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Companding is a method used on various speech channels to reduce the peak value of the modulating signal without reducing its average power [49]. An amplifier with non-linear gain characteristics (the "*comp*ressor") is used at the transmitter to reduce the dynamic range of the modulating signal. An amplifier with the inverse characteristic is used at the receiver to "exp*and*" the signal and recover the original waveform. Companding could be used to reduce the distortion due to clipping and improve the limiting baseband SNR. This would allow more bits to be encoded on each subchannel and would improve the spectral efficiency.

Various modifications to the DFC procedure might improve its performance. Instead of completely substituting the portions of the received signal that are below a fixed threshold, the amount of the regenerated signal that is added could be determined by a weighting function that is a function of the IF SNR. The weighting function could be changed as the correction procedure converges.

Practical methods of recovering timing and phase synchronization should be developed. The timing system could be based on time slots or on detection of the presence of the IF or baseband signal.

A prototype could be built and tested in the field along with a commercial mobile radio modem. OFDM is robust because it is insensitive to the distribution of the noise and because it can be adapted to compensate for non-ideal channel response characteristics such as narrow-band interference and attenuation notches in the spectrum. OFDM should therefore perform equally well outside the laboratory.

Many telephone channel impairments such as frequency offset, jitter, or gain hits can be modelled as interference between the OFDM subchannels [38]. An adaptive equalizer operating on the recovered data values (i.e. across subchannels) was able to significantly reduce this interference [38]. This method was not implemented because the effects of Rayleigh fading were thought to be too severe for the proper operation of an adaptive equalizer. However, an investigation of this method may be worthwhile.

improve the BER performance of OFDM/FM. At a BER of 10^{-3}, the improvement due to this technique is between 3 and 5 dB. The improvement increases as the block size increases or the SNR increases.

The OFDM/FM system studied in the thesis is not as power efficient or as spectrally efficient as a proposed OFDM/SSB system [1] but it is simpler and less expensive.

For BERs below 10^{-2}, the experimental OFDM/FM system provides better power efficiency than any of the serial digital modulation methods that are available for mobile radio data transmission (FSK, GTFM, or GMSK). At a BER of 10^{-3} the OFDM/FM system with a block duration $Tf_d = 2.6$ is about 5 dB more power efficient than GTFM or GMSK. The use of DFC can increase this advantage significantly. However, current GTFM and GMSK systems have better spectral efficiency than the experimental OFDM/FM system. The experimental system was designed for ease of implementation rather than to achieve optimum performance and better results would likely be obtained with further development.

The hardware requirements for OFDM/FM are comparable to those of other high-speed baseband modems and the cost of the required digital signal processing (DSP) hardware is relatively low.

9.2 Topics for Further Study

The spectral efficiency of OFDM can be increased by encoding more bits on each subchannel. However, increasing the number of bits encoded per subchannel reduces the distance between data points in the signal space [11]. The experimental system's limiting baseband SNR would have to be increased to avoid introducing a BER floor. It is also possible to encode more bits on subchannels with high SNRs and fewer on subchannels with lower SNRs. This method is used by many telephone OFDM modems [37,41,42,61,78]. The analysis in Chapter 3 can be extended to predict the BER for other encodings ("signalling constellations") by using the appropriate BER expression (see [79]).

techniques.

An experimental OFDM/FM system was implemented using unmodified commercial VHF FM radio equipment and a fading channel simulator. The BER and WER results obtained from the hardware measurements agreed with the results obtained using the numerical methods. This agreement shows that the EBC model can be used to predict the performance of OFDM/FM systems. The experimental results also validate the analysis and demonstrate that it is feasible to implement an OFDM/FM system using conventional FM radio equipment. The experimental measurements also demonstrated the need to consider the limitations of practical FM channels such as clipping, bandwidth restrictions, preemphasis and deemphasis, and the baseband noise spectrum. Methods were developed to select the modulating signal level, the baseband frequency range, and the amount of "software preemphasis".

Several common techniques of improving the performance of communications systems (forward error correction (FEC), space diversity, automatic gain control (AGC), and squelch) were tested. It was shown that the independent error assumption can be used to predict the distribution of the number of errors in a word. This result is useful in predicting the performance of FEC codes. The two rate-$\frac{1}{2}$ random-error and burst-error correcting FEC codes tested did not significantly improve the power efficiency (E_b/N_0 performance) of OFDM/FM. It was shown that OFDM/FM works well with switching diversity because OFDM can average out the effects of impulses created by switching. The optimum squelch and AGC thresholds for large blocks were found by evaluating the bounds on the BER for large blocks. The actual BER performance for blocks of various durations was obtained with baseband simulations. The use of squelch produced a small (about 1 dB) performance improvement and the use of AGC provided a negligible improvement.

A new technique to reduce the crosstalk interference between the OFDM subchannels was developed. This method, decision feedback correction (DFC), can significantly

Chapter 9

Conclusions

9.1 Conclusions

A novel modulation method, OFDM/FM, has been proposed for data communication over mobile radio channels. Orthogonal Frequency Division Multiplexing (OFDM) is an efficient method of transmitting a block of bits in parallel and thus reducing the symbol rate. The use of OFDM averages the effects of fading over all of the bits in the block and this can result in better power efficiency than conventional serial modulation techniques. OFDM/FM is the transmission of a baseband OFDM signal over an FM channel. OFDM/FM systems can be implemented simply and inexpensively by retrofitting existing FM radio systems.

A simple and versatile model for the mobile radio FM channel, the *equivalent baseband channel* (EBC) model, was developed to study the performance of OFDM/FM. This model is quite general and so allows various receiver effects to be be modelled.

A simple expression was derived for the Bit Error Rate (BER) within a block when each channel is QAM-modulated. An expression was also obtained for the Word Error Rate (WER) by assuming that errors occur randomly within the block.

Several numerical methods were developed to evaluate the overall BER and WER. An expression was obtained for the BER for the case where blocks are very short or very long relative to the average fade duration. An efficient Monte-Carlo numerical integration method was developed to evaluate the BER and WER for intermediate block lengths. A baseband signal-processing simulation that simulates the effects of fading on the baseband OFDM signal was written to evaluate various coding and signal processing

Performance Summary Table

	OFDM/SSB	OFDM/FM	GMSK/GTFM
E_b/N_0 for BER=10^{-2}	13–15 [a]	15–21 [b]	18–22 [c]
E_b/N_0 for BER=10^{-3}	18–22 [d]	18–27	28–32
channel spacing	7.5–10 [e]	25	25–30
bit rate	8.6 [f]	4–12 [g]	16
spectral efficiency (bps/Hz)	1.15–0.86 [h]	0.16–0.48 [i]	0.53–0.64 [j]
delay	$> \approx$ 30 ms [k]	$> \approx$ 30 ms [l]	$<$ 1 ms [m]
signal processing complexity	high	high	low–medium
RF complexity	high	low	low
cost	high	low–medium[n]	low–medium
uses existing radios	no	yes	no

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[a] [1], Tf_d=5 to Tf_d=0.63, no delay spread, assuming SIR $\equiv$ SNR

[b] Tf_d=10.2 with DFC to Tf_d=0.64 without DFC.

[c] [16] and [17].

[d] Estimated from [1, Figure 5 and Figure 12].

[e] 0.5 to 3 kHz guard bands.

[f] [1].

[g] section 8.3.3.

[h] 8.6 kbps at 7.5 to 10 kHz.

[i] 4 kbps to 12 kbps at 25 kHz.

[j] 16 kbps at 25 kHz to 30 kHz.

[k] typical, N =512 at f_s =15 kHz.

[l] typical, N =256 at f_s = 8 kHz.

[m] 16 bits at 16 kbps.

[n] low cost if retrofitting existing equipment.

Table 8.1: Performance summary for various modulation techniques.

8.5.2 OFDM/FM

Transmitters and receivers for FM are much simpler than those for SSB. OFDM/FM receivers can use simple non-coherent discriminator detectors. Since almost all current mobile radio equipment uses FM modulation, OFDM/FM can be retrofitted as a voice-band modem operating over an un-modified FM radio.

8.5.3 GMSK/GTFM

The complexity of GMSK/GTFM systems is mainly in the signal processing required for generating the modulating signal and for demodulation. Simple receivers use discriminators [16] while more sophisticated ones are synchronous and require carrier phase recovery [17]. Some designs use DSP microprocessors for filtering and MLSE decoding.

8.6 Conclusions

OFDM/SSB and OFDM/FM systems have better power efficiency than serial modulation methods because of the long symbol period. OFDM/SSB has better power and spectral efficiency than OFDM/FM but would be more expensive to implement.

OFDM/FM is simple to implement and can be used with existing radio equipment but needs further development to improve its spectral efficiency. The experimental OFDM/FM system was built to verify the analysis and simulation results and thus does not demonstrate the best achievable OFDM/FM performance. Several approaches to improving the performance of OFDM/FM are described in Chapter 6.

GMSK and GTFM are relatively simple to implement and have good spectral efficiencies.

Table 8.1 summarizes the differences among the modulation techniques considered in this chapter.

8.5.1 OFDM/SSB

Transmitters and receivers for SSB are more complex than those for FM. The two common methods of generating SSB signals require either a narrow IF filter to extract a single sideband or a method of generating two modulated signals in exact quadrature [49]. However, the increased spectral efficiency of SSB has led to the design of at least one experimental mobile radio SSB system [24]. Good results are reported for both voice and data transmission with an SSB system using an in-band pilot carrier.

Carrier Frequency Synchronization

Since OFDM/SSB is a coherent modulation technique, it is necessary to estimate the carrier phase and frequency in order to recover the transmitted data. The OFDM/SSB system proposed in [1] uses pilot carriers above and below the signal to provide carrier frequency synchronization. Filters with bandwidths of 100 Hz are used to extract the carriers. Some form of carrier frequency acquisition and tracking would be required because of Doppler shifts of ± 80 Hz at 60 mph (at 850 MHz), as well as transmitter and receiver frequency errors. The design of mobile radio systems that require high frequency stability would have to take into account poor environmental conditions that include vibration and large temperature and power supply variations.

RF Amplifier Efficiency

Amplification of OFDM/SSB signals generally requires linear (class A) power amplifiers to avoid distortion that could produce harmonics. The constant-amplitude OFDM/FM, GTFM, or GMSK signals can be amplified by more efficient non-linear (class C) power amplifiers. The power efficiency of OFDM/SSB relative to constant-amplitude modulation schemes is reduced by up to 3 dB if the efficiency of the RF amplifier is taken into account.

8.4 Delay

OFDM systems introduce a transmission delay of at least the duration of the OFDM block. In addition, gaps must be left between blocks, there are delays in computing the forward and inverse DFTs, and there may be delays in transferring data between the terminal and the modem. These additional delays will depend on the implementation (see Chapter 6).

The permissible delay depends on the application. In [1] the interval between blocks for the proposed OFDM/SSB cellular telephone system was restricted to 20 ms to reduce delays. Longer delays (several hundred milliseconds) would be acceptable for many mobile data terminal applications.

The MLSE for the GTFM receiver described in [18] introduces a negligible decoding delay of up to several tens of bits.

8.5 Implementation Considerations

Performance results should not be the only basis of comparison between modulation techniques. There may be practical limits to a system's performance which do not show up in theoretical or simulation results. Experimental work can uncover some of these problems but experimental results only give a lower bound on performance – different implementations may give better performance. Alternatively, systems that can be shown to work in the laboratory may not be successful commercially because of cost, manufacturing, regulatory, or market considerations. It is difficult to estimate the relative costs of implementing the different modulation techniques because new technology and techniques are constantly being developed. This section discusses some of the difficulties that might be faced in implementing the different modulation methods.

and 0.53 bps/Hz.

8.3.2 OFDM/SSB

The design of the OFDM/SSB system in [1] transmits 8.6 kbps with 7.5 kHz channel spacing. The nominal spectral efficiency is thus 1.15 bps/Hz.

However, the design only allows for guard bands of 500 Hz between channels. This guard band must account for the following frequency errors:

- differences in Doppler shifts (±100 Hz at 80 mph),
- transmitter and receiver frequency errors, (quartz frequency standards age about 5×10^{-10} per day (150 Hz per year)), and
- IF filter roll-off (typically 200–600 Hz between channels for crystal filters).

Channel spacing of 7.5 kHz would require much more sophisticated technology than is currently used. If we assume a more realistic guard band of 3 kHz between channels, the channel spacing becomes 10 kHz and the spectral efficiency drops to 0.86 bps/Hz.

8.3.3 OFDM/FM

The experimental OFDM/FM system described in Chapter 5 transmits at 4 kbps over channels with 25 kHz spacing giving a spectral efficiency of 0.16 bps/Hz.

However, by reducing the modulating level it should be possible to use 8-QAM or 16-QAM modulation thus increasing the bit rate to 6 or 8 kbps and the spectral efficiency to 0.24 or 0.32 bps/Hz. Modifications to transmitter and receiver audio processing circuits and transmitting a variable number of bits per subchannel should allow bit rates of 12 kbps (without increasing the peak deviation or RF bandwidth), giving spectral efficiencies of about 0.48 bps/Hz. However, the reduction in modulation level to increase the spectral efficiency would reduce the power efficiency somewhat.

8.2.3 OFDM/SSB

In [1] the performance of OFDM over mobile radio channels was studied for the case of a single fading cochannel interferer rather than additive white noise. Therefore it may not be valid to compare the OFDM/SSB system's SIR (Signal-to-Interference) performance to other systems' SNR performance.

Figure 8.1 shows software simulation BER versus E_b/N_0 results from [1, Figure 5] assuming that the effect of the fading interferer is equivalent to that of a fixed white noise source. The Doppler rate was 38 Hz and the block duration was 68 ms[2] giving Tf_d of about 2.6.

8.2.4 OFDM/FM

The experimental results for OFDM/FM without DFC for Tf_d=2.6 and Tf_d=10.2[3] (section 5.5.1) are also shown in Figure 8.1.

8.3 Bandwidth Efficiency

Bandwidth efficiency is the number of bits per second that can be transmitted per unit (Hz) of channel bandwidth. The bandwidth efficiency will be computed as the data rate on each channel divided by the channel frequency spacing. For example, a system that transmits 15 kbps on each channel and uses channels spaced every 30 kHz would have a spectral efficiency of 0.5 bps/Hz.

8.3.1 GTFM/GMSK

The proposed GTFM and GMSK systems operate at 16 kbps with IF bandwidths of about 16 kHz. However, to provide protection against adjacent channel interference the channels are spaced 25 or 30 kHz apart. Thus their spectral efficiency varies between 0.64

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[2] Note that in [1] the variable N is the number of subchannels instead of the number of samples in a block.

[3] The performance of OFDM/SSB would also improve with a larger Tf_d.

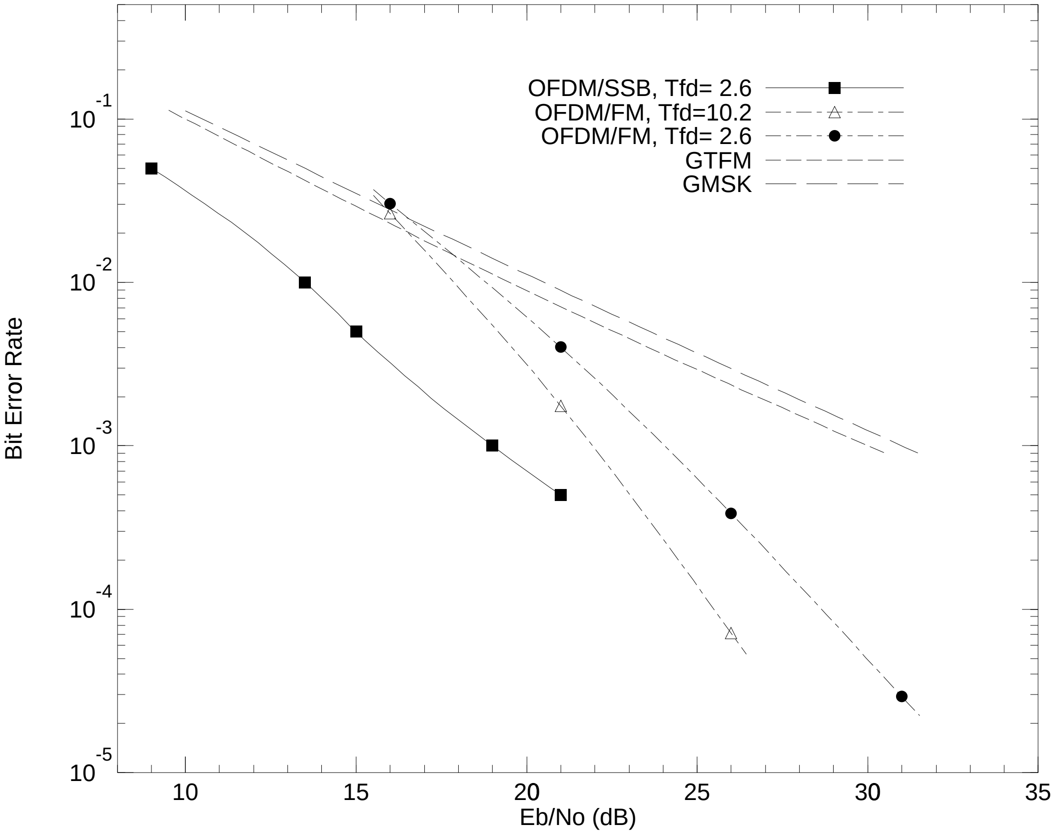

Figure 8.1: E_b/N_0 performance of various modulation methods.

IF filter with a 16 kHz noise bandwidth is assumed. The demodulator was a (two bit) differential detector.

In [17] another GMSK system with B_bT =0.25 is described. This system uses a coherent receiver and the experimental results are about 2 to 3 dB better than those in [16].

These serial transmission methods when used with non-coherent demodulation, all have approximately the same BER performance as non-coherent FSK. Their BER performance in Rayleigh fading can be approximated by

$$\mathrm{BER} = \frac{1}{2 + \mathrm{E}_b/\mathrm{N}_0}. \tag{8.1}$$

a 3-bit-period transversal filter followed by a raised-cosine low-pass filter[18]. GMSK and GTFM signals have a constant envelope and can be demodulated with coherent, differential, or discriminator detectors[76].

OFDM/SSB

The notation OFDM/SSB is used in this thesis for the transmission of the OFDM signal by directly translating the baseband OFDM signal to the carrier frequency as described in [1].

8.2 Power Efficiency

8.2.1 GTFM

The E_b/N_0 performance of one GTFM implementation is shown in Figure 8.1 [18, Figure 18]. This system used GTFM parameters B=0.62 (transversal filter's center tap coefficient) and r=0.36 (raised-cosine low-pass filter roll-off). The receiver used a discriminator followed by a maximum-likelihood sequence estimator (MLSE) to decode the three-level signal produced by filtering. The bit rate is 16 kbps and the -3 dB filter bandwidth is about 16 kHz (noise bandwidth not given). Since $B/R \approx 1$, the SNR is numerically equal to E_b/N_0. The results shown in Figure 8.1 are from simulations of operation over a Rayleigh fading channel[1]. Experimental results in the non-fading case are about 2 dB worse than the (non-fading) simulation results.

8.2.2 GMSK

Figure 8.1 also shows the experimental E_b/N_0 performance for a 16 kbps GMSK system given in [16] with B_bT (product of filter -3 dB bandwidth and bit period) of 0.25. An

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[1] Random FM produces an error floor at a BER of approximately 2×10^{-5} for a Doppler rate of 25 Hz, about 1×10^{-4} for a Doppler rate of 50 Hz, and about 3×10^{-4} for 100 Hz.

Chapter 8

Comparisons With Other Modulation Methods

8.1 Introduction

This chapter describes alternative modulation techniques for data transmission over mobile radio and compares them with OFDM/FM. OFDM/FM is compared with OFDM/SSB and also with two bandwidth-efficient serial modulation techniques: GMSK (Gaussian-filtered Minimum-Shift Keying) and GTFM (Generalized Tamed FM). After a brief description of the other modulation techniques, their performances are compared on the basis of:

- power efficiency (BER versus E_b/N_0),
- bandwidth efficiency (bps/Hz),
- delay, and
- implementation complexity.

8.1.1 Description of Other Modulation Techniques

GTFM and GMSK

There are a large number of possible digital modulation techniques available for mobile radio data transmission [76,77]. GTFM and GMSK are two of the most promising bandwidth-efficient modulation techniques [17,18]. Both GMSK and GTFM are forms of MSK (FSK with a modulation index of 0.5) in which the modulating signal is shaped by filtering to reduce the RF bandwidth. GMSK uses a Gaussian filter[16]. GTFM uses

7.7 Sampling Frequency Error and Jitter

An error in the sampling frequency shifts the effective frequencies of the subchannels. The frequencies of the subchannels are no longer orthogonal and this results in crosstalk interference between the subchannels. Jitter in the sampling clock varies the position of the sampling instant and this causes an effect similar to additive noise. Neither of these effects is likely to be a significant problem because inexpensive, accurate, and stable crystal-controlled sampling clocks are available.

7.6 A/D and D/A Quantization

Figure 7.3 shows the BER performance results from a simulation of the OFDM/FM system described in Chapter 5 using 16, 8, 4, and 2 bits of D/A (transmitter) and A/D (receiver) quantization with a quantization range of 20 times the rms value. The theoretically achievable SNR for Gaussian-distributed signals with a quantization range of four times the rms value is given by $6b - 1.24$ dB where b is the number of bits of quantization [74]. Because the baseband SNR is limited to less than 18 dB, even inexpensive 8-bit D/As and A/Ds are sufficient for this system. The effect of quantization on OFDM systems (not including clipping or fading) has been studied by Ingram [75].

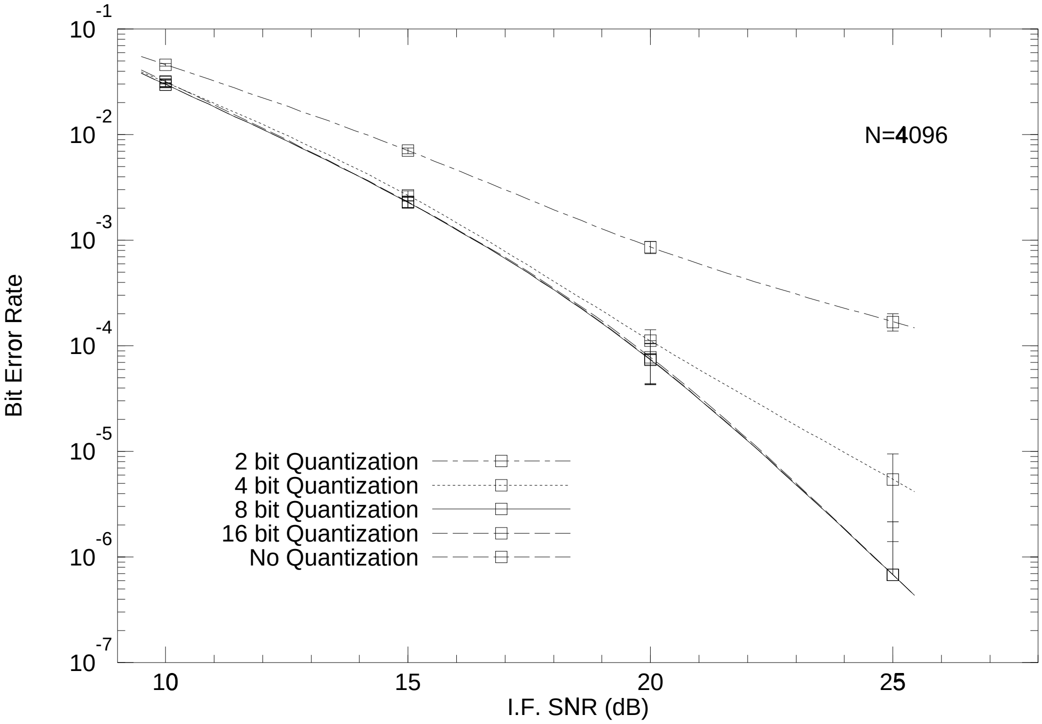

Figure 7.3: Effect of quantization on BER.

7.5 Hardware Cost and Complexity

Inexpensive OFDM modems can be built with DSP microprocessors. This section gives examples of the complexity and cost of the DSP hardware required to implement a baseband OFDM modem.

The first commercial OFDM modem was the Gandalf SuperModem [38,40]. This 9600 bps telephone modem used OFDM modulation with 52 subchannels. The signal processing was performed by a custom processor built with medium scale integration transistor-transistor logic (TTL) circuits [39]. This modem was sold in the late 1970's and early 1980's for about $4000 [40].

A more recent example is the Telebit Trailblazer [42]. This modem uses DAMQAM (Dynamically Adaptive Multicarrier Quadrature Amplitude Modulation). DAMQAM is OFDM with up to 511 subchannels and using 2, 4, or 6 bits per subchannel depending on the subchannel quality. The aggregate bit rate is between 10 and 17 kbps. The hardware includes a Motorola 68000 microprocessor and a Texas Instruments TMS32010 DSP microprocessor. The retail price in 1988 was $1400; approximately the same as CCITT V.32 (QAM) 9600 bps modems [72].

The DSP hardware is a small fraction of the cost of an OFDM modem. For example, the quantity price of a TMS320C10 is under $18[1].

Hirosaki has compared the complexity (in terms of multiplications per sample) of OQAM[2] and conventional serial QAM with equalization [73]. OQAM was found to be less complex for systems requiring spectral efficiencies greater than about 1.9 bits/s/Hz.

These comparisons show that the cost and complexity of the signal processing hardware required for OFDM is comparable to that required for conventional high speed serial transmission over bandlimited channels.

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[1] Price quote for 1000's quantities from Future Electronics, April 1989.

[2] OQAM is OFDM combined with frequency-domain equalization that allows OFDM blocks to be transmitted without guard time delays between blocks.

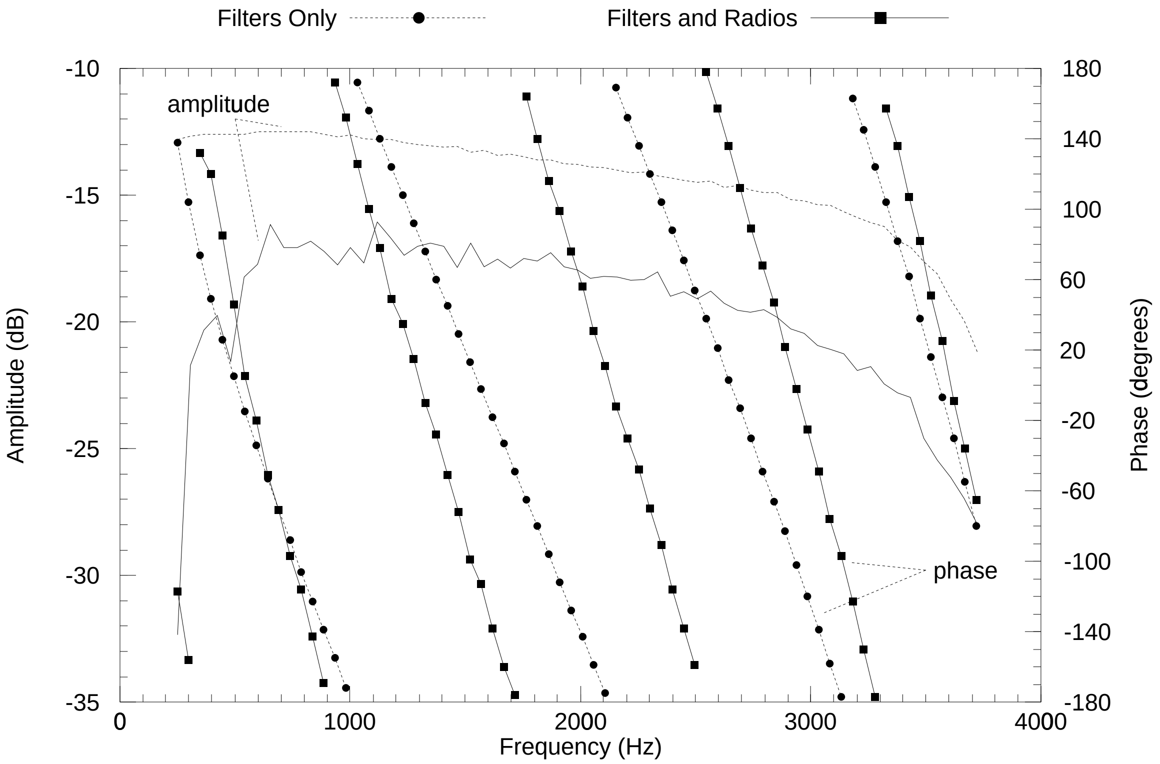

Figure 7.2: Measured baseband channel transfer function.

7.4.4 Differential Coding

Differential coding for OFDM was first proposed as a way to avoid equalization [36]. If the phase shift between adjacent subchannels is small, the data can be coded as the difference in phase between the subchannel carriers instead of their absolute phase. For example, the lowest subchannel is taken to be a fixed reference and the data on the other subchannels are encoded differentially from the next lower subchannel. The measurements in Figure 7.2 show that after phase synchronization the assumption of small phase differences between adjacent subchannels is quite good. Differential coding simplifies receiver design by eliminating the need for equalization but degrades performance due to error propagation.

equalization, described in the following section.

7.4.3 Equalization

The various circuits (amplifiers, filters, modulators, etc.) that process the baseband signal at the transmitter and receiver will introduce some linear distortion. The amplitude and phase changes at each subchannel (the baseband channel's transfer function) must be estimated and corrected to allow accurate data recovery.

In some systems this linear distortion can be measured and the measurement can then be used to correct it. For example, dial-up telephone modems use a training sequence at the start of each call to measure the channel characteristics.

The typical mobile radio system involves one base station that communicates with many mobile stations. Each mobile receiver and transmitter may have a different transfer function. This makes equalization difficult. Each receiver could do its own training in the base-to-mobile direction but the base station might need to store one set of correction characteristics for each mobile unit. An alternative would be differential coding, described in section 7.4.4.

In the experimental measurements the phase and amplitude changes on each subchannel were measured and used to correct the received data values. A training sequence of pseudo-random data was used to measure the channel phase and amplitude characteristics. This measurement was done at high RF SNR and without fading to increase the accuracy of the measurement. The measured phase shifts and gains at each subchannel were used to correct all subsequent received values as follows: if the transmitted value at one frequency was X and the received value at that frequency is Y, each value received subsequently at that frequency was multiplied by the (complex) value X/Y to undo the channel's phase and amplitude changes.

Figure 7.2 shows the measured phase and amplitude characteristics for the hardware prototype described in Chapter 5.

of the transmission it may start sampling late. The second part of the OFDM block transmission is an un-windowed extension of the guard time that allows for delays in timing the start of the sampling. Longer allowances for timing errors means that the receiver need not be as accurate in detecting the start of the block. Shorter extensions give higher system throughput.

Since the FFT is periodic, any N contiguous samples may be used to demodulate the data. The effect of a delay at the start of the sampling is a phase shift at each subchannel proportional to the frequency and the delay. The phase shifts can be estimated and subtracted (see Section 7.4.2).

Transmitting blocks within “slots” reduces the timing problem since the receiver can start sampling at the start of every slot and can ignore the block of samples if no signal is detected during the slot.

The program used to make the experimental measurements (Chapter 5) allows a variable amount of extension before and after the OFDM block samples. This extension can be up to 32k samples (4 seconds). These long extensions allowed the average signal levels to be measured on meters. In the experimental BER measurements guard times of 2000 samples were used to eliminate any possible effect on the performance. The guard time samples were not windowed.

7.4.2 Phase Synchronization

A delay between transmitter and receiver will result in a phase shift at each subchannel proportional to the delay and the subchannel’s frequency. This delay must be estimated and used to correct the phase of each subchannel. The delay can be estimated from the phase errors of the demodulated data values since the phase errors should all increase in proportion to the subchannel frequency.

In the experimental work, the delay between the D/A and A/D sampling instants was exactly the same for each block. Correction for this fixed delay was included as part of

- *phase synchronization* to estimate the delay between the transmitter and receiver sampling clocks,
- and *equalization* to compensate for the frequency-dependent linear distortion (phase and amplitude changes) of the receiver and transmitter circuits.

7.4.1 Sampling Timing

Figure 7.1 shows the three parts of the OFDM block transmission.

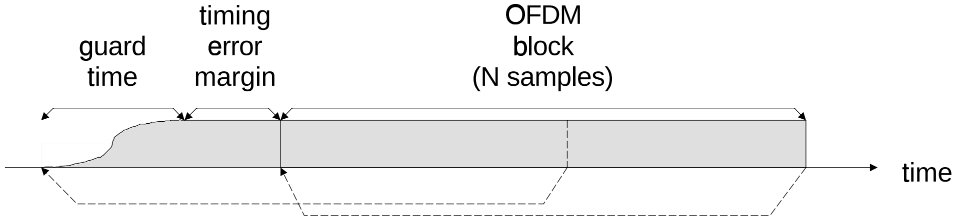

Figure 7.1: OFDM block transmission timing.

The first part, the guard time, allows transients to settle before sampling begins. Since the signal is periodic with a period of N samples, the samples in the guard time are copied from the trailing portion of the block. Shaping of the transmitted signal with a window function (e.g. a Hamming window) during the guard time allows transients to settle more quickly and can reduce the required guard time [1].

Although the guard time reduces the system throughput, the effect of guard time on system throughput is small for the expected block lengths. For example, the Gandalf modem uses a 4 ms guard time for the telephone channel of approximately 3 kHz bandwidth [39]. Since the duration of the OFDM block will typically be more than 100 milliseconds, only a few percent of the channel time will be lost to the guard time.

The receiver must detect the start of block and then take N samples immediately after the guard time. However, if the receiver cannot accurately determine the start only one message and it may be inefficient to make the OFDM block size much larger than the average message size.

However, typical packet sizes require reasonably long OFDM block durations. For example, a popular mobile radio data communication system uses packets of between 294 and 3388 bits with a typical message of 735 bits [68]. A 735-bit packet would require an OFDM block length of over 1470 samples for the experimental 4000 bps system described in Chapter 5. An OFDM system could use a number of different block sizes with the block size being determined from the signal duration as measured at the receiver.

Although FFT computations are most efficient for block sizes of 2^n, fast algorithms are available for other block sizes. A DFT can be computed for any block size but it may not be practical for long block sizes because it requires N multiplication and addition operations per sample.

7.3 Reducing Dependence on Vehicle Speed

The Doppler rate and the performance of OFDM decrease as the vehicle slows down. This is also a problem for any time-diversity scheme whose performance depends on the fading rate. One proposal is to artificially increase the fading rate by continuously switching between several antennas (spaced sufficiently far apart) whenever the vehicle speed falls below a certain speed [71]. This can be considered a simple form of switched diversity in which the antennas are switched at random. At UHF frequencies it is practical to mount several antennas around a cylinder with a diameter of a half-wavelength [71].

7.4 Timing, Synchronization and Equalization

Data recovery from the baseband OFDM/FM signal requires three types of synchronization:

- *sampling timing* to select a block of N samples to demodulate,

Chapter 7

System Design

7.1 Introduction

The purpose of this research was to examine the performance of OFDM over mobile radio FM channels rather than to design an OFDM/FM system. However, this chapter briefly examines some possible implementation problems and how they might be solved. Many implementation decisions will involve cost/performance trade-offs that will depend on the application.

The first section deals with the choice of block size. This will be affected by the traffic statistics and system delay specifications. Other sections deal with sampling timing, phase synchronization, and equalization. As in serial modulation techniques, differential coding can be used to simplify synchronization requirements. The final sections deal with hardware requirements. These are comparable to those of other high-speed baseband modems.

7.2 Block Size

Longer OFDM blocks give better performance because more fades are averaged. However, long OFDM blocks introduce correspondingly long delays and may be inefficient if there is little information to be transmitted per block. The block size (or sizes) must therefore be tailored to the traffic statistics and transmission delay requirements.

Continuous broadcast (e.g. base-to-mobile) systems can combine messages for several receivers into one OFDM block. In this case the block size can be made as large as delay specifications will allow. In the mobile-to-base direction the OFDM block typically has

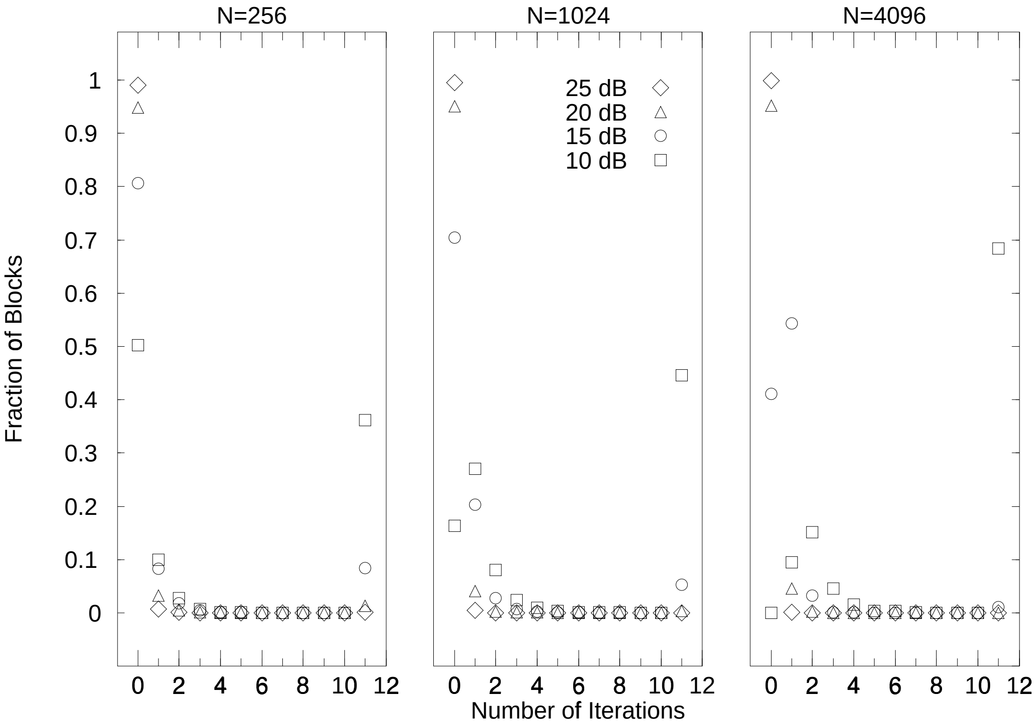

Figure 6.14: Distribution of the number of DFC iterations. Based on simulations of over 2.9 million samples for each block size.

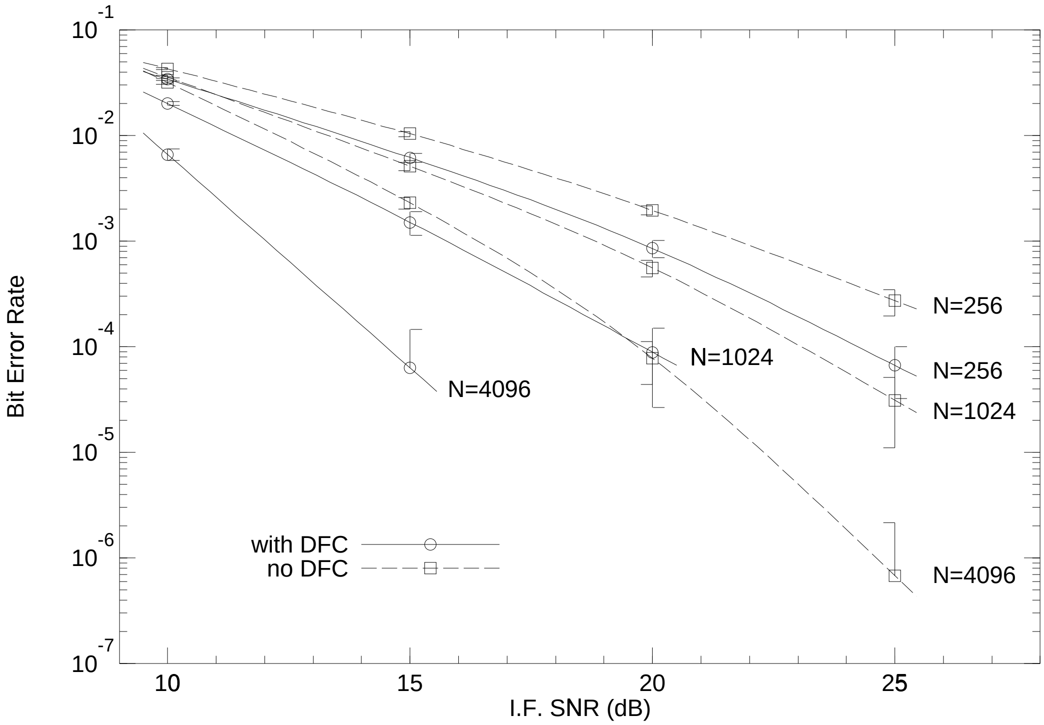

Figure 6.13: BER performance with DFC.

show that there is little to be gained by allowing more than about five iterations. Examination of the number of errors remaining after each iteration showed that the number of errors corrected per iteration decreases very quickly.

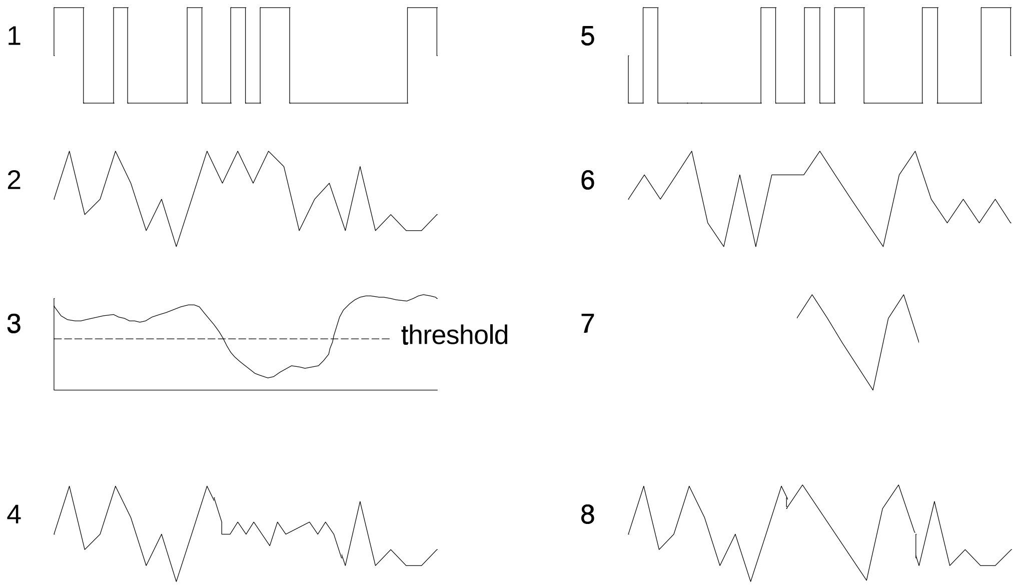

Figure 6.12: Sample signals during DFC processing.

received signal level. Also, DFC does not involve increasing the receiver gain (as does AGC) and so avoids the problems associated with amplifying noise.

6.6.2 Simulation Results

Figure 6.13 shows simulation BER results with and without DFC. In these simulations a maximum of eleven iterations were allowed and the DFC threshold was 4 dB SNR. These results show that DFC can significantly improve the performance of OFDM over a fading channel. At a BER of 10^{-2} the improvement due to using this method is 2 to 3 dB. At a BER of 10^{-3}, the improvement is between 3 and 5 dB. The performance improvement is greater for longer blocks. These results also show that error propagation due to DFC is not a significant effect. Complete results are not given for the longer blocks because the error rates were too small to be measured.

The number of iterations required for the method to converge to a solution was also measured. Figure 6.14 shows the distribution of the number of iterations. These results

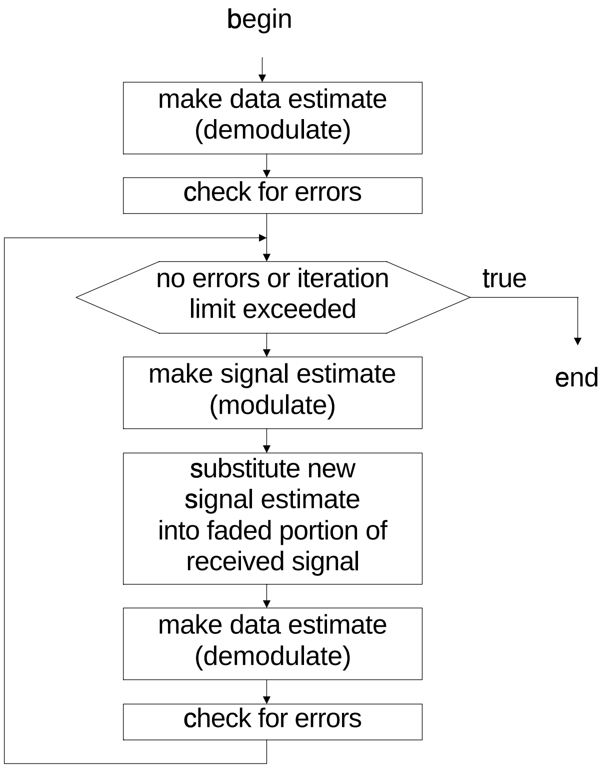

Figure 6.11: Flowchart for DFC processing.

Measuring the IF SNR

DFC, squelch, and AGC require that the received signal level or the IF SNR be known. There are several ways of measuring the signal level or measuring the IF SNR. Typical squelch circuits measure the IF SNR indirectly by measuring the decrease in baseband noise power above audio frequencies as the IF SNR increases (see Chapter 2). Cellular radio systems use the envelope of received signal to measure the received signal strength [70]. Systems that use SSB modulation [1,24] use a pilot carrier to estimate the signal magnitude and phase.

A measurement of the signal level is not required for DFC, simply a “fade/no-fade” indication. Therefore DFC should be insensitive to small errors in the estimate of the