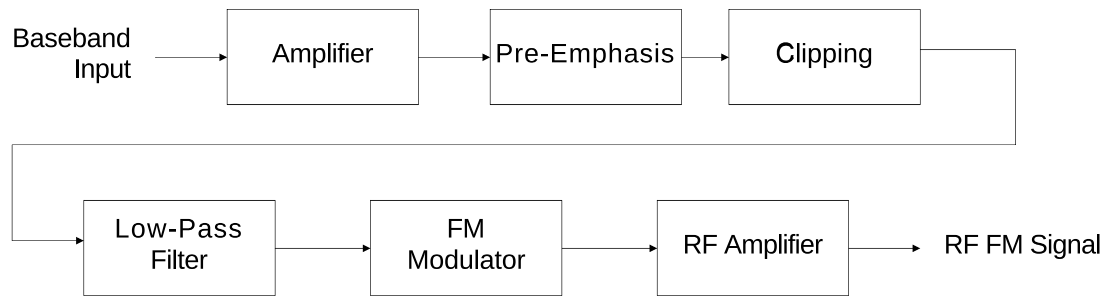

Figure 2.3: Block diagram of an FM transmitter.

peak frequency deviation. Increasing the level of the modulating signal increases the amount of clipping and the resulting distortion. Reducing the modulating signal level reduces clipping distortion but also reduces the received signal-to-noise ratio (SNR). Thus the clipping level is a compromise between distortion and receiver power output. The ratio of peak power to rms power is set to about 10 dB for speech signals [3].

A low-pass filter removes harmonics produced by the clipping and the resulting signal is used to vary the frequency of an RF oscillator. This oscillator's output is amplified and transmitted over the channel.

2.4.2 The FM Receiver

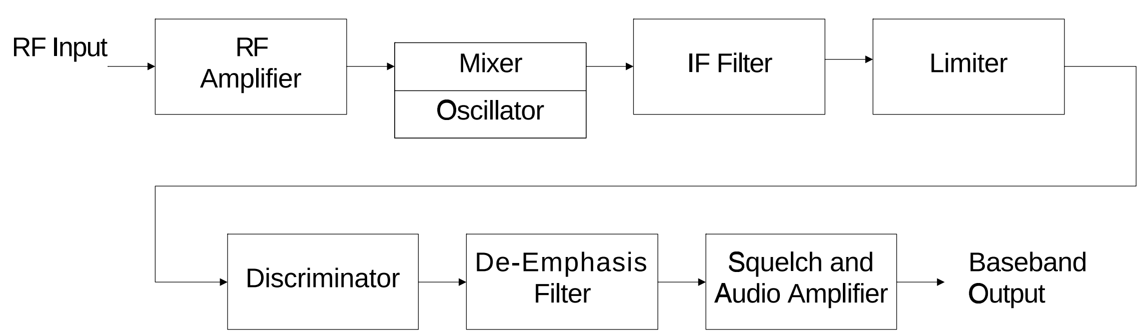

Figure 2.4: Block diagram of an FM receiver.

OFDM modems can adapt to channel conditions by sending fewer bits on subchannels with high error rates [41,42]. The Telebit company manufactures one such modem, the *TrailBlazer*. Telebit's modulation technique, DAMQAM (Dynamically Adaptive Multicarrier QAM), sets the number of bits transmitted on each subchannel according to the quality of that subchannel [42].

HF Modems

The fading on HF channels differs from the fading on mobile radio channels. The narrowband mobile radio channel fades quickly but is not frequency selective while the HF channel fades slowly and is frequency selective [43]. The coherence bandwidth of an HF channel can be less than a few hundred Hertz.

Many narrow channels, each less than 100 Hz, can be used to avoid the distortion that would result from a single wide-bandwidth signal. Such modems have been used on HF channels since the early 1950s [43,44,45,46]. Multi-carrier systems can also be used for channel quality measurements [47].

2.4 The FM Channel

An OFDM/FM system could use the same narrowband FM radios that are currently in use by almost all land mobile radio systems. This section describes the performance characteristics of narrowband FM transmitters and receivers.

2.4.1 The FM Transmitter

Figure 2.3 shows a block diagram of an FM transmitter. After the baseband modulating signal is amplified, it is put through a preemphasis filter. The purpose of this filter will be explained in Section 2.4.7.

The signal's RF bandwidth must be restricted to avoid interference with adjacent channels. A clipper limits the peak value of the modulating signal and thus limits the

2.3.4 Disadvantages of OFDM

OFDM is sensitive to any distortion that disturbs the orthogonality of the carriers. Any such distortion causes crosstalk interference between the subchannels. An important cause of such distortion is amplitude modulation caused by fading. Another cause is frequency offsets due to synchronization errors.

The effects of phase and amplitude jitter and the effects of a single phase or gain change during a symbol were studied in [38]. It was found that the crosstalk noise produced by small amounts of amplitude jitter or gain hits (typically up to 15% or 2 dB) could be reduced about 10 dB by using an adaptive equalizer consisting of a seven-tap transversal filter operating in the frequency domain.

2.3.5 Previous Applications of OFDM

OFDM modems are currently being used for data transmission over telephone channels. OFDM-like multi-carrier modems have also been used for HF (3 to 30 MHz) radio channels.

Telephone Channel Modems

OFDM modems are used on telephone lines because the subchannels do not need to be equalized and because OFDM is less sensitive to impulse noise.

The Gandalf *Supermodem* is a 9600 bps OFDM modem developed in the late 70's [39,40]. It was intended for operation over switched telephone lines. The modem encoded 5 bits on each of 52 carriers at 37 baud. The signal processing was done by a custom MSI TTL processor and the modem sold for several thousand dollars.

NEC manufactures a 19.2 kbps voice-bandwidth modem for use over conditioned telephone lines that uses a type of modulation (Orthogonal QAM, see Chapter 6) that is similar to OFDM [37].

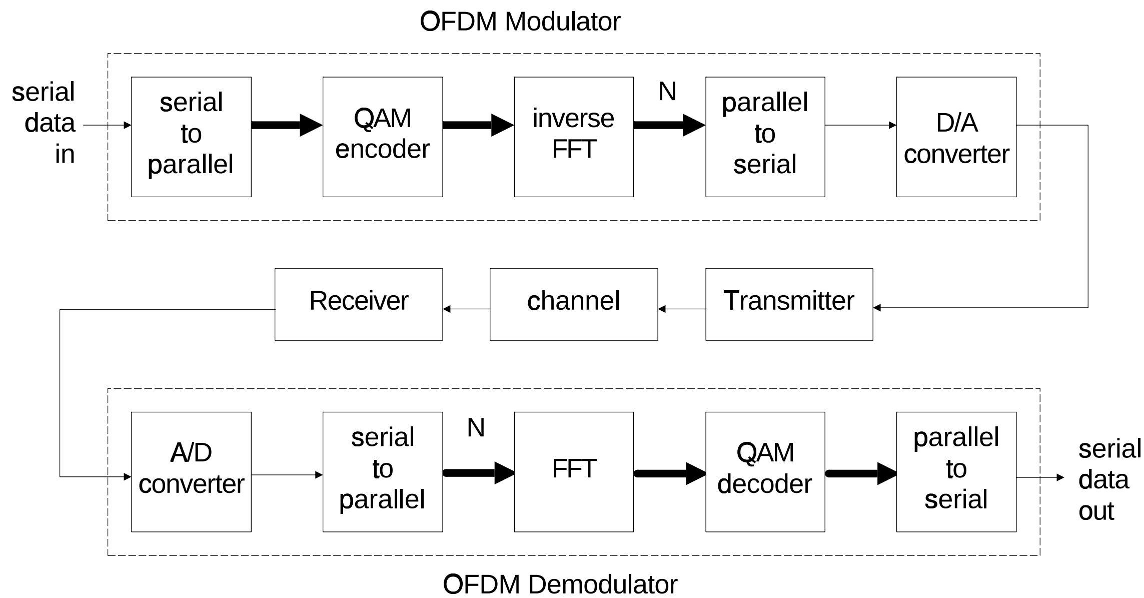

Figure 2.2: An implementation of an OFDM system.

quantizes the signal. The demodulator collects a block of samples from the A/D, converts the samples to complex data values using an FFT, and decodes the complex data values back into bits.

2.3.3 Advantages of OFDM

OFDM is less sensitive to the distribution of the additive noise than serial modulation techniques [38]. The averaging of the signal noise over the symbol period gives a Gaussian distribution to the noise on the demodulated data values. This usually results in a lower error rate.

Conventional high-speed modems need equalizers to undo the frequency-dependent effects of the channel. Since the bandwidth of each OFDM subchannel is much narrower, the phase and amplitude response is approximately constant over each subchannel and equalization is not required.

OFDM can also be made resistant to narrowband interference by not transmitting data on the affected subchannels.

duration.

Consider the prototype system transmitting blocks of $N = 4096$ as an example. The sampling rate was 8 kHz since the audio channel bandwidth was less than 4 kHz. For a block size of 4096 samples, the block duration is 512 ms. A DFT on the 4096 real samples produces 2048 (complex) subchannels. Pairs of bits are encoded into complex values ($\pm 1 \pm j$) and used to set the amplitude and phase of the subchannels using the 4-QAM constellation shown in figure 4.3. Although up to 4096 bits could be transmitted with each block, only half of the subchannels are used (those between 1 kHz and 3 kHz) resulting in only 2048 bits being transmitted per block. Since the duration of the block is 512 ms, the overall bit rate is 4000 bps. This bit rate stays constant as the block duration decreases because the number of subchannels also decreases by the same factor.

The OFDM modem generates a signal with carrier frequencies between DC and one-half of the sampling rate. Any analog modulation method, for example FM or SSB, can be used to transmit the OFDM signal over the channel. OFDM/SSB has better energy and spectral efficiency. OFDM/FM has the advantage of being compatible with existing mobile radio equipment.

2.3.2 Implementation of OFDM/FM

Figure 2.2 is a block diagram of an OFDM implementation. The OFDM modulator and demodulator are implemented with digital signal processors. The modulator collects a block of bits from the data source, encodes them into complex (QAM) data values, and converts the data to signal samples using an inverse FFT. The digital to analog (D/A) converter then produces the baseband OFDM signal.

This baseband signal modulates a transmitter. The modulated signal is transmitted over the fading channel. A receiver recovers the baseband signal which may have been corrupted by fading and additive noise.

The demodulator does the inverse. An analog to digital converter (A/D) samples and frequency diversity reduces fading. Spread spectrum systems also degrade gracefully as the number of users increases and are less sensitive to jamming. However, spread spectrum systems are not widely used except in military applications due to challenging synchronization problems that increase their complexity and expense.

2.3 Orthogonal Frequency Division Multiplexing

2.3.1 Description

OFDM is a modulation method that uses frequency division multiplexing with subcarrier frequencies spaced at the symbol (baud) rate. This frequency spacing makes the carriers orthogonal over one symbol interval [4,34,35,36,37]. This allows efficient modulation and demodulation by using discrete Fourier transforms (DFTs) [36].

Modulation is done by using several bits (typically two to five) to set the amplitude and phase of each OFDM carrier. The modulator is an inverse DFT that converts the complex phase/amplitude data for each subchannel into samples of an OFDM signal. The demodulator is a DFT that extracts the phase and amplitude of each carrier from the sampled OFDM signal.

Because OFDM can be used to efficiently multiplex many bits into one block (symbol), the baud (symbol) rate can be greatly reduced compared to conventional serial modulation methods. The symbol rate is typically reduced by hundreds or thousands of times.

The sampling rate must be greater than twice the bandwidth of the baseband OFDM signal. The number of samples per block, N, is the product of the sampling rate and the block duration. The DFT extracts the phase and amplitude information for $N/2$ (complex) subchannels from the N (real) samples in the block. The number of bits in a block is determined by the number of subchannels used and the number of bits transmitted on each subchannel. Some subchannels may not be usable because some subchannel frequencies may be too noisy, or may be reserved for synchronization information. The bit rate of the system is the number of bits transmitted per block divided by the block

2.2.2 Modulation Suitable for Non-Coherent Receivers

Frequency shift keying (FSK) is a common digital modulation technique for mobile radio channels. The carrier is modulated by changing the carrier frequency. FSK can be demodulated non-coherently. FSK is less sensitive to fading than modulation techniques that use amplitude or phase modulation.

The spectral efficiency of FSK can be improved by selecting the amount of frequency shift and by filtering the modulating waveform. [Gaussian-filtered] minimum-shift keying ([G]MSK), and [Generalized] Tamed FM ([G]TFM) are variations of FSK with better spectral efficiency [16,17,18].

2.2.3 Modulation Suitable for Coherent Receivers

Coherent modulation methods such as phase shift keying (PSK) tend to be more power efficient than non-coherent modulation methods. However, demodulation of PSK requires carrier phase synchronization. Estimating the carrier phase is difficult on fading channels because the received phase is constantly changing. One popular approach is to transmit a pilot carrier with the data and recover the pilot carrier at the receiver [19,20,21,22,23, 24,25,26,27,28,29,30,31].

Many modulation techniques such as GTFM and GMSK can be demodulated coherently or non-coherently. Coherent demodulation can result in better power efficiency at the cost of increased receiver complexity.

2.2.4 Spread Spectrum Modulation

Spread spectrum modulation methods spread the transmitted signal over a bandwidth many times the bit rate, typically several MHz [32,33]. One spreading method is to multiply the data with a pseudo-random signal (*Direct Sequence* modulation). Another method is to shift the carrier frequency many times during each bit period (*Frequency Hopping*). If the signal bandwidth is much greater than the coherence bandwidth the resulting bandwidth is typically greater than 40 kHz in urban areas and more for suburban areas [15]. Frequency-selective fading is therefore not a significant effect for narrowband (15 to 25 kHz) FM signals [3].

2.1.2 Log-Normal Fading

The mean signal level also changes as the mean path length changes and as the types of scatterers change. The distribution of the mean signal level is often approximated as log-normal. This *log-normal* fading is slower and affects the modulation much less than the Rayleigh fading.

2.1.3 Noise

Field measurements have been made of typical noise levels in urban areas. The man-made noise at 100 MHz is 20 to 40 dB above the thermal noise limit. At 1 GHz the man-made noise is 0 to 20 dB above the thermal noise limit. Car ignitions, electric motors, fluorescent lighting, and computers are some sources of RF noise [3].

2.2 Digital Modulation for Mobile Radio

2.2.1 Performance Criteria

Three important measures of the performance of a modulation scheme are spectral efficiency, power efficiency, and delay. *Spectral efficiency* measures how many bits per second can be transmitted in a given bandwidth. For example, a state-of-the-art serial modulation technique, GTFM (Gaussian Tamed FM), can transmit about 16 kbps on a 25 kHz channel [16]. *Power efficiency* measures the energy required per bit for a given BER. *Delay* is important in interactive systems. The acceptable delay depends on the application.

of the received signal envelope can be derived from this power spectrum. Two of these are the level crossing rate (LCR) and the average fade duration ($\overline{\tau}$) [3].

The level crossing rate is the average rate of envelope crossings up through a threshold level. The level crossing rate (LCR) (for a vertical monopole antenna) is [3]:

$$\text{LCR} = \sqrt{2\pi} f_d \rho e^{-\rho^2} \tag{2.4}$$

where ρ is the level above the mean and f_d is the maximum Doppler rate.

The average fade duration is the average time that the envelope stays below a threshold level. The average fade duration $\overline{\tau}$ is given by [3]:

$$\overline{\tau} = \frac{e^{\rho^2} - 1}{\rho f_d \sqrt{2\pi}} \tag{2.5}$$

where ρ and f_d are as above.

2.1.1 Frequency-Selective Fading

A more complex propagation model includes many discrete scatterers. Each propagation path can have a different amplitude, propagation delay, and Doppler shift. The distribution of these three variables is called the *delay-Doppler* profile [12] and defines the way the received signal will be distorted.

When components are received with different delays, the phase differences between them will be a function of the signal frequency. The times or the positions of the fades will depend on the frequency. This is known as frequency-selective fading.

Field measurements [6,7,8,13,14] have shown that the distribution of the propagation delay is different in urban and rural areas but that the rms delay spread[1] is seldom more than 10 μs.

The frequency range over which the correlation of fading signals exceeds 0.9 is defined as the *coherence bandwidth* [3]. In general, however, the channel will severely distort a signal whose bandwidth significantly exceeds the coherence bandwidth. The coherence

[1] The rms delay spread is the root of the second central moment of the delay distribution [3].

Each of the received components will have a different Doppler shift. The shift will depend on the relative velocity between the scatterer and the vehicle. The maximum Doppler shift (f_d) is given by

$$f_d = \frac{f_c v}{c} \tag{2.3}$$

where f_c is the carrier frequency, v is the vehicle speed, and c the velocity of propagation. The nomograph in Figure 2.1 shows this relationship.

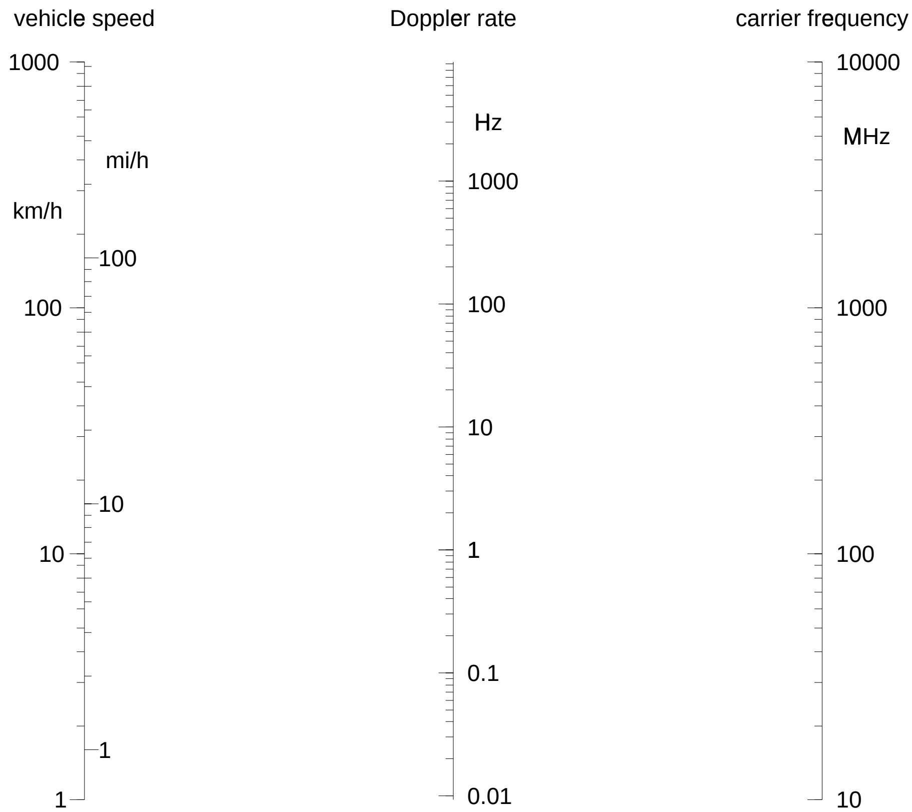

Figure 2.1: Nomograph showing the relationship between maximum Doppler rate (f_d), vehicle speed(v), and carrier frequency (f_c). Draw a straight line intersecting the appropriate axes at the two known quantities. The unknown is read at the intersection of the line with the axis of the unknown variable.

The distribution of the Doppler shifts and the response of the antenna to the different components define the power spectrum of the combined in-phase and quadrature components [10]. The spectrum of the envelope can then be computed. Some useful statistics

Chapter 2

Review of Previous Work

This chapter reviews several topics that are relevant to the work described in subsequent chapters. The sections briefly describe the mobile radio channel, other digital modulation techniques, OFDM, and FM transmitters and receivers.

2.1 The Mobile Radio Channel

Propagation at VHF and UHF frequencies is mostly by reflection, diffraction and scattering from buildings and other objects. As the receiver moves in the interference pattern created by the different propagation paths, the received signal strength varies.

Clarke's simple model [10] assumes many scatterers uniformly distributed in a circle around the moving receiver. The signal components received from the scatterers are assumed to have equal amplitudes and independent, uniformly-distributed phases. If each of the received components is expressed in complex notation, the central limit theorem [11] implies that the probability distributions of the real (in-phase) and imaginary (quadrature) components are Gaussian. The probability density function (pdf) of the envelope (magnitude of the complex sum) can then be shown to be Rayleigh [11],

$$p(r) = \begin{cases} 0 & \text{if } r \leq 0 \\ \frac{r}{b} e^{-r^2/2b} & \text{if } r > 0 \end{cases} \tag{2.1}$$

and the cumulative distribution function (CDF) is

$$P(r) = \begin{cases} 0 & \text{if } r \leq 0 \\ 1 - e^{-r^2/2b} & \text{if } r > 0 \end{cases} \tag{2.2}$$

where r is the level of the envelope and the mean is $\sqrt{\pi b/2}$.

Chapter 5 describes the measurements on a prototype OFDM/FM system. These measurements include the BER and some FM receiver and transmitter characteristics. The measurements verify the assumptions in the model and the numerical results.

Chapter 6 explains some ways to improve the BER performance of OFDM/FM. A method to reduce the crosstalk caused by fading is described. This method, decision feedback correction (DFC), uses the received data to recreate the parts of the signal lost in fades. Switching diversity and forward error correction (FEC) coding are also briefly examined.

Chapter 8 compares OFDM/FM with OFDM/SSB and with more conventional serial modulation techniques.

Chapter 7 covers various topics on the implementation of OFDM/FM systems. The complexity of the digital signal processing (DSP) hardware required and the problem of synchronization are briefly considered.

Chapter 9 summarizes the contributions of the thesis and suggests some topics for further research.

source of noise. The main contributions of the research include:

- several methods to predict the bit error rate (BER) performance of OFDM/FM systems,
- a method to reduce the crosstalk caused by fading,
- measurements on a prototype OFDM/FM system to verify the performance analysis and to demonstrate the feasibility of OFDM/FM, and
- investigation of the performance of OFDM/FM systems using forward error correction (FEC) and switching diversity.

1.4 Organization of the Thesis

Chapter 2 provides background information on mobile radio propagation, other digital modulation methods for mobile radio, the characteristics of FM channels, and previous applications of OFDM.

Chapter 3 describes the model used to analyze the BER performance of OFDM/FM. The model converts the fading of the RF signal into equivalent effects on the baseband signal. The model can include receiver functions such as automatic gain control (AGC) and squelch. The model also applies to OFDM/SSB in the case of perfect carrier synchronization. An expression for the BER of OFDM is obtained as a function of three statistics of the received signal level.

Three methods that were developed to evaluate the BER performance of OFDM are described in Chapter 4. First, bounds on the BER can be obtained for block durations much shorter or much longer than the average fade duration. Second, the BER expressions derived in Chapter 3 can be evaluated with a Monte Carlo numerical integration method. Finally, a signal-processing simulation can be used to study OFDM in more detail.

split up into many QAM[1]-modulated subcarriers [4]. OFDM thus transmits blocks of data in parallel instead of serially. The symbol duration is typically increased by a factor of hundreds or thousands. The increased duration of each symbol creates a time-diversity effect by making it less likely that the complete symbol will be severely faded. However, fading distorts the subcarriers and reduces their orthogonality[2]. This results in crosstalk between the subchannels that degrades performance.

The OFDM signal must be modulated onto an RF (radio frequency) carrier. One approach is to translate the baseband OFDM signal up to the desired RF frequency by using single side-band (SSB) modulation (OFDM/SSB, or simply OFDM). The performance of a cellular telephone system using OFDM/SSB was studied in [1]. FM (frequency modulation) can also be used (OFDM/FM) [5].

OFDM/SSB systems require new and complex SSB receivers and transmitters while OFDM/FM systems can use existing FM radio equipment. For this reason OFDM/FM would be less expensive to implement than OFDM/SSB. However, the OFDM/SSB system proposed in [1] is more spectrally efficient and more power efficient than the OFDM/FM system described in this thesis.

1.3 Scope of the Thesis

This thesis presents the results of research into the performance of OFDM/FM for mobile radio data communication.

Flat (non-frequency-selective) fading will be assumed because propagation surveys [6, 7,8,9] have shown that this is a good assumption for narrow-band (under 20kHz) signals. The radio system design is assumed to be a conventional non-cellular design that provides enough protection from cochannel interference to make additive Gaussian noise the major

[1] Quadrature Amplitude Modulation, see Section 4.5.6.

[2] The functions $a(t)$ and $b(t)$ are said to be orthogonal if $\int_0^T a(t)b(t)dt = 0$ where T is the period or duration of the signal. When $a(t)$ and $b(t)$ are distorted the magnitude of the integral increases and in this sense the orthogonality is "reduced".

and other objects. The interference between signal components propagating along different paths forms a pattern of varying field strength. The received signal level fluctuates as a vehicle moves through this pattern. Figure 1.2 shows the deep fades that are characteristic of the received signal. The challenge is to provide efficient and reliable data communication through this channel.

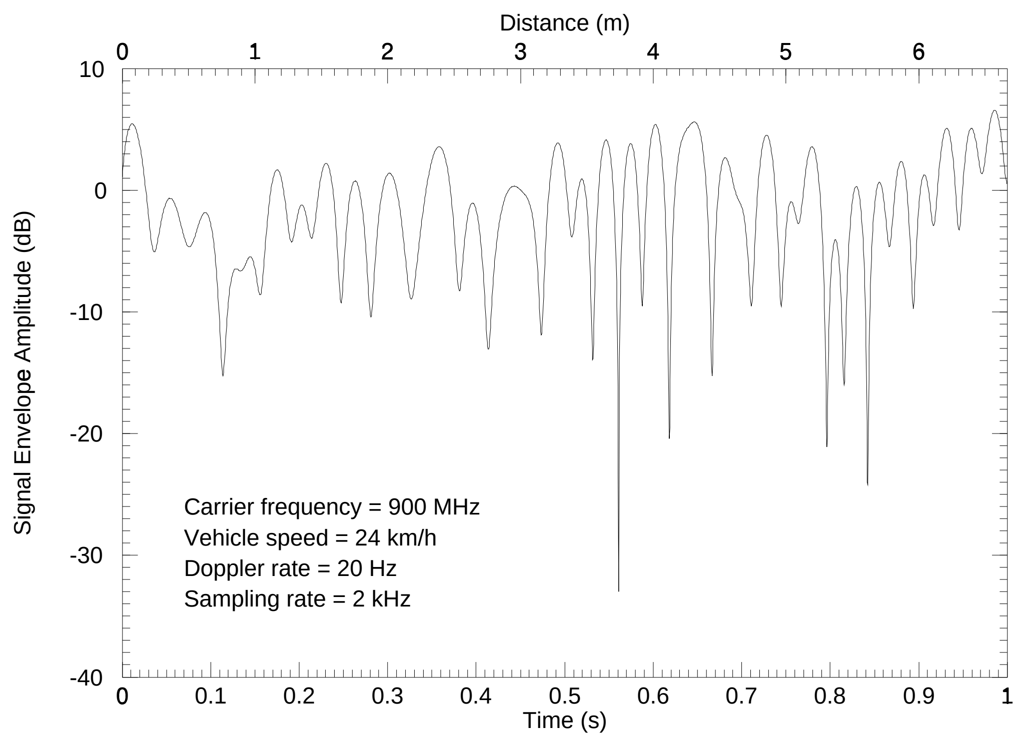

Figure 1.2: A sample plot of the received signal level.

1.2 OFDM/FM for Mobile Radio Data Communication

Orthogonal Frequency Division Multiplexing (OFDM) modulation has been proposed as an approach to the problem of fading [1]. OFDM is a modulation method that uses frequency division multiplexing to reduce the baud rate. A single serial data stream is

Chapter 1

Introduction

1.1 Mobile Data Communication

Mobile data communication has become increasingly popular over the past ten years [2]. For example, many police departments now use mobile data terminals (MDTs) to access vehicle and criminal databases. MDTs are also used by taxi companies to dispatch cabs and by courier companies to track deliveries. MDTs can support more users per channel, offer increased accuracy and security, and allow the transmission of information in new forms such as graphics. Figure 1.1 shows the main components of a mobile data communication system.

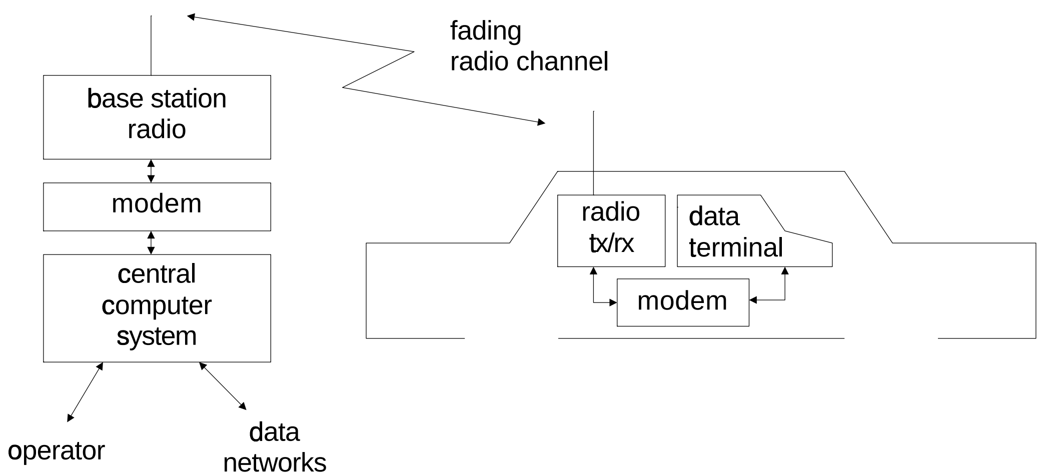

Figure 1.1: A mobile data terminal (MDT) system.

Data transmission over the mobile radio channel presents a challenging problem [3]. Radio signals propagate over these channels by reflecting and scattering from buildings

Acknowledgement

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List of Figures

List of Tables

Table of Contents

Abstract

The use of Orthogonal Frequency Division Multiplexing (OFDM) for digital communications over Rayleigh-fading mobile radio channels was proposed by Cimini [1]. OFDM transmits blocks of bits in parallel and reduces the bit error rate (BER) by averaging the effects of fading over the bits in the block. This thesis studies the performance of OFDM/FM, a new modulation technique in which the OFDM baseband signal is used to modulate an FM transmitter. OFDM/FM can be implemented simply and inexpensively by retrofitting existing FM communication systems.

Expressions are derived for the BER and word error rate (WER) within a block when each subchannel is QAM-modulated. Several numerical methods are developed to evaluate the overall BER and WER. An experimental OFDM/FM system was implemented using unmodified VHF FM radio equipment and a fading channel simulator. The BER and WER results obtained from the hardware measurements agree closely with the numerical results.

The effects of forward error correction (FEC), switching diversity, automatic gain control (AGC), and squelch were tested. A new technique, decision feedback correction (DFC), was developed to reduce the crosstalk interference between the OFDM subchannels. This method significantly improves the BER performance of OFDM/FM.

At BERs below 10^{-2} the experimental OFDM/FM system has better power efficiency than the serial modulation techniques conventionally used for mobile radio (NCFSK, GTFM, or GMSK). At a BER of 10^{-3} and a normalized block duration (Tf_d) of 2.6, the experimental OFDM/FM system is 5 dB more power efficient than serial techniques. The use of DFC can significantly increase this advantage. However, current GTFM and GMSK systems have better spectral efficiency than the OFDM/FM prototype.

OFDM/FM FOR MOBILE RADIO DATA COMMUNICATION

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We accept this thesis as conforming

to the required standard

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