

## Spread Spectrum Techniques

### **Introduction**

Spread Spectrum Techniques either modulate the input signal with a carrier that has many frequencies contained in it (CDMA) or rapidly switches the carrier frequency (Frequency Hopping), resulting in the transmitted signal being of a much wider bandwidth or they modulate a data source on many different individual carriers (COFDM) and combine different data sources such that these carriers are intermingled resulting in the transmitted signal having a wider bandwidth than that required for the single source. In all these systems many different data signals share the same transmitted spectrum, but are still being able to be separated. Having a wider spectrum gives immunity to interference at one frequency or signal cancellation at one frequency due to multipath fading.

### **Code Division Multiple Access (CDMA)**

In AM or ASK the data is modulated with a single carrier, resulting in a shift of the baseband spectrum to around the carrier frequency. In CDMA the data is modulated with a “carrier” that is a Pseudo Random Sequence, Gold Code or Walsh function. This “carrier” has many spectral components and occupies a bandwidth that is far greater than the bandwidth of the baseband signal. The resulting modulated signal spectrum will thus occupy a much greater bandwidth than the original data signal. This technique is called Direct Sequence CDMA (DS-CDMA) and is normally referred to simply as CDMA. Different users can have different coding sequences as carrier signals and if these coding sequences are orthogonal, that is if the result is zero when they are multiplied together over a certain period, then those two data signals can be transmitted in the same RF spectrum and they can be separated by using this orthogonal property. CDMA systems were initially developed for military uses to firstly make the signal look like noise, so that others cannot detect it, secondly to make it very difficult to jam the transmission and thirdly to provide encryption, since without knowing exactly what the carrier sequence is, the signal cannot be demodulated.

Qualcom in the USA was behind the development of a CDMA cellular mobile radio system that uses DS-CDMA techniques for modulating the data. The block diagram of a DS-CDMA system is shown in Figure 1. At the transmitter the data is multiplied by the coding sequence as a “carrier”. At the receiver the signal is demodulated by multiplying it with the same Coding Sequence as a “Local Oscillator”. The “chip rate” is the clock rate of the Coding Sequence and that is normally many times that of the input data rate. The chip rate determines the spectral bandwidth of the transmitted signal. Figure 2 shows this process. The input data spectrum is much narrower than the spread spectrum coding sequence, which corresponds to the Carrier in an AM or DSB-SC modulation system. Since the “carrier” now is a noise-like signal the resulting transmitted signal is also a noise-like signal with a wide spectral bandwidth, closely matching that of the coding sequence. At the receiver the received signal is multiplied with exactly the same coding sequence as is used in the transmitter and as a result, they will correlate and the demodulated data is the same as the input data.

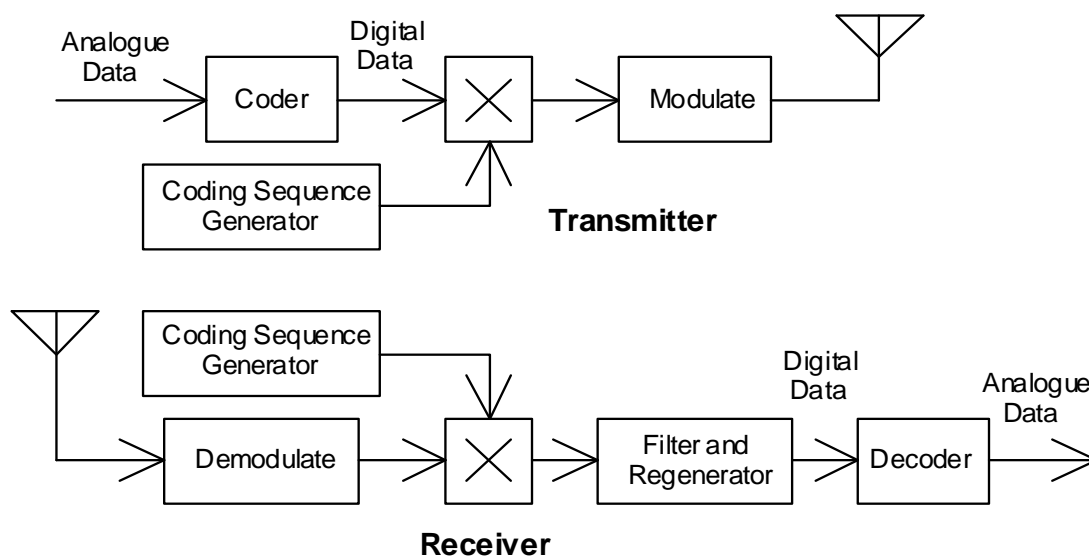


Figure 1. Block Diagram of a DS-CDMA system

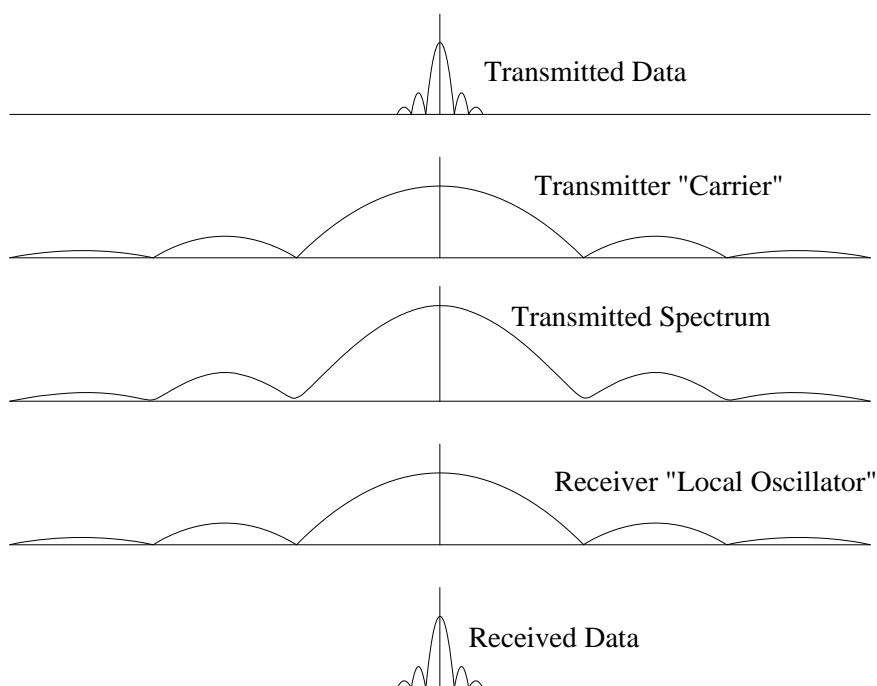


Figure 2. CDMA waveforms.

Since the modulation process and the demodulation process in a CDMA system are the same, the signal spectrum from other users and interferers are spread during demodulation. The wanted signal however correlates and its bandwidth is reduced. If there are  $N$  Coding Sequence bits per data bit period, the wanted signal produces an output of  $N$  units all the same, while an uncorrelated signal produces  $N$  random output signals, resulting in a negligible output.

During the demodulation process the spectrum occupied by the signal is reduced by a factor  $N$  and since the same signal power now occupies a reduced bandwidth, the Signal to Noise Ratio is increased by the same factor  $N$ . This is called the Process Gain.

$$\text{Process Gain} = \frac{\text{ChipRate}}{\text{DataRate}}$$

The energy of a CW interferer is spread during the demodulation and is reduced by the process gain. Noise and other CDMA users are spread by the coding sequence, but since their bandwidth is wide to start off with the resulting noise power in the data bandwidth is not changed.

Code Division Multiple Access, together with Frequency Division Multiplexing and Time Division Multiplexing form the 3 basic means whereby multiple users can be combined onto the same communication channel. Some communication systems like the GSM mobile radio system use a combination of two or more of these techniques.

The number of users that can be accommodated per MHz bandwidth per transmitter cell is bigger for CDMA mobile phone systems than for the GSM TDMA system, as a result all third generation mobile phone systems use CDMA techniques.

The coding sequences, used for the different users, should be orthogonal or close to orthogonal. That is when one coding sequence is multiplied by another coding sequence the result should as small as possible. When Walsh codes are used, under ideal conditions the other users produce no crosstalk into the wanted user's signal. During the demodulation process the wanted signals correlate, while the unwanted signals do not. Several possible codes can be used. The most common ones are briefly described below:

### **Pseudo Random Sequences (PRS)**

By taking feedback from a number of flip-flops in a shift register, a pseudo random code is produced, as shown in Figure 3. The code is random in that the probability of a logic one or logic zero occurring is close to 0.5 and is independent of the previous data bit. The code is known since one obtains the same output code by loading the shift register with the same data. For an M bit register the maximum length sequence repeats after  $2^M - 1$  clock pulses. In addition there exist many different maximum length sequences, so that it is unlikely that another user would use the same sequence. For example for a 15 bit register the maximum length sequence is 32767 bits long and there are 1800 different feedback connections all of which will cause different maximum length sequences [8].

There are two possible means of connecting the shift registers, as shown in Figure 3. Tap positions for maximum length sequences are shown in Table 1. These are not the only possible tap positions for maximum length sequences. Only the simplest tap selections are included and other tap selections may require more connections. For example for an 8 bit register, maximal length tap combinations are: 8,4,3,2 or 8,6,5,3 or 8,6,5,2 or 8,5,3,1 or 8,6,5,1 or 8,7,6,1 or 8,7,6,5,2,1 or 8,6,4,3,2,1.

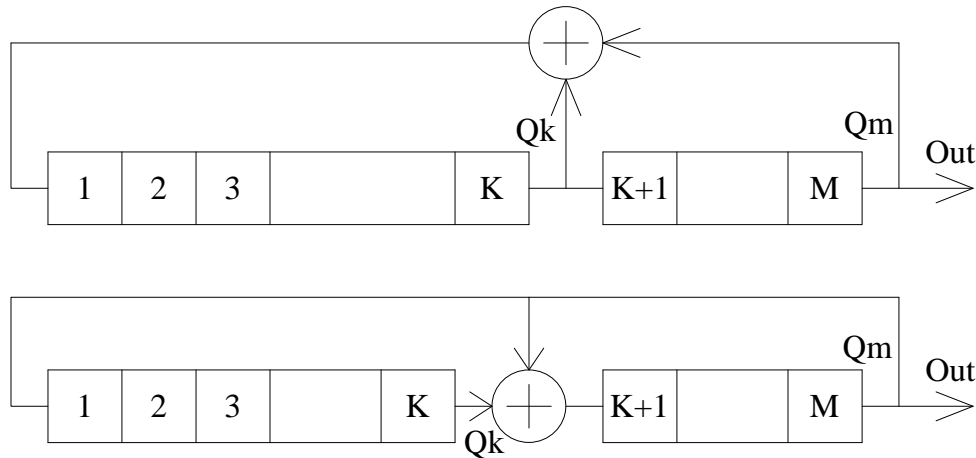


Figure 3. PRS generator block diagram.

| M  | Seq. Length | Tap Posn.          | M  | Seq. Length | Tap Posn.      |
|----|-------------|--------------------|----|-------------|----------------|
| 2  | 3           | 2, 1               | 18 | 262 143     | 18, 7 or 11,18 |
| 3  | 7           | 3, 1               | 20 | 1 048 575   | 20, 3 or 17,20 |
| 4  | 15          | 4, 1 or 3,4        | 21 | 2 097 151   | 21, 2 or 19,21 |
| 5  | 31          | 5, 2 or 3,5        | 22 | 4 191 303   | 22, 1 or 21,22 |
| 6  | 63          | 6, 1 or 5,6        | 23 | 8 388 607   | 23, 5 or 18,23 |
| 7  | 127         | 7, 1 or 6,7 or 7,3 | 25 | 33 554 431  | 25,3 or 22,25  |
| 8  | 255         | 8, 4, 3, 2         | 28 | 268 435 455 | 28,3 or 25,28  |
| 9  | 511         | 9, 4 or 5,9        | 29 | 536 870 911 | 29,2 or 27,29  |
| 10 | 1 023       | 10, 3 or 7,10      | 31 | 2147 483647 | 31,3 or 28,31  |
| 11 | 2 047       | 11, 2 or 9,11      | 33 | 8589 934591 | 33,13 or 20,33 |
| 15 | 32 767      | 15, 1 or 14,15     |    |             |                |

Table 1. PRS tap positions for maximum length sequences

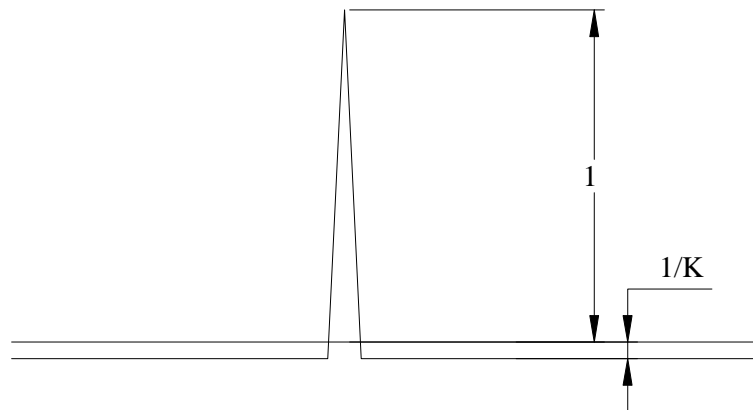


Figure 4. PRS Autocorrelation function

Figure 4 shows the autocorrelation function of an M register maximum length PRS. It can be seen that if the sequence is in phase, an output of 1 is obtained, since all K bits align and if the sequence is not in phase an output of 1/K results where  $K=2^M-1$ . The longer the sequence, the more the unwanted signals are suppressed. If the clock rate of the receiver Coding Sequence is slightly different from that of the transmitter, a demodulated output

time waveform like the one shown in Figure 4 results. This can then be used to determine the correct synchronisation of the Coding Sequences.

It can be seen that if a multipath signal arrives one PRS bit later than the direct signal and the receiver is locked onto the direct signal, the multipath signal will produce very little output. CDMA receivers are thus very tolerant to multipath propagation. If the multipath signal has a delay of less than one PRS bit, then there will be some correlation between the multipath signal and the receiver's coding sequence. Depending on the phase shifts produced by the reflections making up the multipath signal, the multipath signal may reinforce or cancel the direct signal. For an IS95 CDMA receiver, the chip rate is 1.2288 Mbps, so that a multipath signal that has travelled 244 m more, corresponding to a 1 chip delay will be ignored. High chip rates are preferred since they minimise the effect of multipath propagation. A higher chip rate causes a wider transmitted spectrum. In many systems, the permitted bandwidth is limited, thereby setting a limit on the multipath immunity.

The IS95 CDMA cellular radios use a 42 bit register code producing a "Long Code" which is used as the master clock to synchronise all the CDMA radios. This long code is ANDed with a user assigned long code mask, which allows each user to be uniquely identified. The IS95 CDMA cellular radio also uses other important Digital Communication Techniques. The block diagram of its forward link, from the base station to the mobile, is shown in Figure 5 [Ref 1, Fig 8]. The reverse link uses a different configuration.

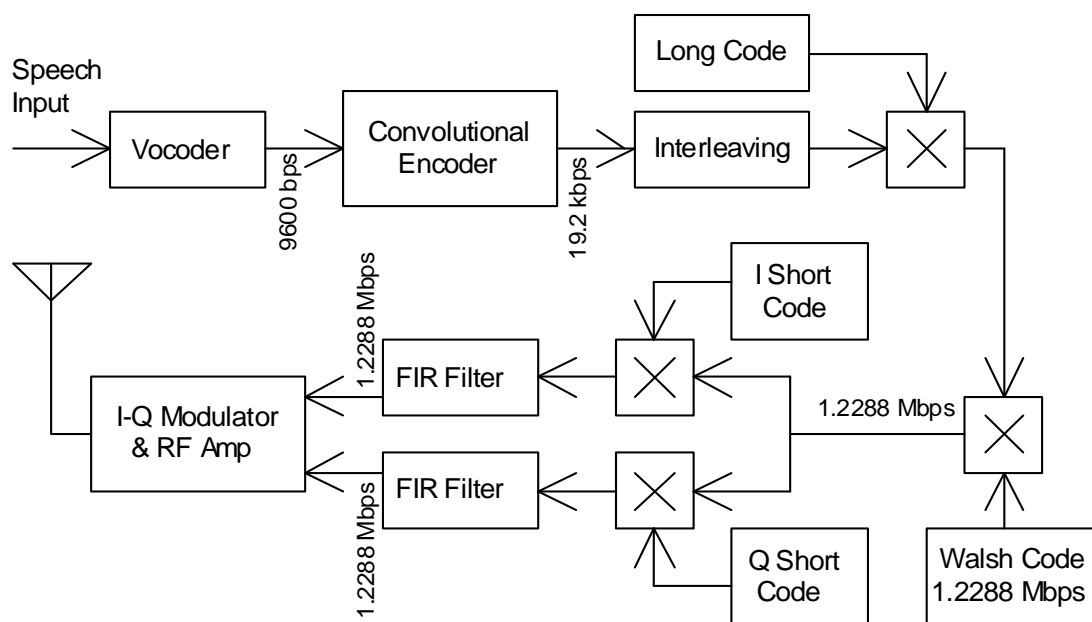


Figure 5. IS95 CDMA mobile phone block diagram.

## Gold Codes

Gold Codes are produced by modulo-2 adding two different maximal length pseudo random sequences of the same length. The combination of sequences are chosen such that the cross correlation between the codes is uniform and bounded to the value  $2^{(n+1)/2} + 1$ . For a 7 bit register, the correlation bound is thus 17. Shifting the phase, that is the starting position, of one of the sequences produces a different pseudo random sequence. Two 7 bit registers can thus each produce a maximum length sequence of 127 bits and can produce 127 different 127 bit random sequences by simply shifting the phase of one of the sequences and the cross-correlation of any of these sequences is then less than 17.

Gold codes are thus very useful in CDMA system design. Gold codes are used in the GPS global navigation system, where DS-SS techniques are used to provide immunity from interferers.

### Walsh Functions

Walsh Functions or Walsh Codes have the property that they are orthogonal to each other and orthogonal to the logical NOT of each other. Walsh codes are available with lengths of integer powers of 2, i.e. 1, 2, 4, 8, etc. Walsh codes are generated by the recursive expansion:

$$W_{2n} = \begin{bmatrix} W_n & W_n \\ W_n & \overline{W_n} \end{bmatrix} \quad \text{where } W_1 = 1$$

|    |   |   |   |   |   |   |   |   |
|----|---|---|---|---|---|---|---|---|
| W0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| W1 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 0 |
| W2 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 0 |
| W3 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 1 |
| W4 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| W5 | 1 | 0 | 1 | 0 | 0 | 1 | 0 | 1 |
| W6 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 1 |
| W7 | 1 | 0 | 0 | 1 | 0 | 1 | 1 | 0 |

Table for Walsh Codes of length 8.

The set of Walsh codes to be used would normally be evaluated and stored in a ROM for subsequent use. The IS95 CDMA cellular radio system uses 64 bit Walsh Codes to provide for 59 user channels. In addition there are the following 3 Channels types:

- 1) A Pilot Channel, containing the final I and Q spreading sequences thereby enabling all radios to obtain a coherent phase reference.
- 2) A Synchronisation Channel, which transmits the time of day information, which is required for the mobile and the base station to align their clocks, so that the coding sequences are in phase.
- 3) One or more Paging channels.

It can be seen that for a 64 bit long Walsh code, W0 and W32 have less spreading properties than the other sequences. For this reason W0 is used for the pilot channel and W32 is used for the synchronisation channel in the IS95 forward link (Transmitted by the base station).

### Frequency Hopping

In Frequency Hopping, the data is modulated onto many carriers, covering a wide frequency spectrum. A pseudo random number generator is used to determine the selection of a carrier frequency for a conventional AM or SSB modulator. The carrier frequency is changed many times per second. Other users can occupy the same frequency band provided that two carriers do not coincide. A typical time frequency plot for 7 users is shown in figure6, where each colour denotes a different user. It can be seen that the frequency of one user, say the red user, occupies many times the bandwidth required for the transmission if no frequency hopping is used. Frequency Hopping systems are also called CDMA (FH-CDMA) systems because the hopping code is required to demodulate the signal.

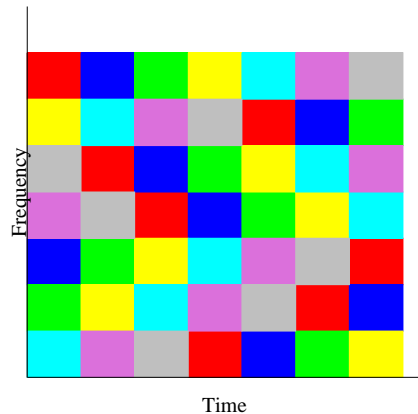


Figure 6. Carrier frequency allocation in a frequency hopping system

There are two basic types of frequency hopping:

### **Slow hopping**

Slow hopping where the carrier frequency is changed less than or comparable to the data rate. The bandwidth around each carrier is thus the same as the bandwidth of the data. A typical example of this use is in a secure analogue or digital military communications system using shortwave or UHF radio receivers. SCIMITAR, SINCGARS and JAGUAR are such commercial products. The GSM mobile radio system standard allows for slow frequency hopping to be used in conjunction with Time Division Multiplexing. The mobile radio needs to respond to 224 hops per second, with a required settling time of less than 1 millisecond. Slow frequency hopping systems have basically the same noise and interference immunity properties as single frequency systems except that an interferer on one of the carriers will only affect the system when that carrier is used.

The Bluetooth short range communication system used slow frequency hopping at 1600 hops per second and 79 different frequencies being used for the frequency hopping. The frequency hopping avoids interference from other services using the same licence free 2.5 GHz ISM frequency band.

### **Fast hopping**

With fast hopping the carrier frequency is changed at the same or faster rate than the data rate. In practice a small odd number typically 3 or 5 frequency hops are used per data bit. The data is demodulated for each chip interval and a majority decision is made to minimise the effect of interference on one of the frequencies used. The faster the hopping rate, the better the noise immunity and the better the tolerance to multipath fading. In many fast hopping systems, the frequencies and the data rate are selected such that the centre of the channel occurs at the first null of the data modulated on the adjacent channel.

### ***OFDM and COFDM***

Orthogonal Frequency Division Multiplexing (OFDM) or Coded Orthogonal Frequency Division Multiplexing (COFDM), is a system where the individual data bits of a word are coded onto individual carriers as shown in Figure 7. The carrier frequencies are chosen to be mutually orthogonal over one symbol period. For two frequencies to be orthogonal over one symbol period, their product must be zero when integrated over one symbol period. This is satisfied when an integral number of carrier cycles to fit into the symbol period.

Those carriers are then modulated using standard digital communication techniques such as FSK, PSK or QAM. Many different data sources can be combined into one OFDM signal, so that the spectrum corresponding to one data source occupies a wider bandwidth than if it is transmitted by itself. For Terrestrial Digital Video Broadcasting (DVB-T) using standard definition TV images, typically 4 TV channels, some radio channels and data services like Electronic Program Guide (EPG), time information and Teletext are all transmitted using one OFDM transmission.

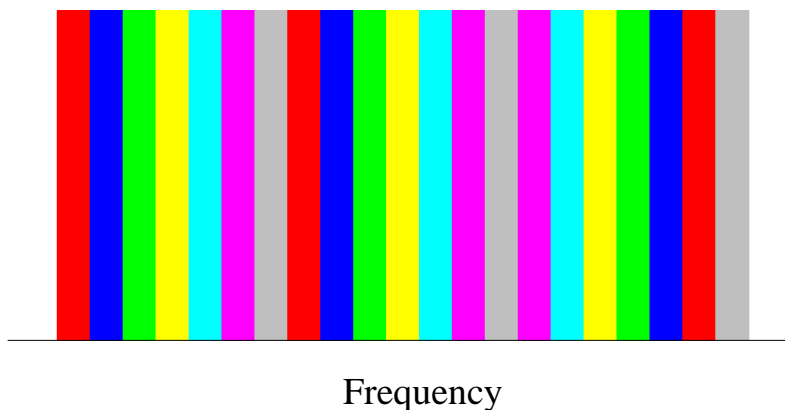


Figure 7. OFDM spectrum, for 7 data sources combined.

Typical OFDM systems use more than one thousand carriers, resulting in a low symbol rate for each carrier. This has advantages for overcoming multipath fading. Multipath fading will tend to cause a notch in the received spectrum at one of the carrier frequencies, causing a corresponding error in those data bits transmitted by that carrier. To make the system tolerant to these errors, error correcting codes are included as part of the transmission scheme resulting in Coded OFDM (COFDM). Some literature uses the term OFDM when discussing COFDM systems and the terms OFDM and COFDM can be used interchangeably, with COFDM being the more correct term.

COFDM is used for the Digital Video Broadcasting (DVB) or Digital Television in Europe, Australia and South East Asia (Except South Korea), where it allows full utilisation of the available spectrum for each channel and the avoidance of frequency carriers that would cause interference to or from other services. The major power in a PAL broadcast is concentrated near the Vision, Colour and Sound subcarrier frequencies. A typical spectrum of a PAL TV spectrum and an adjacent COFDM - DVB system is shown in Figure 8, where 6817 carriers are used to fill this spectrum. This is a measured spectrum of transmissions from Mount Stuart in Townsville, Australia. Notice the better spectrum utilisation of the DVB transmission compared to the PAL transmission. In addition for PAL TV transmissions a channel allocation below a used TV channel cannot be used as this lower channel would interfere with the wanted channel during VSB demodulation. This is called a “taboo channel”. No such restrictions apply to DVB transmissions and the required TV channels can be allocated in one block.

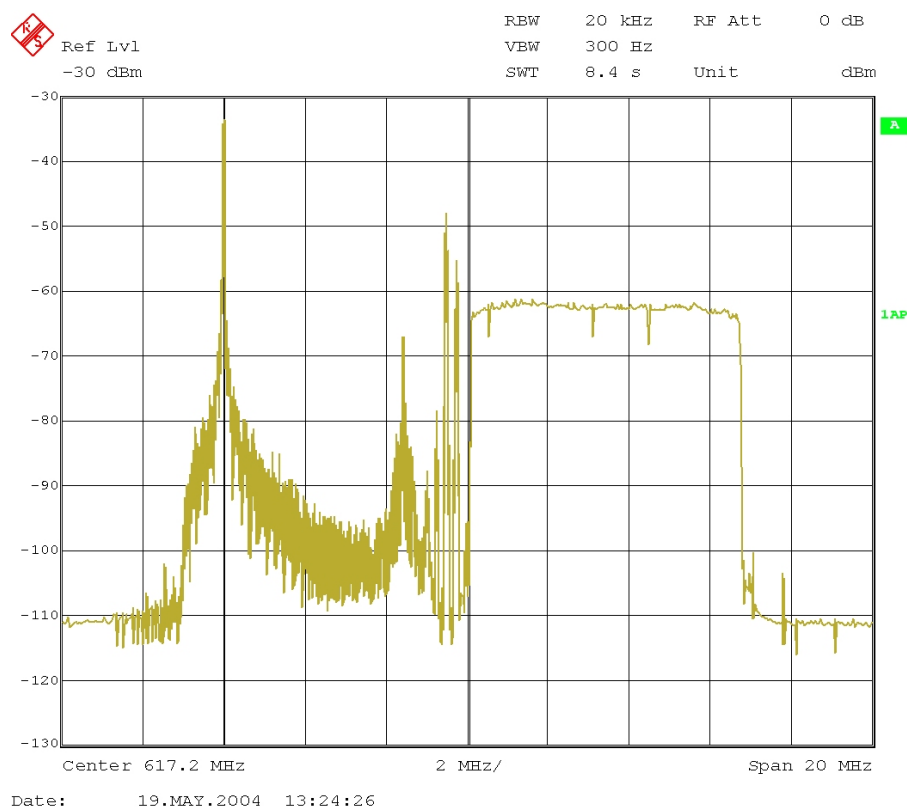


Figure 8. Spectrum of adjacent PAL(Left) and DVB(Right) TV transmissions.

### Single Frequency Networks

For DVB-T the symbol rate is approximately 1 millisecond in the 8k mode and for a one eight guard period, a multipath delay of less than 38.4 km has no effect on the transmissions. This allows transmitters broadcasting the same program to be operated on the same frequency, resulting in a Single Frequency Network. A receiver will then receive signals from several locations and if these do not completely cancel, the signals will aid each other in giving a suitable received signal. For Single Frequency Network, the transmitters at different locations must operate with a frequency difference less than 0.1% of the inter carrier spacing, ie for an 8 k mode at a frequency error of less than 1Hz for a transmitter frequency of up to 800 MHz. This is a significant limitation and requires external synchronisation control. The benefits of a single frequency network however can be great. In the UK, UHF PAL transmitters are typically located about 50 to 80km apart. Because of the “taboo channels” and not being able to reuse a channel frequency for a considerable distance, only 5 separate TV programmes can be allocated throughout the country. Using DVB, 350 standard definition (SD) TV channels can be used, resulting in a 70 times better spectral efficiency. Singapore used a single frequency network to provide good DVB coverage in the difficult urban propagation conditions with many tower blocks causing severe shadowing. In Australia local fill-in translators rebroadcasting signals from the same the main transmitter will operate at the same frequency. Since there is more isolation between these fill-in translators, the frequency tolerances are eased.

COFDM is used for the Eureka 147 Digital Audio Broadcasting (DAB) system which was introduced in the UK during 1995 and in Australia test transmissions are taking place, using a frequency of 1.5 GHz. However with the added cost of the receiver, it remains to be seen if the service becomes very popular. Reasonably priced car receivers are only now available.

## Multipath Propagation

### Introduction

Multipath Propagation occurs when signals arrive at the receiver both direct from the transmitter and via a reflection from or transmission through an obstacle. Depending on the dielectric constant and conductivity of the reflecting surface or transmitting medium, the reflecting signal will undergo a phase change and a polarisation change. Depending on the amplitude and phase of the reflected signal, these reflected signals can cancel the direct signal, causing no signal to be received. For a fixed receiver, these reflections cause nulls in the received spectrum to occur at frequencies where the difference in the path length is  $n\lambda/2$ . Figure 9 shows such a spectrum. In the time domain the multipath signal can be represented by the reception of one direct signal together with one or more slightly delayed signals being received from the reflecting objects. Depending on the type of modulation used, either the frequency domain or the time domain representation will most clearly illustrate the effects of the multipath signals and the susceptibility or immunity of the modulation system to multipath fading.

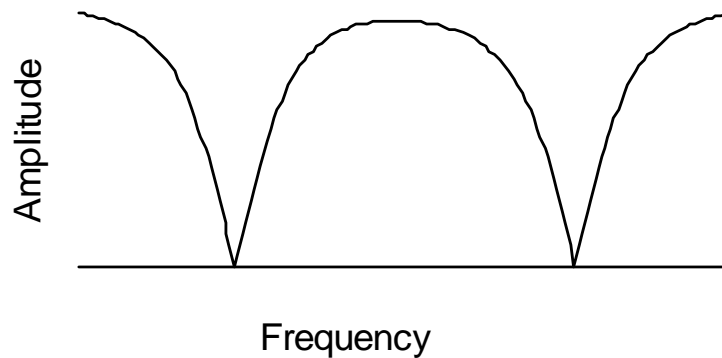


Figure 9. Multipath Attenuation versus Frequency.

For a moving receiver and a fixed carrier frequency, the multipath signals cause an interference pattern with a spacing larger than the wavelength of the carrier. At 1 GHz the nulls of interference will thus be 300 mm apart in worst case. The distance can be larger depending on the geometry. The area where the attenuation due to multipath is more than 10 dB is 1%. As the receiver travels, the received amplitude is thus Amplitude Modulated with the multipath signal. The frequency of that modulation depends on the change of path lengths of the direct and the reflected signals and it thus depends on the geometry. The maximum frequency is:

$$f_{\text{carrier}} \cdot \text{speed} / c \quad \text{where } c \text{ is the speed of light.}$$

As shown below, spread spectrum techniques offer some immunity from multipath propagation.

### Multipath with Frequency Hopping

In slow frequency hopping systems, the interference pattern for each of the carrier frequencies is different. There is thus 0.01% chance that two frequencies being used both have an attenuation in excess of 10 dB. GSM cellular mobile radio systems can use frequency hopping with up to 26 frequencies. As a consequence the probability of enough

data to be corrupted to make the system inoperable due to multipath fading is negligible when frequency hopping is used. The number of carrier frequencies that can be used for frequency hopping in each mobile radio cell is governed by the available frequency band, the number of adjacent cells and their allocated frequencies. The number of frequencies available for the GSM system is at present limited and no frequency hopping is used by the GSM operators. As a consequence the GSM system has no immunity from multipath fading.

In fast frequency hopping systems the immunity to multipath propagation is even better. Firstly, for a 3 chip per data bit system, the probability of 2 of the 3 chip bits being affected, causing the majority decision to give the wrong result is very small. Secondly, if the reflected signal arrives after the receiver has switched to the next carrier frequency, the reflected signal will be rejected by the IF chain of the receiver. It can be seen that the faster the hop rate, the more chips per data bit and the shorter time the transmitter is tuned to each carrier frequency, the better the immunity from multipath fading. Unfortunately increasing the chip rate also increases the bandwidth, so that in practice a compromise is required.

It should be noted that the nearly complete removal of certain frequencies is not the only effect of multipath fading on frequency hopping systems. The additional reflected signals cause some phase shifts to all the other carriers. Depending on the modulation techniques, those phase shifts can cause errors. For analogue input signals such as audio and amplitude or frequency modulation, these phase shifts do not cause any problems. For digital transmissions and phase modulation, the resulting constant phase shift must be allowed for. Differential coding techniques, such as DQPSK achieve this.

### **Multipath with CDMA**

For CDMA systems the effects of multipath are best described in the time domain. The reflected signal will arrive at the receiver with a slight time delay compared with the direct signal. In the receiver the signal is correlated with the local Coding Sequence. If the transmitted and received coding sequences are exactly in phase they correlate to give the correct data output. If the reflected signal arrives more than one chip time after the direct signal, the reflected signal will not produce a correlated output and is ignored by the receiver. For a chip rate of 10 MCps (MChips/sec), a transmission bandwidth of 20 MHz is required. Any multipath signal that has travelled 30m farther than the direct signal will be one chip bit delayed and will thus be ignored. Multipath signals with shorter delay times will produce an interference with the direct signal. The higher the chip rate the shorter the path difference required to produce interference and the better the immunity from multipath fading. Increasing the chip rate also increases the bandwidth required to transmit the signals, so that a compromise is required.

It is possible to demodulate each of the multipath signals individually, using separate correlators for each multipath signal. In this case several different demodulated outputs are obtained. Provided the differences in path lengths in the multipath signals are less than a quarter of the data bit rate, these signals can then simply be added to improve the signal to noise ratio. The compromise is that the SNR can be increased at the expense of hardware complexity. For 2 marginal signals, the demodulated signals when added result in a 3 dB increase in SNR. As shown in Figures 3 and 4 of the Digital Communication Systems and their Modulation Techniques by C. J. Kikkert 2004, for a typical digital communication system without error correction, that can result in a change in error rate from one error in 800 bits to one error in 100 000 bits. For a system with error correction the improvement is even more dramatic. Using the multipath signals to obtain useful data is very worthwhile.

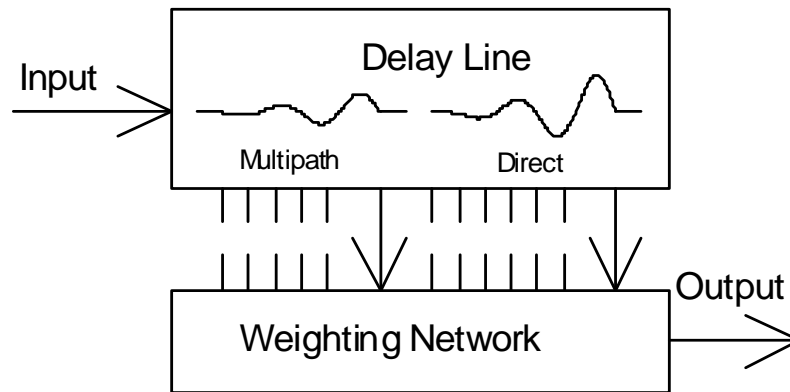


Figure 10. Rake Receiver Block Diagram.

The RAKE receiver passes the received signal through a multi-tapped delay line. The signals from these taps are weighted and combined. The process is most easily illustrated by considering a direct signal and one reflected signal. The direct signal will pass through the whole delay line and is normally added directly to the output. Reflected signals will have a delay with respect of the direct signal and the time signal from the direct path that is at the end of the delay line occur at one of the taps in the delay line, as shown in Figure 13. By then setting that weight to  $\pm 1$  according to the phase of the reflected signal, that reflected signal will then add in phase with the direct signal. The direct signal component at the tapped output will not correlate and appear as noise. By making the weights other values than just  $\pm 1$ , the SNR can be maximised, rather than simply maximising the signal. All other weights are zero, so that no additional noise is included. Multiple reflections can be accommodated by setting the appropriate weights. The receiver has to adjust the weights at each of the taps, in order to maximise the SNR. A simple optimisation process can achieve this. The Rake receiver is primarily used to minimise the multipath effects that are more than one chip clock delay from the direct path.

### Multipath with COFDM

In COFDM systems the data is coded onto many carriers and each of those carriers is modulated using PSK or QAM at a low data rate. The more carriers are used, the lower the modulation rate and the narrower the bandwidth of each of these carriers. The carriers become thus virtually like pure sine wave sources. During one of the bit periods the received signal will contain 3 separate intervals as shown in Figure 11.

The First time interval, occurs during the latter part of the Guard Interval. The direct signal is present but the multipath signals have not yet arrived. The received signal is thus exactly as expected. This time interval is normally very short, too short to accurately demodulate the signal. The second time interval occurs during the Measure Interval, both the direct and multipath signals are received in a steady state manner. The received I-Q vector has been shifted a fixed amount from the ideal locations due to the multipath signal. The multipath signals will change the phase and amplitude of the individual carrier sine wave. Since the carriers are nearly constant sine waves, the data modulation does not change the phase shift between the direct and the multipath signals. The multipath signals will thus cause a fixed change in the received phasor, with the whole I-Q pattern being rotated and changed in size by a fixed amount. The standard DQPSK demodulator can thus be used to demodulate the data without being affected by the multipath signal. This time interval is the largest and the signal detection takes place during this time. The receiver simply allows for this phase shift and if differential transmission and detection techniques are used this phase shift simply

cancels. The third interval occurs during the first part of the Guard Interval. The direct signal is not transmitted but the multipath signals still exist. At the end of this period the multipath signals will have disappeared as well. This time interval is again too small to make any useful measurements.

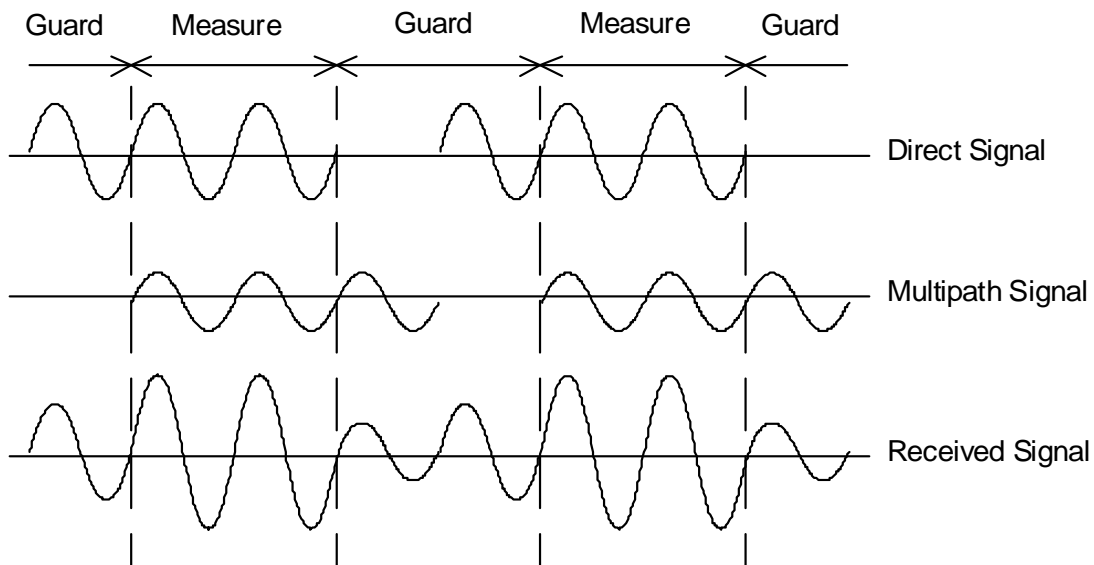


Figure 11. COFDM Received Waveforms.

The multipath signal can be compensated for during the measurement period and will thus not cause any serious errors to the COFDM system. Since the first and the third periods are transient in nature and no measurements are made during this time, they are called a guard period. The guard period should be long enough to accommodate the delay from all the multipath signals, but short enough not to reduce the data rate too much. The two parts of the guard period are normally merged, so that the new carrier data is already transmitted while the multipath signals are still decaying. The higher the number of carriers, the bigger the guard period can be without affecting the data rate and the more tolerant the system is to multipath signals. The Guard period is normally 5% to 20% of the total symbol period. The length of the Guard period is exaggerated in Figure 14.

Some of the carriers will be affected more by multipath propagation. If the reflected signals cancel the direct signal exactly, corresponding to the nulls in the spectrum of Figure 12, then no signal is available to measure phase shifts on. Only 1% of all the carriers suffer more than 10 dB of attenuation due to multipath. For 99% of all the carriers the phase can thus be determined accurately and the correct data determined. Error correcting techniques are used to compensate for the attenuated carriers. COFDM receivers can through the digital signal processing carried out in the receiver determine which carriers are being reduced in amplitude, making their phase measurements more prone to errors. The receiver can then reduce the weighting of that particular subcarrier and hence reduce the resulting error rate.

With the error correcting techniques, the COFDM systems can tolerate multipath signals that are of the same amplitude as the direct signal without degrading the data. The multipath signals can in fact be generated by a transmitter in an adjacent cell, provided the same programme is transmitted and the carriers are all synchronised. It is thus theoretically possible to use the same allocated frequency for all the transmitters in a broadcasting network.

The tolerance does not extend to other carriers which are at the same frequency but are not in synchronism with the desired signal. If the unwanted signals are 20 dB below the required signal, they will cause less than  $6^\circ$  phase shift to the required carrier and the data will still be able to be demodulated without error. An outdoor antenna will achieve a selectivity greater than this, so that the interference affects of adjacent transmitters are virtually eliminated. Even with different programmes being transmitted the frequencies should be able to be repeated on a chessboard type pattern, i.e. a 2 cell structure, rather than the 7 cell structure commonly used in cellular radio.

### References

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