimum antenna length for efficient generation of electromagnetic waves is ¼ wavelength. At 50 MHz, a ¼-wavelength antenna is 5 feet long, has a gain of 2 dBi and fits on any vehicle. If we are willing to forgo communication with aircraft, the antenna pattern can be compressed in elevation and remain omnidirectional in azimuth. However, the pattern cannot be compressed to less then 6° as this would compromise communication between stations at different altitudes. This antenna has a gain of 16 dBi and would be approximately 5 feet long at 2.4 GHz. The difference in total path loss is:

| | |
|---|---|
| +34 | Increase in path loss from 50 MHz to 2.4 GHz |
| -14 | Additional antenna gain at 2.4 GHz vs. 50 MHz |
| -12 | Reduction in noise level from 50 MHz to 2.4 GHz |
| 8 | dB increase in power required at 2.4 GHz vs. 50 MHz |

Therefore, the frequency allocations for the amateur radio service that are below 1.3 GHz are preferred, as they require four times less power for a given data rate.

The final consideration is spectrum availability. Above 902 MHz, there are no FCC limits on data rate. The only limitations are those in the ARRL band plans and the local band plans. Several 3 MHz sub-bands are allocated for high-rate data transmission. With 384 data carriers at 6 kHz spacing, a 4800 Baud symbol rate and 768 bits per symbol, a data rate of 3.6864 MBPS can be achieved for land mobile and maritime mobile operation.

In the 219-220 and 420-450 MHz bands, the FCC limits data communication to a 100 kHz occupied bandwidth. With 48 data carriers at 1200 Baud and 96 bits per symbol a data rate of 115.2 KBPS is possible. The FCC classifies digital video differently so a wider bandwidth can be used. With 384 data carriers at 1200 Baud and 768 bits per symbol a data rate of 921.6 KBPS can be achieved. This would require a 750 kHz wide channel. The rates could be doubled for fixed stations.

The 50-54, 144-148 and 222-225 MHz bands have a 20 kHz maximum occupied bandwidth limit for data transmission. This limits the data rate to 20-40 KBPS. With a rules change 100-400 KBPS would be practical.