CHAPTER 3

Q²PSK — MOBILE COMMUNICATION SYSTEM

This chapter introduces the general architecture of the Q²PSK communication system proposed for spectrally efficient ($\eta_f \geq 2.0$ *bits/s/Hz*) V/UHF mobile digital communications. A study of the communication environment is undertaken, including the fading channel model. This chapter is concluded with a summary of the primary system specifications.

There are a multitude of modulation/demodulation schemes available to the designer of a digital communication system required for data transmission over a band-pass channel. Each scheme offers *system trade-offs* of its own. The final choice made by the designer is determined by the way in which the available primary communication resources, *transmitted power* and *channel bandwidth*, are to be best exploited. In particular, the choice is made in favor of the scheme that attains as many of the following design goals as possible [1, 57]:

- Maximum data rate.
- Minimum probability of symbol error.
- Minimum transmitted power.
- Minimum channel bandwidth.
- Maximum rejection of interference.
- Minimum circuit complexity.

3.1 GENERAL SYSTEM ARCHITECTURE

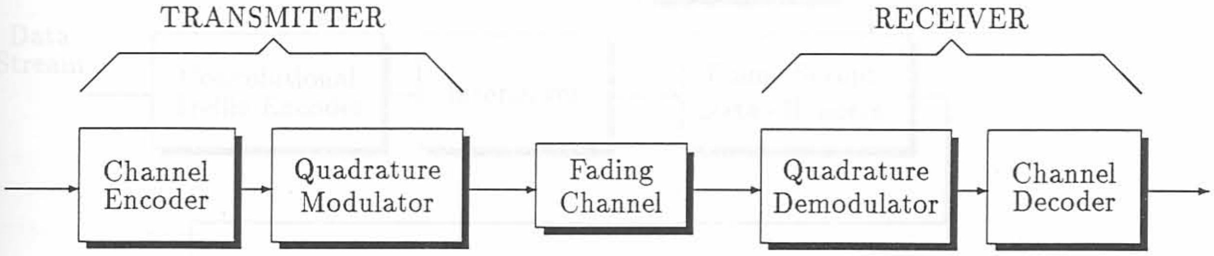

Figure 3.1: Basic communication system model.

Figure 3.1 presents the most basic block diagram of the system model under investigation. The *Transmitter* is identified as consisting of the channel encoder and quadrature modulator; the *Receiver*, consisting of the quadrature demodulator and channel encoder; and a fading channel that links the transmitter and receiver.

In the following subsections the different system building blocks are introduced in some detail.

3.1.1 Transmitter

The transmitter can be further subdivided. This detailed transmitter block diagram is illustrated in Figure 3.2.

3.1.1.1 Information source

A data stream is obtained from an information source where the output elements can take on only binary (1s or 0s) values. A desirable source is random so that it has maximum information. If the probabilities of occurrence of 1^s and 0^s are the same, its entropy is maximised. If for some reason or other, the source is not random (for example in a video image), it will necessitate the implementation of a source encoder. The role of the latter is to randomise the source. In our system a random information source is employed, canceling out the need for a source encoder and the associated source decoder at the receiver.

3.1.1.2 Channel encoder

The goal of the channel encoder is to introduce an error detection and correction capability into the information source to combat channel transmission errors. To achieve this goal, some redundancy must be added to the information carrying data stream. The detection of errors is also a key item in channel coding since retransmissions of a code word containing errors can be requested, when a feedback channel is utilised.

In this dissertation the techniques of trellis coding will be applied, for adding redundancy to the information stream so that efficient channel utilisation can be achieved. The basic idea involves no change in data transmission rate; rather, the number of points in the signal constellation is increased

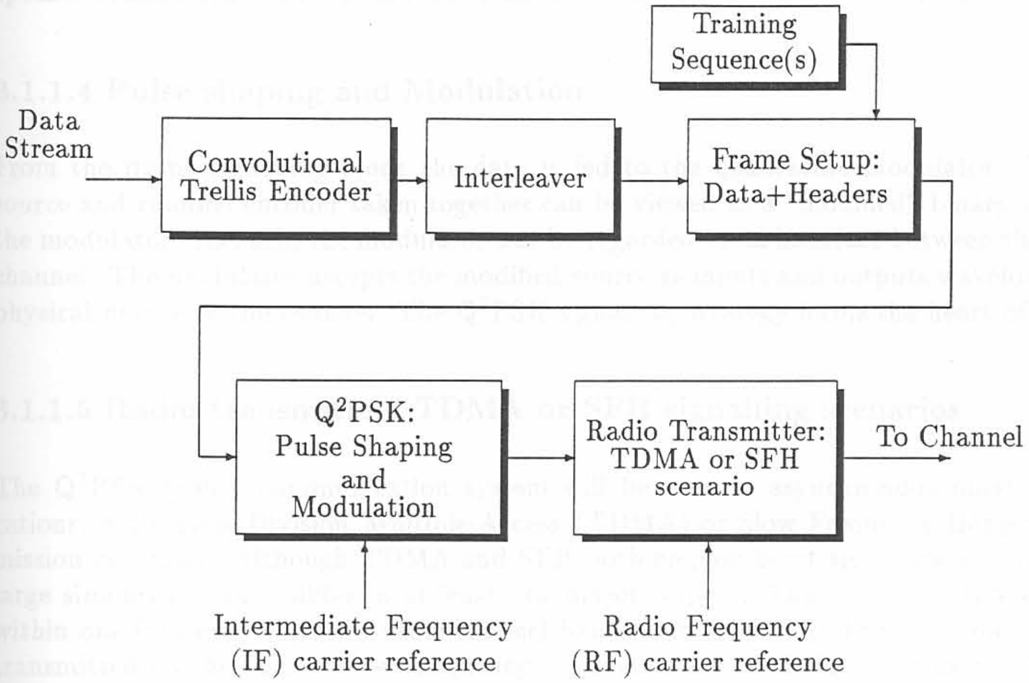

Figure 3.2: Detailed transmitter block diagram.

to achieve the required redundancy. The concepts of trellis coding or Trellis-Coded Modulation (TCM) and its application to four-dimensional Q^2PSK signalling will be discussed in detail in Part II of this dissertation.

After the encoding of the data, it is sent through an interleaver which is included for *burst error* protection when a transmission over a *multipath* channel with *memory* is considered. Two types of interleavers are commonly used, *block interleavers* and *convolutional interleavers* [1, 58]. An example of a channel with memory is a fading channel, particularly when the fading varies slowly compared to the duration of one data symbol. Multipath impairments involves signal arrivals at the receiver over two or more paths of different lengths, resulting in a distorted resultant received signal.

Under the assumption that the channel has memory, the errors can no longer be characterised as being random and independent. Most convolutional codes are designed to combat random independent errors. The result of a channel having memory on such coded signals is to cause degradation in system error performance.

3.1.1.3 Frame transmission strategy

Almost all digital communication systems have some sort of frame structure. This is to say that the data stream is organised into uniformly sized groups of bits. Furthermore, for the receiver to make sense of the incoming data stream, the receiver needs to be synchronised with the data stream's frame structure. Frame synchronisation is therefore accomplished by organising the data transmitted in a special signalling format at the transmitter. Hence the need for a *frame transmission strategy.* In general the signalling procedure may become fairly complex depending on the specific communication environment in which the system is required to operate.

3.1.1.4 Pulse shaping and Modulation

From the frame signalling block the data is fed to the quadrature modulator. The information source and channel encoder taken together can be viewed as a "modified" binary source that feeds the modulator. As such, the modulator can be regarded as an interface between the source and the channel. The modulator accepts the modified source as inputs and outputs waveforms that suit the physical nature of the channel. The Q^2PSK signalling strategy forms the heart of the modulator.

3.1.1.5 Radio transmitter: TDMA or SFH signalling scenarios

The Q^2PSK mobile communication system will be used in asynchronous burst-mode communications, with Time-Division Multiple-Access (TDMA) or Slow Frequency-Hopping (SFH) transmission scenarios. Although TDMA and SFH both employ burst signalling strategies and exhibit large similarities, they differ in at least one major respect. That is, in TDMA successive bursts within one frame all share the same channel bandwidth (albeit, at different time instants) and are transmitted on the same carrier frequency. In the case of SFH signalling each successive burst is transmitted on a different carrier frequency and therefore experiences completely different channel conditions.

The primary consequences of the foregoing difference between TDMA and SFH are as follows:

- In TDMA, carrier phase and Doppler frequency offset information obtained from one burst can be transferred to the next (i.e., *burst-to-burst* control is possible), whereas in SFH, carrier phase and frequency information gathered from one specific burst (or hop) cannot be used in successive bursts. This is true, since the channel conditions corresponding with these bursts may be totally different from the former and subsequent bursts by virtue of the nature of the variation of the channel response with frequency.

- In SFH systems, carrier phase and frequency control can therefore be regarded as truly bursty in nature, i.e., control is exclusively limited to the burst and must be obtained and exercised strictly within the burst period. Carrier information associated with one particular burst is only applicable to that burst and must be reacquired for each successive burst.

One of the advantages of frequency hopping systems is that when the hopping rate is fast enough the "spread spectrum" signals produced show strong resistance to interference and frequency selective (multipath) fading [59].

3.1.2 Receiver

The receiver follows the channel in the block diagram of Figure 3.1. Here, the transmitter fulfills the task of matching the source to the channel, whereas the receiver performs the inverse of this operation and recover the source symbols. The inverse of the detailed transmitter block diagram shown in Figure 3.2, is illustrated in Figure 3.3, constituting the receiver block diagram.

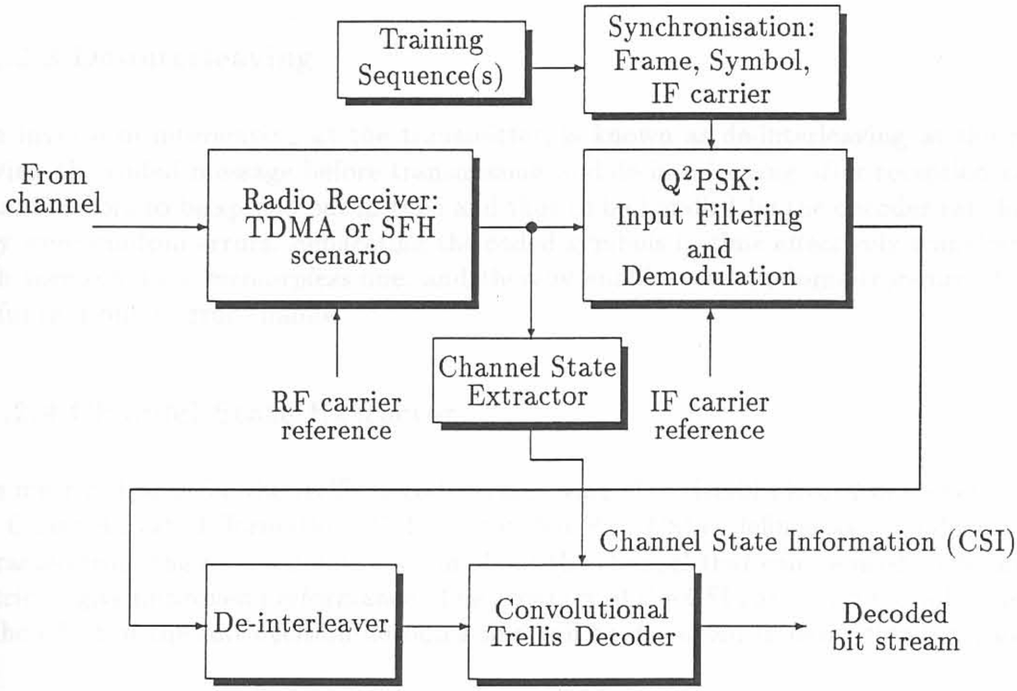

Figure 3.3: Detailed receiver block diagram.

3.1.2.1 Frame synchronisation

A *synchronisation sequence* is sent as part of the *message header* to enable rapid synchronisation acquisition at the receiver. The header should provide buffer time to accommodate any timing uncertainty as well as any information required for equaliser training (when included) and information to provide frequency hopping or TDMA signalling. The synchronisation sequence is known at the receiver, which is constantly searching for it in the data stream. Detection of the synchronisation word normally involves the utilisation of a correlator. In chapter 4 a novel multidimensional frame synchronisation procedure will be described, specifically designed for the four-dimensional Q^2PSK modem employing complex correlation sequences [60]. The advantage of this synchronisation procedure lies in the effective use of all the available dimensions to ensure that frame acquisition will be immediate with low probability of false detection.

3.1.2.2 Q^2PSK: Input filtering and demodulation

At the output of the radio receiver, the modem receiver front-end consists of the input filter and demodulation subsystem. The demodulator is the inverse of the modulation process, where the faded, noise-corrupted channel signal are demodulated. The demodulated in-phase and quadrature signal components are fed to the de-interleaver (block or convolutional).

3.1.2.3 De-interleaving

The inverse of interleaving at the transmitter, is known as de-interleaving at the receiver. Interleaving the coded message before transmission and de-interleaving after reception causes bursts of channel errors to be spread out in time and thus to be handled by the decoder (at the receiver) as if they were random errors. Separating the coded symbols in time effectively transforms the channel with memory to a *memoryless* one, and thereby enables the random-error-correcting codes to be useful in a burst-error channel.

3.1.2.4 Channel State Extractor

The metric chosen for the trellis decoder, employing the Viterbi algorithm, depends on whether or not Channel State Information (CSI) is provided [61]. CSI is defined as the information derived or extracted from the received data stream about the channel that can be used to design the decoding metric to give improved performance. The accuracy of the CSI has only a secondary effect compared to the effect of the soft decision decoding and will be discussed in more detail in Chapters 6 and 7.

3.2 FADING CHANNEL

The most important channel constraints come from the variations of mobile radio propagation. In this study, only the effects of *flat* or *non-frequency* selective fading are investigated. These effects are common to narrowband channels, in which the transmitted signal frequency spectrum is narrow enough to ensure that all the frequency components are affected in a similar way by the fading process.

Two distinct types of flat fading can be defined, namely *fast* and *slow* fading.

- Fast Fading:

  Fast fading is the short term fading caused by the local scatters like buildings and other obstructions and is observed over distances of half a wavelength and less. Fades with depths of less than 20 *dB* occur frequently, while deeper fades of 30 *dB* and more appear less frequently. The mobile unit can move through several fades in a second and communication can become extremely difficult under these circumstances.

- Slow Fading:

  Slow fading originates as a result of slow movement of the mobile unit, causing the particular terrain configuration to change from one form to a new configuration, over a period of several seconds and even minutes. Another form of slow fading is known as *shadowing*, which is manifested in the form of an EM attenuation, caused by "shadowing" by hills, buildings, foliage, etc. in a mobile communications scenario.

An exact mathematical model of this type of fading is not available, but measurements indicate that the mean path loss closely fits a log-normal distribution with standard deviation that depends on the carrier frequency and environment [62].

3.2.1 Fading channel model

In this dissertation the effects of a Land Mobile Satellite Channel (LMSC), modeled as a non-frequency selective Rician fading channel, is considered as primary communication scenario. The received signal is a linear combination of a large number of carrier signals spread in time and frequency, each corrupted by AWGN. In typical mobile communication systems, having symbol rates of $R_s < 20$ *ksymbols/s* (*kbaud*), the time delay spread among these signal paths is frequently a negligible fraction of the symbol duration T_s. In this fading model, two signal paths are considered, namely a Line-of-Sight (LOS) component (excluding the effects of shadowing), and a scatter component, which is modeled as Rayleigh distributed envelope [63, 30, 62]. Figure 3.4 shows a basic schematic representation of the fading model.

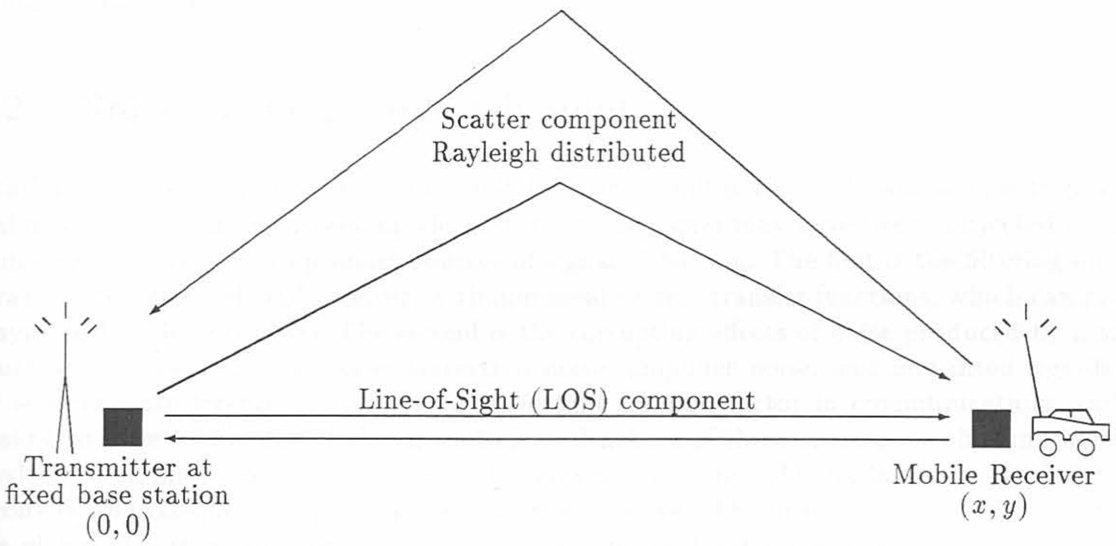

Figure 3.4: Non-frequency selective Rician fading channel model.

The amplitude of the modulated signal is multiplied by the output, r of a random process, normalised so that $E\{r^2\} = 1$. This is done in order to ensure that the average transmitted signal energy remains unaffected by the channel model. The latter simplification is suggested by the fading channel model proposed by Jakes [63]. The probability density function of the amplitude r may therefore be expressed as

$$\rho(r) = \frac{r}{\sigma^2} \exp\left(-\frac{r^2 + s^2}{2\sigma^2}\right) \mathbf{I_o}\left(\frac{r\,s}{\sigma^2}\right) \tag{3.1}$$

where s^2 denotes the average energy (power) of the direct LOS component, and σ^2 is the average power the resultant scattered signal components. In (3.1) $\mathbf{I_o}(\cdot)$ is the modified Bessel function of the first kind and zero order.

Two limiting cases of special interest occur when $\sigma^2 = 0$ (channel reduces to just an AWGN channel), and when $s^2 = 0$ (channel is reduced to a Rayleigh fading channel). Therefore, in those cases where the direct LOS component is totally blocked out, the scatter (diffuse) component dominates and the received signal envelope exhibits a Rayleigh distribution (From (3.1)). The probability density function of the amplitude of a Rayleigh fading channel is simply given by

$$\rho(r) = \frac{r}{\sigma^2} \exp\left(-\frac{r^2}{2\sigma^2}\right) \tag{3.2}$$

However, if in addition to a portion of the reflected (scattered) signal component, the direct LOS component component is also present at the receiver's antenna, the envelope of the received signal follows a Rician distribution; the channel is then called a Rician fading channel, with amplitude probability density function given by (3.1). In order to specify the characteristics of the Rician fading channel one has to define the so called Rician parameter, K. It is defined as the ratio of the power in the direct LOS to the scatter components present at the receiver, i.e.,

$$K = \frac{s^2}{2\sigma^2} \tag{3.3}$$

Thus, for a Rayleigh channel $K = 0$, and for the AWGN channel, $K = \infty$, constituting the two extremal propagation modes.

3.2.2 Noise in the Mobile Channel

The task facing the receiver is to retrieve the bit stream from the received waveform, with minimum probability of error, notwithstanding the distortion the signal may have been subjected to during transmission. There are two primary sources of signal distortion. The first is the filtering effects of the transmitter, channel, and receiver, with non-ideal system transfer functions, which can produce Intersymbol Interference (ISI). The second is the corrupting effects of noise produced by a variety of sources, such as galactical noise, terrestrial noise, amplifier noise, and unwanted signals from other sources (interference). Noise is an important limiting factor in communications and it is necessary to have knowledge of the magnitude and nature of these sources, so that methods may be devised to eliminate or suppress them. An unavoidable cause of noise is the thermal motion of electrons in any conducting media, known as *thermal noise*. The primary statistical characteristic of the global effects of all sources of noise is that the resultant noise amplitudes may be closely approximated by a Normal or Gaussian distribution, with probability density function (assuming zero-mean) expressed as

$$\rho(n) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{n}{\sigma}\right)^2\right] \tag{3.4}$$

where σ^2 is the noise variance [58, 14]. The primary spectral characteristic of white noise is that its two-sided power spectral density is flat for all frequencies of interest for the radio communication system. In other words, thermal noise, on the average, contains as much power per Hz in low-frequency fluctuations as in high-frequency fluctuations — up to a frequency of about 10^{12} Hz. The Additive White Gaussian Noise (AWGN) model is therefore often used to model the noise in the detection process and in the design of optimum receivers.

3.2.3 Mobile Channel Simulator

The block diagram of the channel simulator utilised in this study is shown in Figure 3.5, based on the model proposed by Jakes [63], implemented in software by Opperman [62].

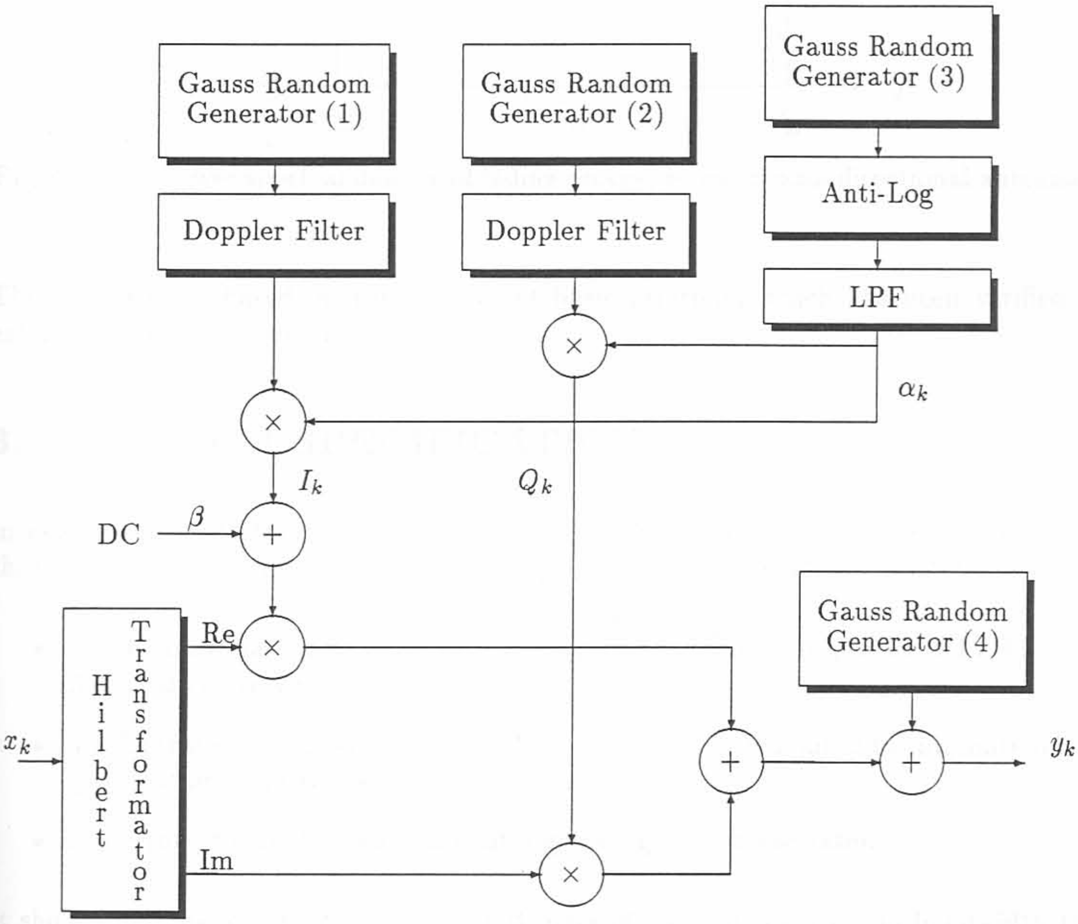

Figure 3.5: V/UHF mobile channel simulator block diagram.

The V/UHF channel simulator is capable of emulating both Rayleigh or Rician distribution envelopes with uniform phase distribution. The PSD of the foregoing, when an omnidirectional antenna is employed, is given by

$$S(f) = \begin{cases} \frac{1}{\pi\sqrt{1-(f/f_D)^2}} & |f| \leq f_D \\ 0 & \text{otherwise} \end{cases} \tag{3.5}$$

which is depicted graphically in Figure 3.6.

These characteristics can be effectively realised by a filtering process, since linear filtering of an input sequence modifies the spectrum, but not the phase and amplitude distributions of the sequence.

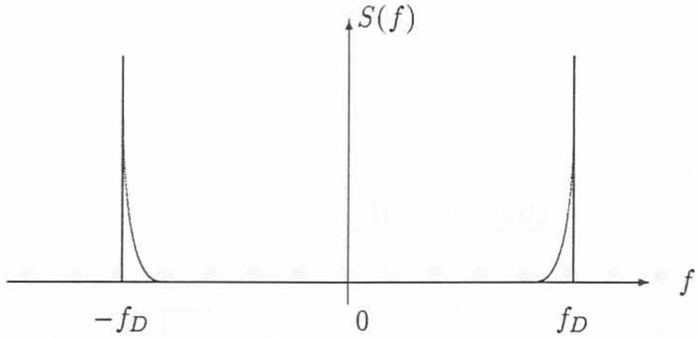

Figure 3.6: Power spectral density of fading process when an omnidirectional antenna is employed.

The simulator is based on this important basic principle, which has been verified by means of extensive computer simulation in [62].

3.3 SYSTEM SPECIFICATION

In general, the selection of modulation and coding formats for transmission on the mobile radio channel is based on the optimum selection of the following design parameters,

- R_b, the information rate, i.e., the maximum number of bits per second achievable within an allocated channel bandwidth.
- W, the transmission bandwidth in *Hertz*, usually strictly limited by international transmission specifications and radio filter limitations.
- The error probability achievable at a given signal-to-noise ratio.

It should be observed that the value of W depends on the definition of bandwidth that has been adopted for the specific application. Note that η_f is inevitably degraded by the presence of guard bands between adjacent channels within the allocated transmission bandwidth.

The primary limitations and specifications of the proposed Q^2PSK digital V/UHF radio communication system are summarised below.

The allocated 30 *MHz* to 2.5 *GHz* frequency band covers most of the VHF and UHF frequency bands. Figure 3.7 depicts a typical multi-channel V/UHF radio channel response.

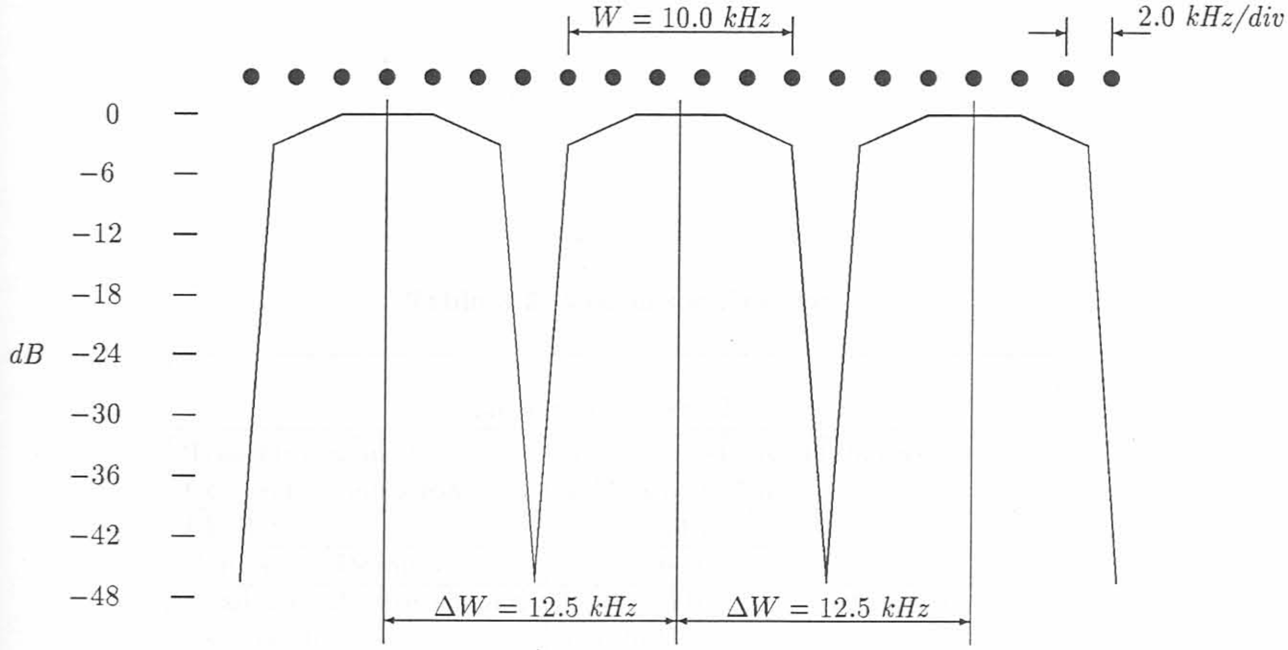

Figure 3.7: Overall radio channel response.

Table 3.1: Channel specifications

Channel characteristics	
Frequency band	VHF/UHF (30 MHz - 2.5 GHz)
Communication mode	Semi-stationary/mobile
Maximum distance	50 $km \leq d_{max} \leq 150$ km (typical)
Fading	Rician and Rayleigh
Maximum Doppler	$f_D \leq 2$ kHz at 1.0 GHz (typical)
Expected time spread	Negligible, ($\tau \approx 10$ μs, typical)

Table 3.2: Modem specifications

Modem characteristics	
Transmission mode	Asynchronous bursts (block) data
Communication scenarios	TDMA and SFH
FH Rates	25, 50 and 100 *hops/s*
Bandwidth Definition	90% of power
Available effective channel bandwidth	W = 10 kHz ($\Delta W = 12.5$ *kHz* channel spacing)
Maximum data rate	$R_{max} = 24$ kb/s
Samples per symbol	$I = 10, 16$, depending on the FH rate
Symbol rate	$f_s = 5, 6$ ksymbols/s
Spectral efficiency	$\eta_f \leq 2.4\ b/s/Hz$
IF subcarrier frequency	$f_{IF} = 25\ kHz$
Sampling frequency	$f_{samp} = 100\ kHz$
Subcarrier modulation	coherent Q^2PSK
Bit Error Probability Uncoded Coded	 $P_b < 10^{-5}$ @ $E_b/N_o < 15.0\ dB$ $P_b < 10^{-7}$ @ $E_b/N_o < 15.0\ dB$
Error correction type	Convolutional Coding TCM and MTCM
Equalisation	To be determined

3.4 CONCLUDING REMARKS: CHAPTER 3

In order to achieve a minimum bit rate of $f_b = 24\ kb/s$ in a V/UHF communications scenario with $\Delta W = 12.5\ kHz$ channel spacing, a modulation technique with post-modulation bandwidth efficiency of $\eta_f \geq 1.92\ bits/s/Hz$ is required. It will be shown in Chapter 4 that this radio response does not provide for excessive Doppler shift in a mobile communication scenario. The radio receiver will therefore have to eliminate most of the Doppler before the signal is passed on to the modem receiver. If this is not done, serious signal distortion will be caused by the misalignment of the received signal within the narrowband radio IF bandpass filters.

The proposed modem must meet the typical uncoded Bit Error Rate (BER) target specification of 10^{-3} for digital speech under fading conditions. The chosen modulation method must be capable of supporting an appropriate coherent detector. E_b/N_o is the ratio of energy per bit to noise power spectral density and is the standard figure-of-merit by which digital modulation and coding schemes are compared. It is analogous to Carrier-to-Noise (C/N) ratio for analog FM modulation. Recall, the lower E_b/N_o the lower is the requirement of transmitter output power.