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NTSC IN-BAND DATA BROADCASTING USING OFDM

by

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Thesis Abstract

The Teletext standard sends data dur ing the VBI (Vertical Blanking Interval) portion of an analogue NTSC (National Television System Committee) video signal and has a bit rate in the order of 150 kbps. More recently, digital data broadcasting systems using a modulation scheme from the PSK family have been implemented. In these systems, the digital carrier is strategicall placed within the active portion of the video signal in order to minimise the interference into the video signal. These techniques offer bit rates up to 525 kbps.

This thesis introduces a new technique for transmitting data using the Orthogonal Frequenc Division Multiplexing (OFDM) modulation scheme, within the NTSC television signal. This technique allows a greater data throughput, while still maintaining the picture q uality at an acceptable level.

With OFDM, the spectrum can be shaped according to a specific set of rules, for example, the subcarriers that overlap with the NTSC spectral components can be set to zero. The data signal is inserted in the vestigial sideband of the video signal. The advantages of this implementation are that the shape of the data spectrum minimises the degradation of the picture quality and increases the noise margin of the data signal.

Two approaches are taken to evaluate the performance of this system. In the first one, computer simulations are used to determine the available bit rate by varying the number of carriers. Bit error rate measurements are also done to evaluate the performance of the system when the data signal is combined wit h the NTSC television signal. In the second approach, the perceptual impact is determined, using accepted subjective assessment methodology, when varying levels of OFDM carriers are injected into the NTSC signal.

The results show that the proposed system has the potential to offer higher data rate throughput than existing system, with negligible impact on the NTSC picture quality.

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List of Acronyms

3G	3rd generation
ADC	Analogue to Digital Converter
ADS	Asymmetric Digital Subscriber Loop
AM	Amplitude Modulation
ANS	American National Standard Institute
ATSC	Advanced Television System Committee
ASCII	American Standard Code for Information Interchange
AWG	Arbitrary Waveform Generator
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BPF	Band Pass Filter
bps	bits per second
BPSK	Binary Quadrature Phase Shift Keying
b/s/Hz	bits per second per Hertz
C/N	Carrier to Noise ratio
CRT	Cathode Ray Tube
CSI	Channel State Information
COFDM	Coded Orthogonal Frequency Division Multiplexing
CRC	Communication Research Centre
CW	Carrier Wave
D/U	Desired to Undesired ratio
DAB	Digital Audio Broadcasting
DAC	Digital to Analogue Converter
dB	Decibel
dBm	logarithmic power ratio with respect to 1 mW
dc	Direct Current
DFE	Decision Feedback Equaliser

DFT	Discrete Fourier Transform
DMT	Discrete Multi-Tone
DQPSK	Differential Quadrature Phase Shift Keying
DSSS	Direct Sequence Spread Spectrum
DTTB	Digital Television Terrestrial Broadcasting
DTV	Digital Television
DVB-T	Digital Video Broadcasting – Terrestrial
DVD	Digital Versatile Disc
EBU	European Broadcasting Union
EIA	Electronics Industries Association
ETS	European Telecommunications Standards Institute
FCC	Federal Communication Commission
FDM	Frequency Division Multiplexing
FEC	Forward Error Correction
FFT	Fast Fourier Transform
FHSS	Frequency Hopping Spread Spectrum
FM	Frequency Modulation
GCR	Ghost Cancelling Reference
GHz	Gigahertz
HBI	Horizontal Blanking Interval
HDTV	High Definition Television
Hz	Hertz
IC	Industry Canada
ICI	Inter-carrier Interference
IDFT	Inverse Discrete Fourier Transform
IEEE	Institute of Electrical and Electronics Engineers
IF	Intermediate Frequency
IFFT	Inverse Fast Fourier Transform
IRE	Institute of Radio Engineers
ISI	Inter Symbol Interference

ITU	International Telecommunication Union
ITU-R	International Telecommunication Union – Radio Telecommunications
JND	Just Noticeable Difference
kbps	kilobits per second
kHz	kilohertz
km	kilometre
LAN	Local Area Network
LPF	Low Pass Filter
Mbauds/s	Mega baud per second
Mbps	Mega bits per second
MCM	Multicarrier Modulation
MHz	Megahertz
ms	millisecond
μs	microsecond
NAB	National Association of Broadcasters
NABTS	North American Basic Teletext Specifications
NDBC	National Data Broadcasting Committee
NTSC	National Television System Committee
OFDM	Orthogonal Frequency Division Multiplexing
PAL	Phase Alternation by Line
PLUGE	Picture Lineup Generating Equipment
PSK	Phase Shift Keying
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RBW	Resolution Bandwidth
RF	Radio Frequency
SAP	Second Audio Program
SCM	Single Carrier Modulation
SFN	Single Frequency Network
SMPTE	Society of Motion Picture and Television Engineers

SNR	Signal to Noise Ratio
TOV	Threshold of Visibilit
TV	Television
UHF	Ultra High Frequency
VBI	Vertical Blanking Interval
VBW	Video Bandwidth
VHF	Very High Frequency
VITS	Vertical Interval Test Signal
VSB	Vestigial Sideband
XDS	Extended Services

List of Symbols

2k	2048
8k	8192
a_k	real component of complex symbol
A	amplitude of modulator
A'	amplitude of demodulator
b_k	imaginary component of complex symbol
d_n	complex symbol at time index n
D	desired signal
f	frequency variable
f_c	carrier frequenc
f_s	sampling frequency
f_v	width of vestigial sideband
$H(f)$	frequency response of VSB filter
I	in-phase component
k	kilo or 1024
k	symbol index
m	order of high level modulation scheme
m_k	data symbol
$m(t)$	baseband signal
$M(f)$	frequency response of baseband signal
n	discrete frequency index
N	length of Fourier transform
N_c	number of data carriers
Q	quadrature component
$r(t)$	downconverted signal
$R(f)$	frequency response of downconverted signal
$s(t)$	VSB modulated signal
$S(f)$	frequency response of VSB signal

t time variable

U undesired signal

$V_o(t)$ low pass filtered signal

$V_o(f)$ frequency response of low pass filtered signal

W bandwidth

$x(n)$ OFDM symbol

$x_k(n)$ OFDM subcarrier

$X_k(f)$ spectrum of OFDM subcarrier

$x_t(t)$ OFDM symbol at time index t

y(t) output of multicarrier modulator

ω carrier frequenc

Δf carrier spacing

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1 Introduction

1.1 Background

With the evolution of digital technologies and the demand for increased bandwidth for data services, considerable research efforts have been done to widen the information superhighway to the end -users. Bi-directional communication is currently available from several different providers such as telephone companies, cable television network operators and wireless phone service providers. As for one -way communications, pagers are the most prevalent choice of service. With the advent of digital radio and digital television, these systems will be poised to offer additional bandwidth to end-users. But until these systems are fully implemented, research has been done to improve the data delivery techniques of existing distribution systems. One such system is the analogue television transmission system, because it is already an established distribution network and is capable of reaching millions of users simultaneously. Specifically, this study investigates a technique using a multicarrier modulation scheme to insert the data into the NTSC (National Television System Committee) standard, which is currently used in the terrestrial and cable distribution of the television signal.

Even though NTSC does not use the spectrum efficiently by today's standard, for a system that was designed in the 1940's and still working today, it is nevertheless a great achievement. With the new digital television system almost upon us, it would seem that the demise of the analogu e television system is close. But given the current rate at which digital television is being implemented, the transition period from analogue to fully digital systems will take longer than initially expected. This means that analogue television will still be in operation for some time to come. If technology can bring any improvements to the current standard, it will have advantages on two fronts. The first will be to broadcasters, who will get additional revenues from their analogue transmitters and the second will be to television viewers who will have more access to digital services.

A recent attempt to improve the NTSC standard came in 1995, when the Federal Communication Commission (FCC) in the United States announced that it was seeking recommenda tions on including digital ancillary data to the NTSC television system [FFC95]. The main requirement was that no perceptible degradation to the video quality could be observed. On June 24 1996, the FCC approved the insertion of digital data, by broadcas ters, within the video portion of the NTSC television signal [FCC96]. In the fall of 1996, Industry Canada authorised the same systems for Canadian television broadcasters [IC96][IC97].

The Television Broadcast Technologies Research group at the Communications Research Centre (CRC) was involved with the National Data Broadcasting Committee (NDBC) in the evaluation of these recently approved systems. The CRC has also been involved in the development of Digital Television Terrestrial Broadcasting (DTTB) for the Canadian industry. Over the last few years, CRC has gained much expertise in this area, including Coded Orthogonal Frequenc Division Multiplexing (COFDM), the modulation scheme chosen for the European standard, but also of interest to North American broadcasters. The work presented in this thesis is based on the application of multicarrier modulation for the development of a new data broadcasting system

1.2 Thesis Objectives

The main purpose of this thesis is to encode a data signal using a multicarrier modulation (MCM) scheme, to combine it within the vestigial sideband of the NTSC video signal, and to study its performance and impact on the quality of the received video signal. The goal is to determine if this approach offers clear advantages compared to single carrier modulation techniques currentl in use.

The first objective is to design a multicarrier modulation simulation and to study the bit error rate (BER) performance when the multicarrier data signal is combined with a host NTSC video signal. The second objective is to subjectively assess the perceived quality of the video signal when the data is combined with the video signal.

1.3 Thesis Contribution

This thesis introduces a new method for inserting a data bit stream inside the NTSC video signal. The modulation scheme is from the multicarrier modulation family and unlike the standard single carrier schemes, it allows the spectrum to be easily shaped to meet the requirements of the design.

It is demonstrated how multicarrier modulation can be used to encode the data in a new way to be combined with NTSC. It also offers broadcasters another option to use their current transmission network to reach viewers with digital data and to generate new sources of revenues.

1.4 Thesis Organisation

In chapter 2, a literature review and an overview of the current data broadcasting systems are presented. The review discusses the limitations of the current systems as well on-going developments in the area of data broadcasting. The third chapter reviews multicarrier modulation methods, as well as new applications and on-going improvements to the technology. Chapter 4 presents a new method for in-band data broadcasting that uses multicarrier modulation. The performance of the data insertion method presented in chapter 4 is evaluated by computer simulation in chapter 5. Chapter 6 presents the subjective evaluation of the video quality when the data broadcasting signal is inserted in the video signal. The last chapter of the thesis, chapter 7, summarises the main conclusions of the work and proposes suggestions for future work.

2 Review of NTSC and Current Data Broadcasting Systems

2.1 Overview

This chapter examines some background information on the current television technologies in order to understand better the goals of this research project. It is divided into three sections. Section 2.2 provides an overview on how the NTSC television signal is generated and transmitted. Section 2.3 examines the existing data broadcasting and their applications. Finally, section 2.4 summarises this chapter.

2.2 NTSC Television System

In North America, the analogue television standard is called the National Television System Committee (NTSC) television standard. The NTSC standard and the frequency allocation of the channels is uniform across North America. Variations of the NTSC standard are used in parts of South America, Japan and Taiwan. In Canada, the standard is defined as NTSC/M [IC97a].

The Federal Communication Commission (FCC) first approved the NTSC standard in 1941[GOR75]. In Canada, television broadcasting first started in Montreal in 1952. The original signal delivered a black and white picture and a single audio channel to television viewers. The standard has not changed much since then, unlike the quality of the signal delivered to viewers, which has improved. Over the last 60 years, colour picture and stereo sounds have been added to the standard. The ingenuity involved in implementing these changes has allowed the system to remain backward compatible with existing television sets. The latest change to the standard has been the option to insert a data bit stream in the analogue signal to deliver data to the viewers.

The visual carrier, the colour subcarrier and the aural subcarrier, are the three distinct carriers that make up the analogue television signal. Embedded in the video signal are other control signals used to synchronise and display the image on the television screen. The following section describes the details of the NTSC video signal.

2.2.1 Structure of the Video Signal

The picture on a television screen is generated by an electron gun, which illuminates a layer of phosphorous on the television tube. To form an image, the gun scans the screen from left to right, top to bottom. The video signal has two important functions: it synchronises the electron gun and carries the video signal. The motion displayed on a television screen is perceived due to the display of approximately 30 static frames per second. The human brain merges the images to give the effect of motion, much like frames on a film reel. A frame of video is made up of 525 lines (see Fig 2-2) of video signal. Each frame is made up of two interlaced fields: the first field displays the odd numbered lines (1,3,5...525) and the second fi eld displays the even numbered lines (2,4,6...524). Figure 2-1 shows how two interlaced fields are combined to produce a complete frame.

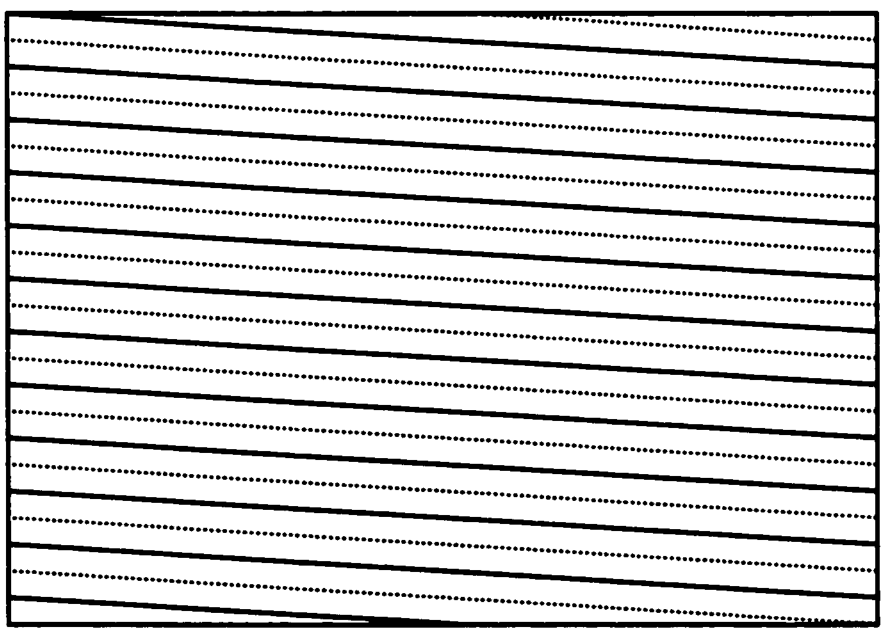

Figure 2-1: Interlaced video frame.

The first 21 lines of each frame, called the vertical blanking interval (VBI), are used for synchronising the electron gun inside the television and cannot be used to transmit a video signal. With the current technology, television sets use the first nine lines of the VBI to synchronise and return the electron gun back to the top left corner of the screen. Earlier television sets also needed the remaining 12 lines of the VBI for synchronising the electron gun, but toda broadcasters can use these lines for other services, such as close captioning of television programs and to deliver data to viewers. The remaining 504 lines are used for the transmission of the video signal, although only 350 to 380 of the 504 lines are actually visible on consumer television screens.

Each line of the video signal has an active portion, which transmits the content of the image, and a non-active portion called the Horizontal Blanking Interval (HBI). Figure 2-2 shows one line of the video signal, with the HBI (10.9 μs duration) composed of the synchronisation pulse and the colour burst. The synchronisation pulse is used to return the electron gun to the left of the screen and the colour burst is used as a reference in decoding the colour of line currently being transmitted.

During the active portion of the line (52.6 μs duration), the visual content of the video is displayed on the screen. The amplitude of the active video, where white is 100 IRE (Institute of Radio Engineers) and black is 10 IRE, represents the luminance of the video signal.

The colour information is encoded by a modulated signal (chrominance), which is superimposed on the luminance signal. The colour of the content is determined by the phase difference between the colour burst and the chrominance signal.

The bandwidth of the video signal is determined by the resolution of the image. For the NTSC standard, the bandwidth is approximately 4.2 MHz, which along with the aural carrier, fits into a 6 MHz transmission channel.

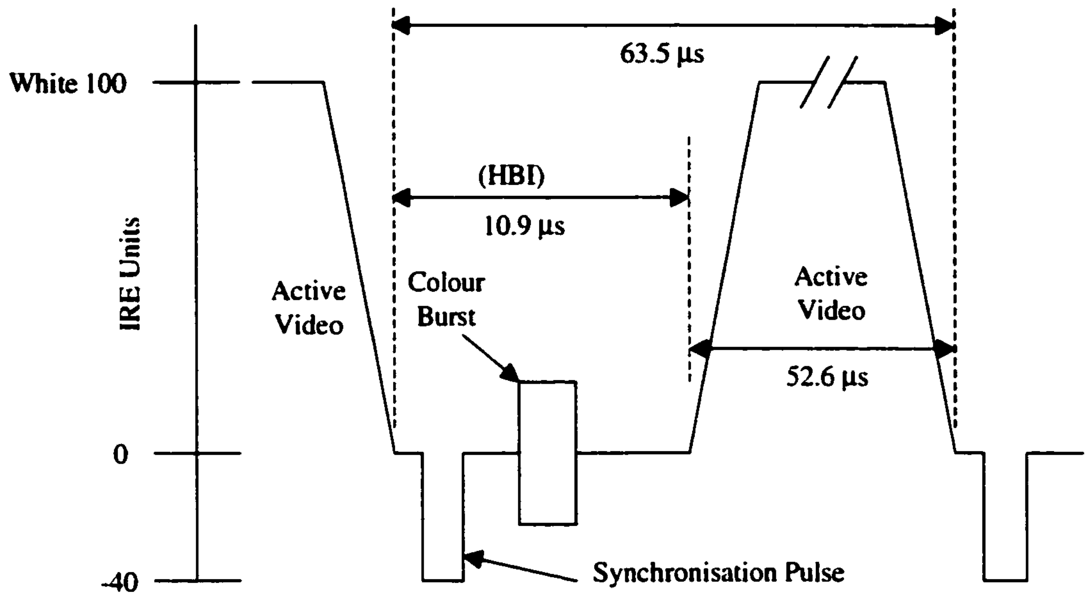

Figure 2-2: Single Line of NTSC Video Signal.

2.2.2 RF Television Signal

In order to transmit the television signal, it must first be modulated onto a carrier. Actually, the television signal is made up of three distinct components: a video carrier, a colour subcarrier and an audio subcarrier. The main carrier is the video carrier and it is obtained by vestigial sideband amplitude modulation of the video signal. The two subcarriers within the channel are the colour burst, 3.58 MHz above the video carrier, and the audio FM subcarrier, 4.5 MHz above the video carrier. Figure 2-3 shows the spectrum of a 6 MHz television signal along with the three carriers. In the video signal, most of the power is located in at the frequency of the video carrier to assist in the synchronisation of the signal during off-air reception.

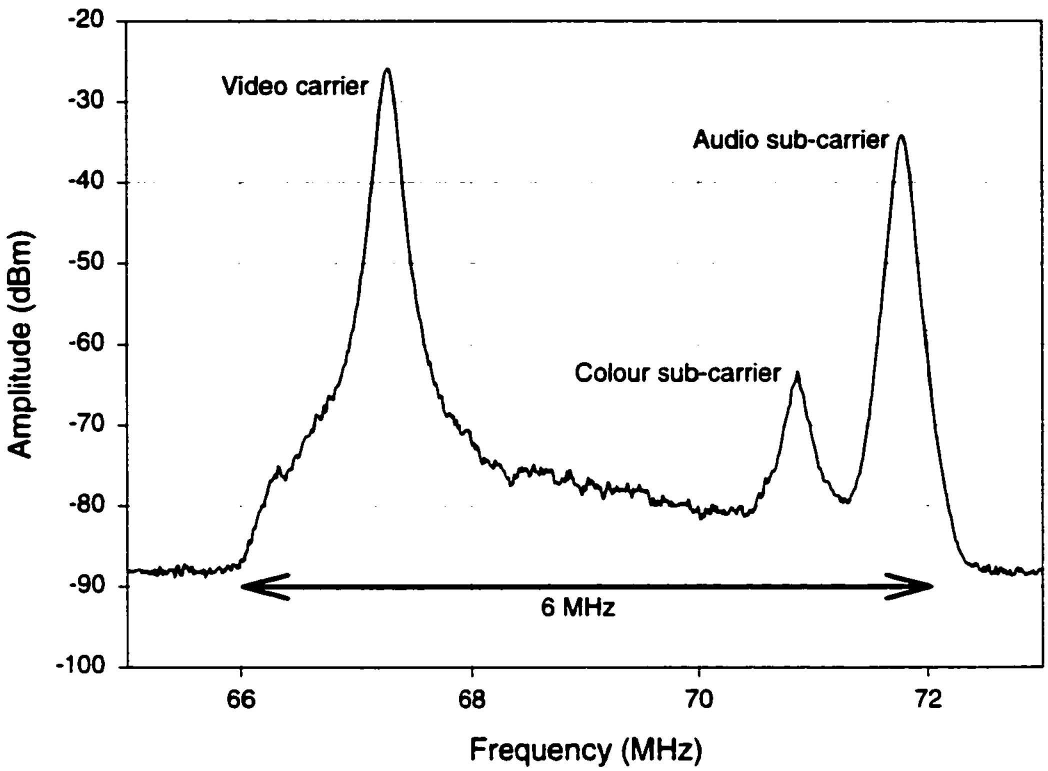

Figure 2-3: Spectrum of 6 MHz NTSC channel 4 (66-72 MHz).

2.2.3 Vestigial Sideband Modulation

Vestigial sideband (VSB) modulation is the modulation scheme used to modulate the video signal onto a radio frequency (RF) carrier. This section describes why the modulation scheme was chosen and how it is implemented.

The decision to use VSB modulation for the transmission of the video s ignal was based on two important characteristics of the signal, namely its large bandwidth and its significant low - frequency components. The VSB signal is obtained by filtering a double -sideband amplitude modulated signal by a filter with a frequency resp onse shown in Fig 2-6. The frequency response of the filter allows the upper sideband to be completely transmitted while only letting a vestige of the lower sideband be transmitted.

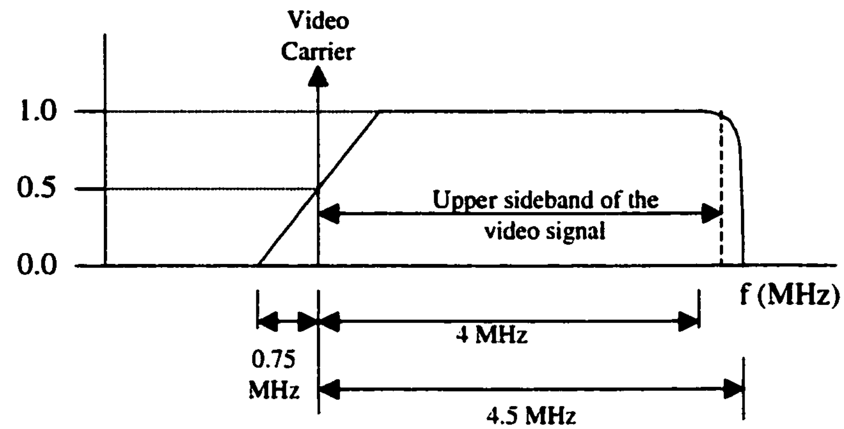

Figure 2-4: Spectrum of video VSB filter.

To ensure the proper reception of the modulated signal, special characteristics must be imposed on the VSB filter. The characteristics of the VSB filter are obtained by observing how a double-sideband modulated signal filtered by a filter, $H(f)$, can be reconstructed at the receiver.

A baseband signal, $m(t)$, with a bandwidth of W is to be transmitted over a channel using VSB modulation. The required transmission bandwidth is equal to $W + f_v$, where f_v is the width the vestigial sideband. If the original source signal, $m(t)$, is a double sideband suppressed carrier wave, with a spectrum of $M(f)$ (see Figure 2-5), the spectrum of the upconverted signal is defined by $S(f)$.

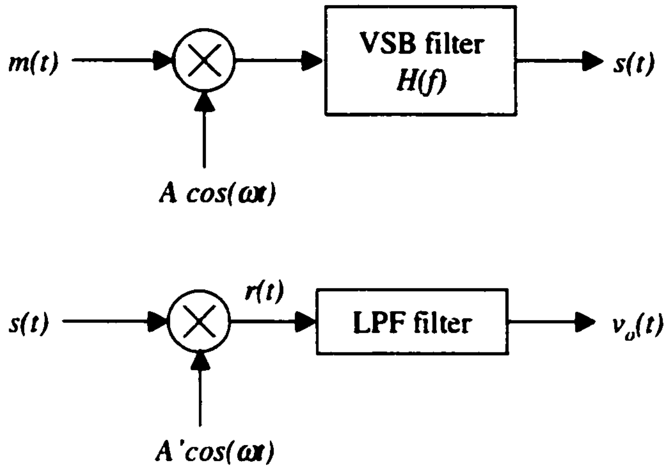

Figure 2-5: VSB modulation/demodulation.

$$S(f) = \frac{A}{2} \cdot H(f) \cdot [M(f - f_c) + M(f + f_c)] \tag{2.1}$$

The signal amplitude of the local oscillators are A and A' for the modulator and the demodulator respectively. Using coherent demodulation, the demodulated signal is represented b *r(t)*:

$$R(f) = \frac{A'}{2} \cdot [S(f - f_c) + S(f + f_c)] \tag{2.2}$$

which equals

$$R(f) = \frac{AA'}{4} \cdot \{H(f - f_c)[M(f - 2f_c) + M(f)] + H(f + f_c)[M(f + 2f_c) + M(f)]\} \tag{2.3}$$

$$R(f) = \frac{AA'}{4} \cdot \{M(f)[H(f - f_c) + H(f + f_c)] + H(f - f_c)M(f - 2f_c) + H(f + f_c)M(f + 2f_c)\} \tag{2.4}$$

After the low pass filtering of the received signal *r(t)*, the receiver's output signal $v_o(t)$ is obtained:

$$V_o(f) = \frac{AA'}{4} \cdot M(f) \cdot [H(f - f_c) + H(f + f_c)] \tag{2.5}$$

In order for the received signal to be a reliable replicate of the original signal, the term [$H(f-f_c)+H(f+f_c)$] must be constant in the frequency interval $-W<f<W$. This requirement is obtained by using a filter with the frequency response shown in Figure 2-6.

The amplitude is normalised so that the magnitude is one half at the carrier frequenc f_c and the magnitude exhibits odd symmetry around the carrier frequency. The sum of the points equidistant from the carrier frequency is equal to unity within the interval $f_c-f_v<f<f_c+f_v$.

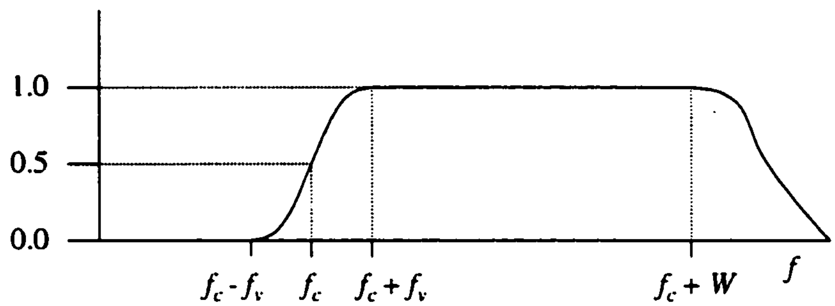

Figure 2-6: Spectrum of the VSB filter.

Receivers in television sets use this demodulation method to demodulate the video signal.

2.2.4 Channel Characteristics

The spectrum allocated for television transmission in North America is located in the VHF (55 to 88 MHz and 174 to 220 MHz) and UHF (470 to 806 MHz) bands. These are not ideal transmission bands for television signals since there are many sources of interference and impairments sharing the same band. Since the start of television transmission, the spectrum has become increasingly congested. For instance, FM radio, numeric pagers, cordless and cellular phones are all transmitting in the same band. There is also the addition of man -made noise, which has greatly enhanced the noise floor that existed 50 years ago.

Along with background noise, the transmitted television signal must overcome other impairments, such as multipaths. One type of multipath impairment is a static multipath, where a television signal is impaired by a delayed version of the same television signal. This occurs when a large building or a mountain reflects the transmitted signal. The result is an echo or a ghost image displayed on the screen.

Another type of multipath phenomenon is the dynamic multipath effect, where the delay and the phase of the echo vary over time. This usually happens when the top of the transmission or receiving antenna sways in the wind, or when there are reflections from a moving automobile or a passing plane.

Smaller scale types of multipath conditions are called micro -reflections and occur on cable television networks when the impedance of a connection is not properly matched.

Depending on the environment, a multipath combined with the noise of the environment and the loss due to the path can severely affect the quality of the signal. To improve the robustness against noise and improve the "quality" of a weak signal, the only alternative is to increase the transmission power. However, in most cases, this is not permitted due to interference with other services in adjacent channels.

A recent modification to the NTSC standard to help mitigate the effect of multipaths has been the addition of the ghost cancelling reference (GCR) signal [CAR92]. This technology allows the known reference signal to be inserted in line 19 of the VBI. At the receiver, the impaired signal on line 19 is compared to the known signal. The difference is used to compute the tap values of a digital filter with a frequency response that estimate the inverse response of the transmission channel. The system is capable of removing echoes in the range of -7.5μs to 42.5 μs.

2.3 Current Data Broadcasting Techniques

Television broadcasters are currently able to send digita l data to viewers using their existing infrastructure. The available data rate is slow compared to today's standards, but the systems have been in operation for some time now and have served their purpose well. This section describes the systems currently in use and the applications they support.

There are currently three types of methods capable of transmitting data within the NTSC television signal. The most popular and mature method uses the vertical blanking interval (VBI to transmit data during the time interval where no video information is transmitted. The second method, called "overscan", inserts a signal in the horizontal blanking interval, that is the interval between the end of the colour burst and the start of the video signal and between t he end of the video signal and the start of the synchronization pulse. This alternative uses the same strategy as VBI methods, to send data while no video information is being sent, except the data throughput is not as high as with the VBI methods. The t hird method called "sub-video" or "in-band", inserts a digital carrier within the spectrum of the active video.

2.3.1 Closed Captioning

An early application of data transmission was the close captioning of television programs for the hearing impaired. Since 1 978, the FCC rules have set aside line 21 on field 1, for the transmission of program-related captions. The total data throughput is 16 bits/frame, or 480 bps, which corresponds to 60 characters per seconds. Even though this rate is fast enough for close captioning, it is not sufficient for newer data services that include graphics and text, such as web pages. To increase the visibility of this service to the viewing public, all television sets manufactured in North America after July 1993, with a screen size larger than 13 inches, must have a closed captioning decoder built-in.

2.3.2 Extended Data Services

In 1993, the FCC authorised [Jur97] the use of line 21 on field 2 for the transmission of captioning, text and extended data, for a service called Extended Data Service (XDS). This service allows the broadcasters to send viewers information about the station and the programming, such as the call sign, network affiliation, program title, length of program, type of show, current time, time left in current program and other information. With XDS, the extended data and the close captioning data are interleaved on line 21 of each field in the VBI.

2.3.3 Teletext

The next step in the evolution of the data rates was to increase the number of lines in the VBI available for sending data. These systems are known as teletext systems. Different countries developed similar teletext systems to meet the needs of different television standards around the world. In North America, the technology developed is called the North American Basic Teletext Specification (ANS -EIA standard 516) and has been around since the 1980's.

The standard defines a method capable of transmitting 288 bits per television field, which represents an instantaneous bit rate of 5.7272 Mbps. Using 11 lines, 60 fields per second and discarding the start and stop bits, the useful payload is 185 kbps. Taking into account the redundancy of the forward error correction method, the actual payload is approximately 150 kbps.

Broadcasters use this service to transmit information such as stock market updates, sports scores, weather update and news services to television viewers equipped with a special decoder. The service was launch in some markets, but widespread acceptance did not materialised.

2.3.4 In-band Technologies

In 1993, the FCC requested applications for high -speed data broadcasting schemes to meet the increasing demand for bandwidth. To study this proposal, the National Association of Broadcasters (NAB) and the Electronics Industries Association (E A) formed the National Data Broadcasting Committee (NDBC). The goal of the NDBC was to standardise a high -speed data broadcasting system for NTSC television capable of transmitting data at rates higher than conventional VBI methods. Several systems were investigated, but only two systems took part in the evaluation process, namely the "D-Channel" system developed by Digideck and the "TVT - 1/4" system from WavePhore.

The system from Digideck uses a low-level DQPSK carrier to transmit the data [Jur97]. Th e carrier is located in the vestigial sideband, roughly 1.0 MHz below the video carrier and has a bandwidth of 450 kHz. Its power is limited to 30 dB below the video carrier at peak of synch. Another characteristic of this system is that out of band emissions are limited to 60 dB below the video carrier. Depending on the configuration, different data rates are possible. The basic data rate of 256 kbps does not requires the video carrier to be filtered at the insertion point, while higher data rates, in t he order of 525 kbps, require the video carrier to be filtered and a higher order modulation schemes. This has the effect of reducing the coverage of the data signal, since it will require a higher signal-to-noise margin.

The WavePhore system [Jur97] transmits the data on a 300 kHz BPSK carrier located between the colour subcarrier and the audio subcarrier. The insertion of the data carrier in the active video bandwidth has the effect of degrading the picture quality of the signal. For this purpose, the video signal is low pass filtered up to 3.9 MHz. The PSK modulator is synchronised by a clock set to 4.197 MHz. The data is then filtered to remove the components above 4.197 MHz, leaving a single sideband data signal. At the receiver, the video signal is band pass filtered to leave the components between 3.9 to 4.2 MHz. A BPSK demodulator then decodes the data to display it on the screen or store it to a memory device for further processing.

Both of theses systems inherently cause some degradation to the picture quality by inserting a data carrier in the active portion of the video signal. To ensure that the impact of the data carriers would not be visible to non-expert viewers, both systems were studied using subjective evaluation methodologies [CRC95].

2.3.5 Other Systems

European and Asian countries are also developing their own data broadcasting systems (see [Soo99], [Doo99], [Wei99]). Each system has their own characteristics: insertion method, data rate and application for the service. Most of the television applications resemble the data carrier insertion scheme presented by Digideck and WavePhore. Other system inserts FM subcarriers in the sideband of the audio carrier.

2.3.6 ATSC Data Broadcasting System

This section discusses how the Advanced Tele vision System Committee (ATSC) HDTV standard will implement data broadcasting.

It is expected that digital television terrestrial transmission will soon replace analogue transmission. The digital system will be transmitting data at a rate of approximately 20 Mbps to the viewers, and seamlessly combine the digitally encoded video, audio and data. The multiplexed data stream will be able to deliver four to five different standard definition programs or one high definition program.

The ATSC standard (A/53) is designed to transmit 19.39 Mbps over a 6 MHz channel. Currentl there are four different profiles for data broadcasting, three offer a guaranteed data throughput (G1: 384 kbps, G2: 3.84 Mbps, and G3: 19.2 Mbps) and the fourth one (A1) offers the possibilit to transmit data up to a rate of 19.2 Mbps. The A1 profile's throughput will vary depending on the content of the multiplexed stream [Cri99].

In order to have a successful data broadcasting service, the consumer electronic industry has been working out the details regarding the interoperability and implementation of data broadcasting with the ATSC standard. The ATSC T3-S13 working Group on Data Broadcasting Services has defined how the computer-related data (not program-related) will be formatted into the MPEG-2 transport stream. However, at the receiver end, the format of the data received will be based on the work of the ATSC T3-S17 Specialist Group on DTV Application Software Environments. This work will ensure that the data transmitted will be compatible with receivers from different manufacturers.

The implementation of the ATSC standard will force broadcasters to change their role of standard program distributor. Broadcasters will have to manage interactive systems that will handle responses and requests from television viewers. The increased power and flexibility that will be available to transmit data will have an impact on how viewers interact with television sets. The next generation of receivers will be able to process the data and send data back to the broadcaster. This will offer new opportunities to television broadcasters and content producer [Abe99].

2.4 Summary

Industry Canada has recently approved the in-band methods presented in section 2.3.4 for the insertion of digital data within the NTSC television signal [IC97]. These methods offer high data rates in the order of 500 kbps. Until digital television replaces analogue television, new systems will continue to be developed to meet the increasing demand for more bandwidth.

This chapter has examined different systems that are used today and operate within the television transmission infrastructure. Original systems had a data throughput of a few hundreds of bit per second. More recently the data rates were increased to about 500 kbps. The newly defined ATSC digital television standard will soon offer the possibility to send data at rates of up to 19 Mbps. Table 2-1 summarises the data throughput of the systems discussed.

Table 2-1: Summary of Data broadcasting Systems.

System	Data throughput	Launch date
VBI Close Caption	480 bps	1978
VBI- XDS	960 bps	1993
VBI - Teletext	150 kbps	Early 80's
Digideck, "D-Channel"	525 kbps	1993
WavePhore, "TVT 1/4"	300 kbps	1993
ATSC System	Up to 19.2 Mbps	2004

3 Multicarrier Modulation

3.1 Overview

This chapter presents an overview of multicarrier modulation methods. It is divided into four sections. Section 3.2 reviews the theoretical development of multicarrier modulation, and includes a literature review of the early work on multicarrier modulation. Section 3.3 describes different applications that use multicarrier modulation. Section 3.4 reviews some of the on-going research on the improvements to multicarrier modulation implementation. Finally, section 3.5 summarises the findings of this chapter.

3.2 Overview of Multicarrier Modulation

The goal of any communication system is to send a message over a transmission channel. The design of a communication system must take into account the different types of parameters such as the transmission medium and the type of message being transmitted. This overview focuses on digital communication systems, which transmit messages using discrete symbols.

Digital communication systems have both their advantages and disadvantages. Some of the advantages are the possibility for the receiver to extract the transmitted message with an arbitrarily low error rate, depending on the noise or interference on the channel. Another advantage is the option to compress the source message in order to use the transmission channel more efficiently. On the other hand, some of the disadvantages of digital systems are the need for precise timing, in order to synchronise the receiver, and the risk of losing the transmitted message if the quality of the received signal falls below a certain threshold.

Based on their modulation scheme, digital communication systems can be divided into two categories: single carrier modulation or multicarrier modulation systems.

3.2.1 Single Carrier Modulation

In single carrier modulation (SCM) schemes, a single carrier modulates the entire symbol and the carrier takes up the entire bandwidth of the transmission channel. Examples of commonly used single carrier modulation schemes are Phase Shift Keyi ng (PSK), Amplitude Shift Keying (ASK), multilevel Quadrature Amplitude Modulation (*m*-ary QAM) and multilevel Vestigial Sideband (*m*-ary VSB). The popularity of these modulation schemes stems from their eas implementation and early acceptance by the electronic industry. Today these schemes are used in satellite communications, cellular phones and in digital television broadcasting.

A signal modulated by a single carrier modulation scheme is susceptible to flat fading, where the frequency response of the channel varies in time over the signal bandwidth. If a notch in the channel frequency response occurs during the transmission of a synchronisation symbol, the transmission link may be lost. It is also possible for some fades to last longer than the durati on of a symbol. A parameter that measures this channel characteristic is the Doppler spread of the channel. As the value of the Doppler spread of the transmission channel increases, the transmitted signal is subject to spectral broadening, which can lead to intersymbol interference (ISI).

3.2.2 Multicarrier Modulation

In multicarrier modulation (MCM) schemes, the bandwidth of the symbol is divided into several subbands that are each modulated by a separate carrier frequency. This section describes two multicarrier modulation schemes: Frequency Division Multiplexing and Orthogonal Frequenc Division Multiplexing.

3.2.2.1 Frequency Division Multiplexing

An early implementation of MCM called Frequency Division Multiplexing (FDM) is defined b dividing the spectrum of the signal into smaller subbands and modulated each subband by a different carrier frequency. Figure 3-1 shows the spectrum of a FDM signal using three carriers to transmit a signal. This implementation is not very spectrally efficient, since it require s a guard-band between each component and it also requires bandpass filters to separate each bands and individual oscillators at the modulator and demodulator.

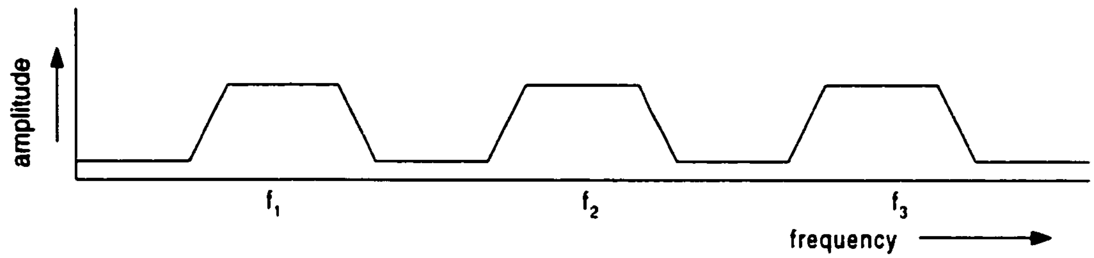

Figure 3-1: FDM Spectrum.

3.2.2.2 Orthogonal Frequency Division Multiplexing

A recent implementation of MCM is called Orthogonal Frequency Division Multiplexing (OFDM). The spectrum of the channel is divided into subchannels, just like FDM, except that the frequencies carrying the data are orthogonal to e ach other. This allows the carriers to be packaged more closely together compared to FDM.

The following example describes how an orthogonal frequency division multiplexing (OFDM) system can be implemented. Let the spectra of three OFDM subcarriers be defined as

$$x_0(n) = \begin{cases} 1 & 0 \le n \le N \\ 0 & \text{otherwise} \end{cases} \quad (3.1)$$

$$x_1(n) = \begin{cases} e^{j2\pi n/N} & 0 \le n \le N \\ 0 & \text{otherwise} \end{cases} \quad (3.2)$$

$$x_2(n) = \begin{cases} e^{j4\pi n/N} & 0 \le n \le N \\ 0 & \text{otherwise} \end{cases} \quad (3.3)$$

Where $x_0(n)$ is a N-point rectangular pulse, $x_1(n)$ is a single cycle of a complex sinusoid and $x_2(n)$ is two cycles of a complex sinusoid, each defined over an N point interval. Figure 3-2 shows the spectrum of the combined three signals.

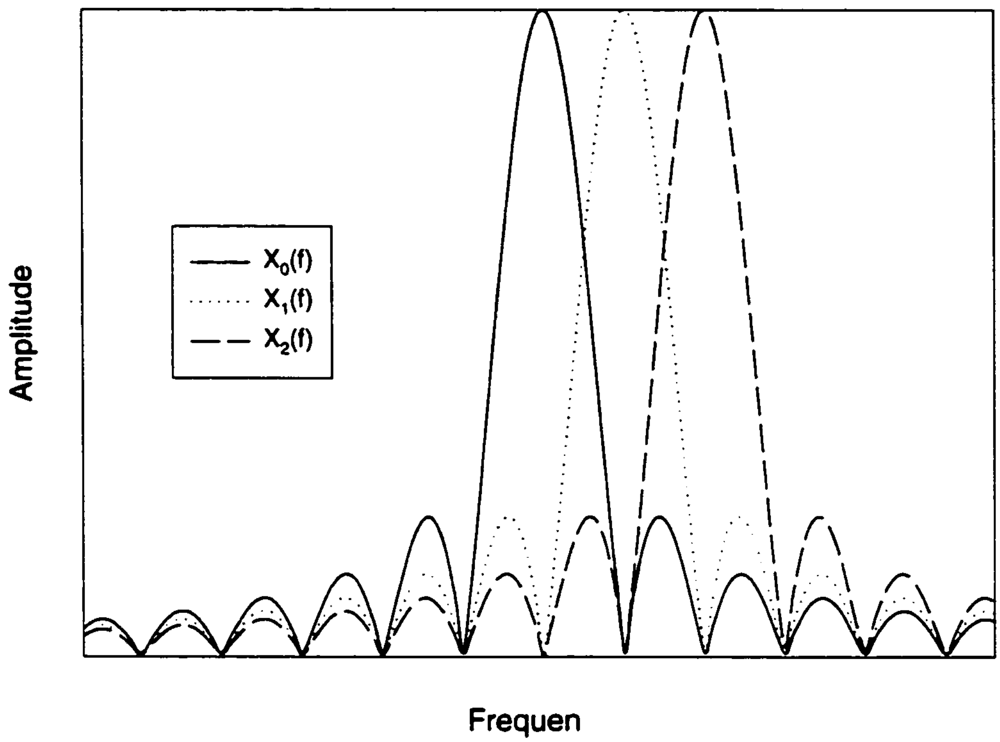

Figure 3-2: OFDM Spectrum (3 carriers).

Two key observations can be made from this figure. First, there is no guar d band between the carriers, which means the spectrum is used much more efficiently. Second, the spectrum of each OFDM carrier has one main lobe and N-1 zeroes. The main lobe of each OFDM carrier overlaps with the zeroes of every the other OFDM carrier. As long as the frequencies remain orthogonal, this condition will be maintained.

By extending this example, it is possible to design a signal made up of N subcarriers, each carrying a different symbol of information. Let the k^{th} subcarrier of such a system, transmitting symbol m_k, be defined as:

$$x_k(n) = \begin{cases} m_k e^{j2\pi kn/N} & 0 \le n \le N \\ 0 & \text{otherwise} \end{cases} \quad (3.4)$$

The sum of N carriers is given b

$$x(n) = \begin{cases} \sum_{k=0}^{N} m_k e^{j2\pi kn/N} & 0 \le n \le N \\ 0 & \text{otherwise} \end{cases} \quad (3.5)$$

Which is equivalent to

$$x(n) = \begin{cases} N\left[\frac{1}{N}\sum_{k=0}^{N} m_k W_N^{-kn}\right] & 0 \le n \le N \\ 0 & \text{otherwise} \end{cases} \quad (3.6)$$

With the substitution $W_n = e^{-j2\pi/N}$.

In equation (3.6), the term within the brackets is the inverse discrete Fourier transform (IDFT). Therefore, computing the IDFT on a sequence of parallel symbols and multiplying the result b N generates an OFDM symbol.

At the receiver, the sequence of parallel symbols is recovered by computing the discrete Fourier transform (DFT) on the OFDM symbol. In practice, the Fourier transforms are implemented with the fast Fourier transform (FFT) algorithms [Arm99] [Wu95a].

The block diagrams of an OFDM modulator and demodulator are shown in Figures 3-3 and 3-4. The suggestion that OFDM is a frequency domain modulation scheme stems from the fact that the data symbols are generated in the frequency domain and transmitted in the time domain. The flow of the symbols also gives an insight to the fact that OFDM is considered a parallel transmission system.

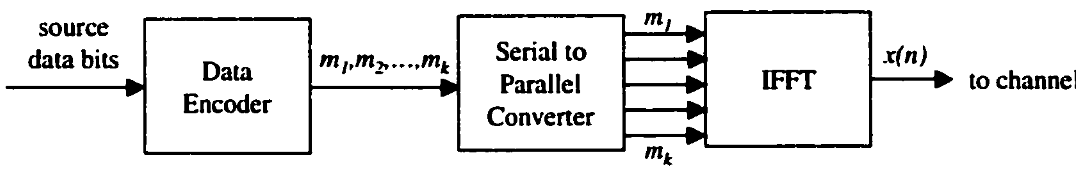

Figure 3-3: OFDM Modulator.

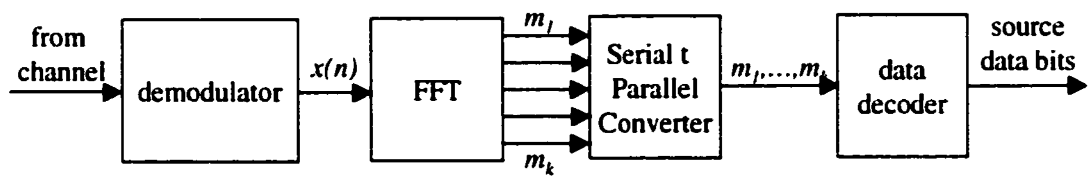

Figure 3-4: OFDM Demodulator.

3.2.3 Mitigating Multipath Propagation

The transmission of any signal over a terrestrial channel is always susceptible to multipath interference. In section 2.1.4, it was explained that the effect of multipaths on an NTSC signal resulted in ghost images displayed on the television screen. In a digital system, multipaths cause different versions of the transmitted signal to arrive at the receiver, all at different times. When more that one symbol arrives at the input of the decoder, intersymbol interference (ISI) can occur, and the decoder may be unable to distinguish between the different symbols and make a decision error.

In single carrier modulation, the symbol duration can be shorter than the delay of a multipath, and create ISI. To mitigate against this type of interferen ce, single carrier modulation schemes use error control coding techniques and equalisers to correct the errors.

To protect multicarrier symbols against multipath propagation effects, a block of known data called the guard interval extends the symbol duration. The guard interval is a block of data that contains a fraction of the original symbol. The guard interval is inserted at the beginning of the symbol before transmission. Since the carriers within a symbol are cyclic, the addition of a guard interval is also cyclic. Which means that, as long as the delay of the multipath is shorter than the guard interval, all the components at the input of the FFT will be from the same symbol and the orthogonality criteria will be maintained after the FFT is computed.

Figure 3-5 depicts an example where the delayed signal is received within the guard interval. At the receiver, the guard interval is removed from the signal and then the FFT is computed on the demodulated period. Even if the time domain signal seems to be corrupted by a delayed signal, having had the data encoded in the frequency domain allows the data to be decoded without any errors.

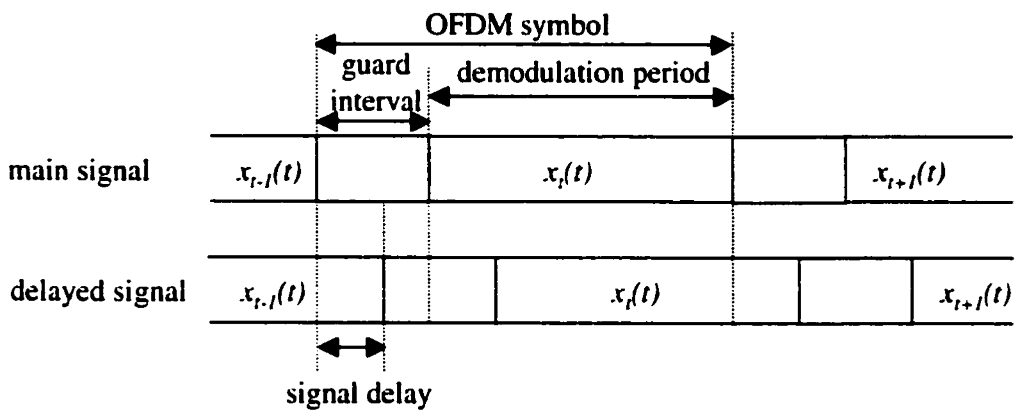

Figure 3-5: Delay within the guard interval.

When the delay is g reater than the guard interval, the previous symbol is received at the same time as the current symbol, as shown in Figure 3 -6. After the FFT process, errors are caused b ISI since components from two different symbols are processed at the same time by the decoder.

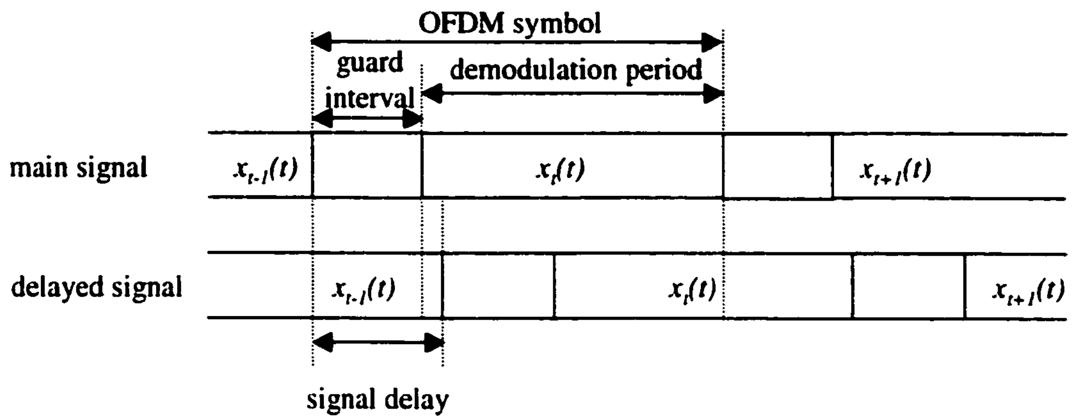

Figure 3-6: Delay larger than guard interval.

This is possible, since the penalty in increasing the duration of a symbol with a long symbol period is small compared to increasing the duration of a symbol with a short symbol duration. Note that in general, the symbol duration of an OFDM symbol is much longer than the symbol duration of a single carrier modulated signal.

The following section reviews the early work in preformed by researchers i n the area of multicarrier modulation.

3.2.4 Early Implementation of Multicarrier Modulation

The original research in multicarrier modulation dates back to the late 60's, when Saltzberg described a parallel transmission system [Sal67], and Chang and Gibby [Cha 68] described an orthogonal multiplexing transmission scheme. These papers discussed systems similar to the one shown in Figure 3-7. The original concept was to divide the available transmission band into several subchannels, as shown in Figure 3 -1, where each subchannel could be independentl modulated. These narrowband channels had the property of being more robust to variations in the channel response, transmission delay distortions and impulse noise.

Saltzberg's article [Sal67] discusses the perform ance of an efficient parallel data transmission system. The following effects of distortion on the system under three different conditions were studied: no impairments, phase offset and delay distortion. The conclusion confirms that the receiver in a parallel system must adjust the carrier phase and sampling time for each channel with a high degree of accuracy to ensure proper reception, since the jitter in these parameters is most likely to cause transmission errors. It states that an efficient parallel system would be costly to implement.

The article by Chang and Gibby [Cha68] examines a technique, which involves the transmission of time limited orthogonal signals, that have *sin x/x* spectra. The system had the following properties:

- a maximum signalling rate for a given channel without the use of sharp cut-off filters;
- more subchannels could be added to increase the bandwidth of the signal;
- the transmitted data was less susceptible to impulse noise and channel distortion, since it was transmitted on narrowband subchannels;
- the system had a minimum probability of error in the presence of Gaussian white noise because there was no ISI constraint;
- the flexibility in turning off some subchannels rendered the system more robust against channel impairments.

An implementation of this system using three carrier frequencies is shown in Figure 3 -7. The serial input is converted into three parallel streams. For each branch, the real part of the symbol is the in-phase component, while the imaginary part is the quadrature component. Each branch is bandpass filtered to ensure that there is no spectral overlap.

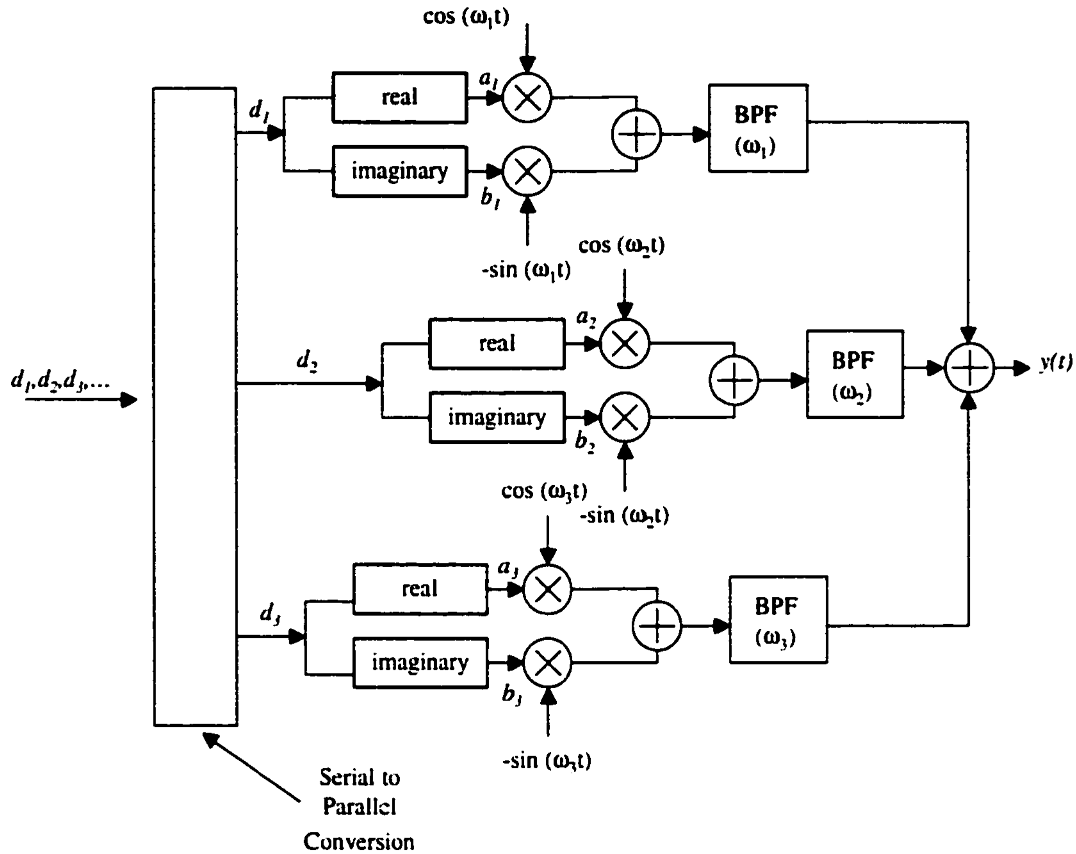

Figure 3-7: Early implementation of a multicarrier modulation system.

For a complex symbol d_n,= $|a_n + jb_n|$, at the input of the multicarrier modulator in Figure 3-7, the output, $y(t)$, is defined by equation (3.7).

$$y(t) = a_1\cos(\omega_1 t) - b_1\sin(\omega_1 t) + a_2\cos(\omega_2 t) - b_2\sin(\omega_2 t) + a_3\cos(\omega_3 t) - b_3\sin(\omega_3 t) \qquad (3.7)$$

To summarise, the symbols can be recovered at the receiver because of the orthogonality that exists between the sine and the cosine components. The frequencies are chosen so that no overlap exists between any subchannels. As Saltzberg reported, such a multicarrier system, including all the modulators, mixers and filters was very expensive to build.

In the early 70's a paper by Darlington [Dar70], suggested the idea of using the DFT in a FDM and Weinstein and Ebert [Wei71] proposed the use of the DFT in a parallel data transmission system. But it was not until the early 80's [Hir81], with the progress in digital signal processing that the design of the modulator with an IFFT process became much widespread in the literature. Today, most of the multicarrier systems are implemented and the IFFT and FFT. The following section describes such applications.

3.3 *Current Applications Using MCM*

This section examines five different applications where multicarrier modulation is being used. One popular multicarrier modulation scheme currently being deployed is Coded Orthogonal Frequency Division Multiplexing (COFDM). COFDM is similar to the OFDM system illustrated in Figures 3-3 and 3-4, the main difference being that the data symbols are coded at the input of the IFFT block. As the technology matures, multicarrier modulation will certainly continue to find its way into new applications.

3.3.1 Digital Audio Broadcasting (DAB)

In 1991, COFDM was chosen as the modulation scheme for the new digital audio broadcasting (DAB) service. Using a bandwidth of 1.536 MHz, the system provides both digital audio and data services. It is designed with different modes of operation where the number of programs and/or the quality of programs can be determined by the broadcasters. Using COFDM, DAB systems are capable of delivering a digital signal to portable and fixed receivers under different environments, including areas with severe multipath conditions [ETS95].

The system is designed to handle the Doppler spread encountered in mobile reception taking into account the environment. The symbol duration was chosen so that it would be larger than the delay spread of a typical channel, hence capable of handling channel fading. In addition, the insertion of a guard interval between successive symbols ensures that channel selectivity and multipath propagation will minimise ISI.

The four modes of operation for DAB standard, ETSI 300 401, are listed in Table 3-1. Each mode is designed for different operating environments. Mode I is for terrestrial single frequenc network (SFN) operation in the VHF range, mode II is for medium scale SFN or for local radio applications using one transmitter. Mode III is designed for cable, satellite and complementar terrestrial transmission, since it can operate up to 3 GHz for mobile reception. Mode IV is designed for L-band and allows greater transmitter distance spacing for SFN than mode II [Jur97]. In all modes, the carriers are modulated using differential quadrature phase shift keying (DQPSK).

Table 3-1: DAB mode of operation.

System Parameter	Mode I	Mode II	Mode III	Mode IV
Frame duration	96 ms	24 ms	24 ms	48 ms
Guard interval duration	246 μs	62.5 μs	31 μs	125 μs
TX separation for SFN	96 km	24 km	12 km	48 km
Freq. range (for mobile reception)	< 375 MHz	< 1.5 GHz	< 3 GHz	< 1.5 GHz
Useful symbol duration	1 ms	250 μs	125 μs	500 μs
Total symbol duration	1246 μs	312.5 μs	156 μs	625 μs
No. of carriers	1536	384	192	768

The time and frequency interleaving is used at the encoder to assists the receiver in decoding a signal corrupted with multipath. For a stationary receiver, with multipath reception, the frequency interleaving insures correct reception by amplifying some carriers while others are attenuated. The average power over the band ensures that a certain level of quality is achieved. For mobile receivers, the time interleaver can redistribute, in the time domain, the symbols that are corrupted in burst. In the case of mobile reception, as the vehicle is moving along, the interleaver should be able to handle the nulls in the received signal. However, when the nulls are present while not in motion, the interleaver will be limited in performance until the vehicle starts moving again.

3.3.2 Digital Terrestrial Television Broadcasting (DVB-T)

The European standard for digital terrestrial television transmission, developed b the DVB group and defined as ETSI/EBU 300 744 [Ben97], uses the COFDM modulation scheme. The DVB standard is capable of operating in two modes, either in the 2k (2048) carriers mode or in the 8k (8192) carriers mode. The parameters for each mode are listed in Table 3.2 [Wu99].

Table 3-2: DVB-T parameters.

Parameter	8k mode	2k mode
Effective number of carriers (N)	6818	1706
Useful symbol duration (T_s)	896 μs	224 μs
Guard interval	T_s /4, T_s/8 or T_s/32	T_s /4, T_s/8 or T_s/32
Carrier spacing (1/T_s)	1116 Hz	4464 Hz
Spacing between edge carriers	7.61 MHz	7.62 MHz
Carrier modulation method	QPSK, 16-QAM or 64-QAM	QPSK, 16-QAM or 64-QAM

The DVB-T system includes the possibility of hierarchical coding with a n on-uniform m-ary QAM modulation scheme. A high-data rate can be transmitted using 16 or 64 QAM and a lower data rate signal can be modulated using QPSK. This allows a high data rate receiver to decode the 16/64 QAM signal while a mobile receiver could dec ode the QPSK constellation. This implementation would allow fixed receivers to decode a high quality video signal, while mobile receivers could decode a lower quality video signal [Far99].

To accommodate the roughly 20 Mbps required for HDTV, the more complex 8k system will be deployed. If implemented with a long guard interval, it will be able to deal with strong echoes and allow the implementation of single frequency networks. The 2k system currently being deployed in Europe for over the air digital te levision transmission is not capable of operating in SFN mode since it was designed for mobile reception [Plu99].

3.3.3 MCM Over Telephone Lines

In order to compete with cable television networks, the telephone companies have introduced a new service to offer high-speed network access to their customers using the twisted pair cable. The system developed, the asymmetric digital subscriber loop (ADSL), offers a high data rate in the downstream direction (to the customer) and lower data rate upstream (from the cu stomer). The ADSL system transmits data carriers in the upper portion of the channel and leaves the lower 4 kHz for telephone conversations.

For this application, the modulation scheme is often referred to as discrete multi -tone (DMT) modulation, which u ses the same principle as COFDM modulation. Two different versions of ADSL are now available: the full rate ADSL can carry up to approximately 8 Mbps downstream and 800 kbps upstream, while a simpler version, can deliver up to 1.5 Mbps downstream and 500 kbps upstream.

In both systems, each subcarrier is spaced 4.3125 kHz apart. In the downstream direction, the 1.1 MHz channel is divided into 256 frequency bands (or subchannels). The lower subchannels (1-6) are typically not used because of the analogue voice channel. The last subchannel is also reserved. The assignment of the channels is very flexible; typical settings might include channels 6-31 for upstream (24 kHz to 136 kHz), 32-250 for downstream (136 kHz to 1.1 MHz). The modulation used on an given frequency channel can be from the QAM family. Some carriers are reserved for pilot tones, which are used to recover timing. The number of bits per symbol within each channel may be independently selected allowing the modem to set the transmission rate dynamically.

To implement the DMT, the use of the FFT is considered to be substandard to other orthogonal transformations, such as the discrete wavelet transform which better isolates the individual frequency spectra. However, the FFT has been chosen for its computational efficiency [Pol99] [Pol00].

3.3.4 COFDM-6 Modem

In 1995, the interest for COFDM for DTV transmission in North America was brought forward by a group of Canadian, American and Brazilian broadcasters. A 6 MHz COFDM modem was built by a Scandinavian laboratory and was evaluated by the Communications Research Centre [CRC96].

The laboratory evaluation of the modem included measurements of the performance of the modem when the signal was affected by random noise, phase noise and impulse noise. The evaluation also covered multipaths, co -channel interference and adjacent channel interference effects. The design of the prototype proved successful in dealing with a 0 dB echo at the input of the receiver.

The modem also demonstrated that COFDM could be used for local multipoint communication systems (LMCS) applications. Both laboratory and field tests were carried out in the 28 GHz frequency band [Led97].

3.3.5 Indoor Wireless LAN

There is a great demand for high -speed wireless services, such as Inte rnet and wireless multimedia. Wireless local area network (LAN) are being implemented for indoor environment where there is low mobility, low delay spread and high data rate to transfer [Bah99].

The standard for wireless LAN is the IEEE 802.11, in the 2.4 GHz and 5 GHz bands: it supports both frequency hopping spread spectrum (FHSS) and direct sequence spread spectrum (DSSS). However, there are problems with the synchronisation and OFDM seems to have better performance in handling the channel for data rates above 10 Mbps.

The capability of handling large channel delay spreads is the reason why OFDM is being looked at for wireless LAN applications. In a wireless environment, it is normal to encounter dela spreads of up to 800 μs. With systems operating at transmission rates greater than 10 Mbauds/s, such delay spreads can extend over several OFDM symbols.

Implementations using single carrier modulation scheme are also possible but with their inherent limitations. If the delay spread is less than 4 symbols , the system can compensate for them by using linear equalisation. If the delay spread is longer, the system's complexity increases exponentially and is no longer viable. Another approach is to use a decision feedback equaliser (DFE), except that it requires a large training sequence to acquire the signal.

3.4 Current Research in the Area of OFDM

The goal of the on-going research in OFDM is to improve the performance of multicarrier systems. The on-going research in five areas is summarised in this section.

The first investigation area, describes a process to improve the performance of OFDM systems with respect to spurious sine wave and frequency deviation. The method, described in the article by Muschallik [Mus96], uses an adaptive Nyquist window at the re ceiver. The windowing process ensures that the possible glitches at the output of the FFT are kept to a minimum and that the carriers remain orthogonal. The system performs a $2N$-point FFT, instead of an N-point FFT. The output sequence is of length N and a null point separating each data point. The white noise contribution is found on all $2N$ points, which leads to an improvement of 3 dB on the C/N for the N data points.

In a second project, Kozek [Koz98] investigates cases where a priori knowledge of the transmission channel is available. He demonstrated that it is possible to use nonorthogonal pulses with a multicarrier system, when conditions on the channel are known ahead of time (i.e. perfect channel state information estimation). A source of errors in OFDM system is the frequency difference between the local oscillators of the transmitter and the receiver.

In a third research project, Luise et al. [Lui98] describes an improved method for blind equalisation/detection when transmitting over a frequen cy selective channel. The approach is based on the observation that the FFT turns a single wideband frequency selective channel into a set of correlated narrowband flat fading channels. Methods previously used for time selective flat fading channels can then be used for joint equalising and decoding of OFDM symbols.

The fourth article by Shi examines a study of bandpass nonlinearity [Shi96]. It gives an insight on the effects to the signal when peaks enter the saturation region of power amplifiers. Improvement in the in -band noise contribution is demonstrated by the fact that clipping induced noise uses a larger spectrum than the OFDM signal. Therefore, some of the out of band components from the noise do not impact on the OFDM signal.

Finally, in the fifth article by Chuang et al., multiple access for broadband wireless networks using OFDM is investigated [Chu00]. Current wireless technologies offer data rates in the order of 10 kbps. The upcoming 3rd generation (3G) systems will offer rates up to 384 kbps in macrocellular environment and up to 10 Mbps in microcellular and indoor environments. This research project looks at combining OFDM with dynamic packet assignment in a 5 MHz wideband channel. Packet data bit rates of 2-5 Mbps are supported in macrocellular environment and up to 10 Mbps peak data rate in microcellular and indoor environment using space -time coding with two transmit and two receive antennas.

3.5 Summary

In this chapter, a review of the differences between single carrier modulation an d multicarrier modulation schemes is presented to show how different types of interferences affect both types of modulation. Time domain interference is typically represented by impulse noise, whereas frequency domain interference is characterised by tone interference.

A single carrier modulation scheme, also known as a time domain modulation scheme, uses the full bandwidth of the channel to transmit the data. A multicarrier modulation scheme, also known as a frequency domain modulation scheme, divides the transmitted bandwidth into several subchannels to transmit the data. Dualities exist between how multicarrier modulation and single carrier modulation schemes are each affected by interference.

The MCM schemes are robust against time domain interferenc e since, the interference can be averaged out over several symbols in the FFT. On the other hand, SCM schemes are more susceptible to errors due to time domain interference since the symbol integration time for a single carrier modulated symbol is much sh orter than for multicarrier modulated symbol [Wu95b].

The multicarrier modulation schemes are vulnerable to frequency domain interference that occur within the channel, since the interference can destroy the data on the carriers that is colocated with the interfering carriers. On the other hand, single carrier modulation scheme is more robust to frequency domain interference, since the signal power is spread over the entire spectrum instead of being concentrated on subchannels.

A final comparison shows how each scheme uses its data transmission capabilities to mitigate the effect of multipath propagation or ISI. A single carrier modulation scheme uses part of its spectrum for pulse shaping in order to minimise the impact of multipaths, while multicarrier modulation schemes such as OFDM, use part of its symbol duration to insert a guard interval to mitigate the effect of multipaths. To assist the receiver in decoding the data, an adaptive equaliser is often required to remove multipath components. In sin gle carrier modulation, a training sequence is sent to assist with the convergence of the equaliser, while MCM sends out reference carriers to accomplish the same task.

The implementation of these techniques has an impact on the available data throughput, but the are required in most communication systems. The choice of modulation scheme for a given system, is left to the designer. But this choice should normally be based on the requirements of the system and the type of transmission channel to be used.

4 A Proposed In-band Multicarrier Data Broadcasting System

4.1 Overview

This chapter describes the in-band multicarrier data broadcasting system designed for the NTSC standard. Section 4.2 presents a description of the proposed multicarrier system. Section 4.3 describes how the data signal is combined with the NTSC signal without causing interference. In section 4.4, the process by which the NTSC signal is sampled for the performance evaluation of the proposed system is described. Section 4.5 describes the parameters by which the multicarrier data broadcasting system is implemented in this evaluation. In the summary of this chapter, section 4.6, the methods by which the performances of the data broadcasting system are evaluated in chapter 5 and 6 are introduced.

4.2 Description of the Proposed Multicarrier System

The goal of this study is to demonstrate that multicarrier modulation using OFDM is a viable alternative to current methods for inserting a digital signal within the spectrum of the NTSC video carrier. This objective is achieved by demonstrating two points: firstly, that the technique is capable of offering data rates that are superior to the current data broadcasting technologies, and secondly, a multicarrier signal can be inserted within the video carrier without causing noticeable degradation to the picture quality. The major constraint of current digital data broadcasting techniques described in chapter 2 is the impact the data signals have on the picture quality. The proposed system encodes the data to ensure that interference into the video signal is minimized.

The coding technique presented in this section demonstrates the flexibility in shaping the spectrum of the data signal. Instead of using a filtering system to shape the spectrum of the data, the system uses the inverse fast Fourier transform (IFFT) to encode the data. The multicarrier modulation scheme offers the choice of turning on a data carrier by transmitting data, or turning off by setting the input to zero. This flexibility allows the data carriers that are susceptible to cause interference into the video signal to be turned off. Therefore limiting the mutual interference each signal would have on each other.

There are portion of the video carrier spectrum that do not carry a ny information. The multicarrier data broadcasting technique takes advantage of this by transmitting the data within these unused portions in the vestigial sideband of the video carrier. The exact location of the data carriers is carefully chosen since previous research results [ITU86] has demonstrated that different parts of the analogue television spectrum experience different sensitivities to narrowband or tone interference.

4.2.1 NTSC Signal Spectral Components

In section 2.2.2, the NTSC video carrier was described as having a bandwidth of approximately 4.2 MHz, (see Figure 2-3). An observation of the video carrier, made with a resolution bandwidth (RBW) smaller than 15 kHz, shows that the video carrier is made up of over 250 distinct spectral components, which are all separated by 15.75 kHz. The discrete lines that make up the video signal cause these discrete spectral components. The location of the spectral components is fixed in frequency, but varies in amplitude with the content of the video signal.

Figure 4-1 illustrates the spectrum of the video carrier with a span of 400 kHz. The peak represents the frequency of the video carrier and other spectral components make up the spectrum of the video signal.

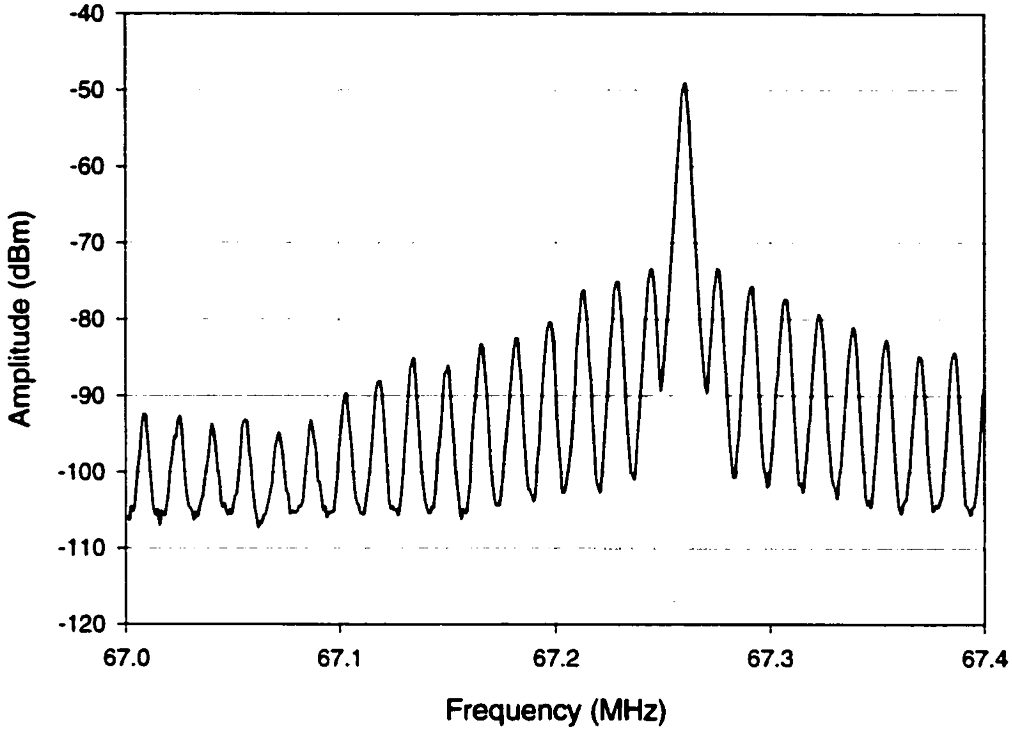

Figure 4-1: Spectrum of video carrier.

Figure 4-2 illustrates a few spectral components of the video carrier (with a frequency span of 150 kHz and RBW of 1 kHz). Within the 1.25 MHz that makes up the vestigial sideband of the video carrier, there are approximately 80 spectral components. The proposed data broadcasting system takes advantage of the characteristics of these spectral components to combine the data signal and the NTSC video signal.

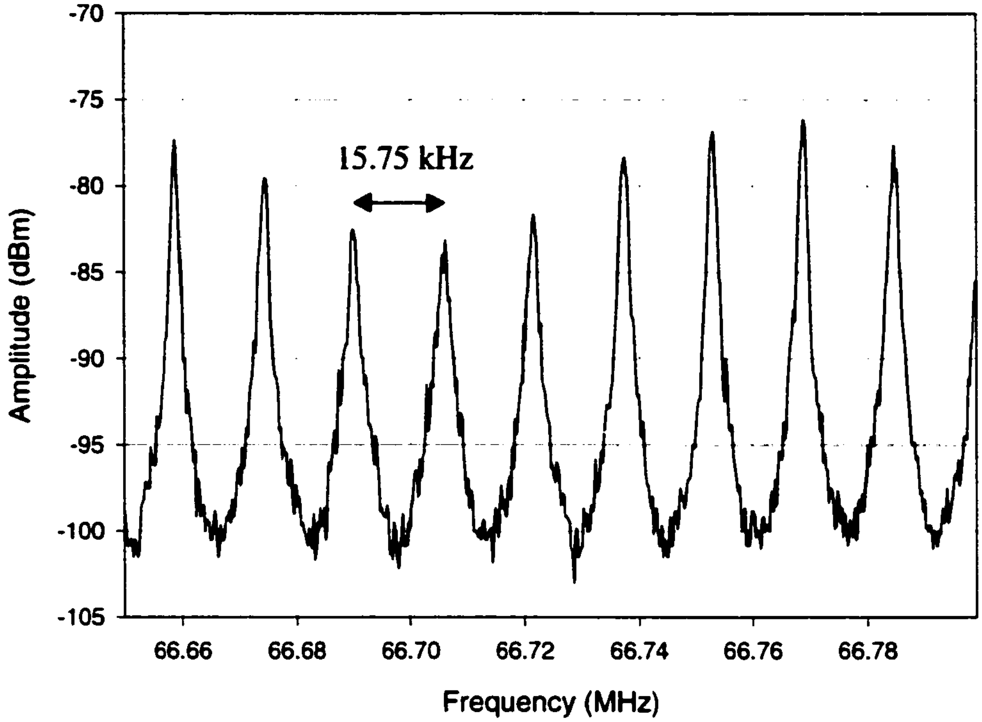

Figure 4-2: NTSC signal spectral components of Channel 4 (RBW=1kHz).

The next section describes the method used to encode the data such that the spectrum of the data signal is confined within the nulls between the spectral components of the NTSC signal.

4.2.2 Spectrum of the Data Signal

The spectrum of the data signal must have notches or nulls it its spectrum in order to minimise its effect into the host video carrier. By coding the data with an inverse fast Fourier transform (IFFT), it is possible to create notc hes in the spectrum, by placing a zero at a particular bin (or point) at the input of the IFFT. The width of the spectral notches is determined by the number of consecutives zeros at the input of the IFFT.

For the data broadcasting signal, the notches in the spectrum must be 15.75 kHz apart and wide enough as to not interfere with the video signal. This is to ensure that both signals can share the same bandwidth without causing mutual interference. A real life implementation would also have to take into account possible drifts in the frequency carrier. To cope with this problem, an additional margin might need to be implemented.

The output of a programmable waveform generator is shown in figure 4 -3. It represents an OFDM signal with a bandwidth of 300 kHz. Within the signal, there are 18 notches that each separated by 15.75 kHz: the depth of the notches is limited by the resolution bandwidth of the display.

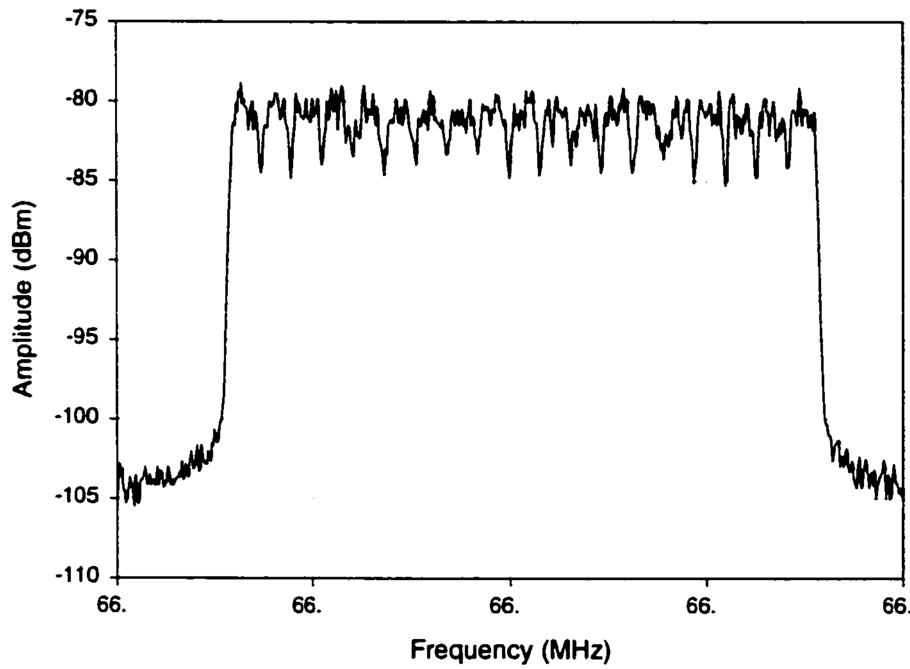

Figure 4-3: 300 kHz wide OFDM symbol spectru .

Figure 4-4 shows the edge of the OFDM symbol spectrum. With a resolution bandwidth of 1 kHz, the depths of the notches are more visible.

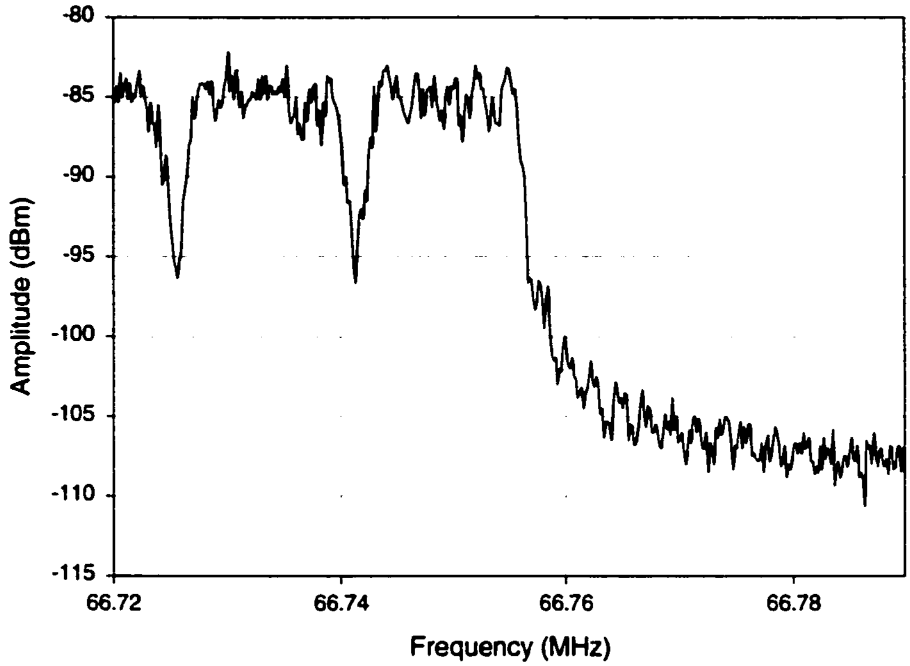

Figure 4-4: Edge of OFDM symbol spectrum.

Figure 4-5 demonstrates the sum of the video signal and the data signal. The NTSC spectral components line up with the notches of the spectrum in the data signal.

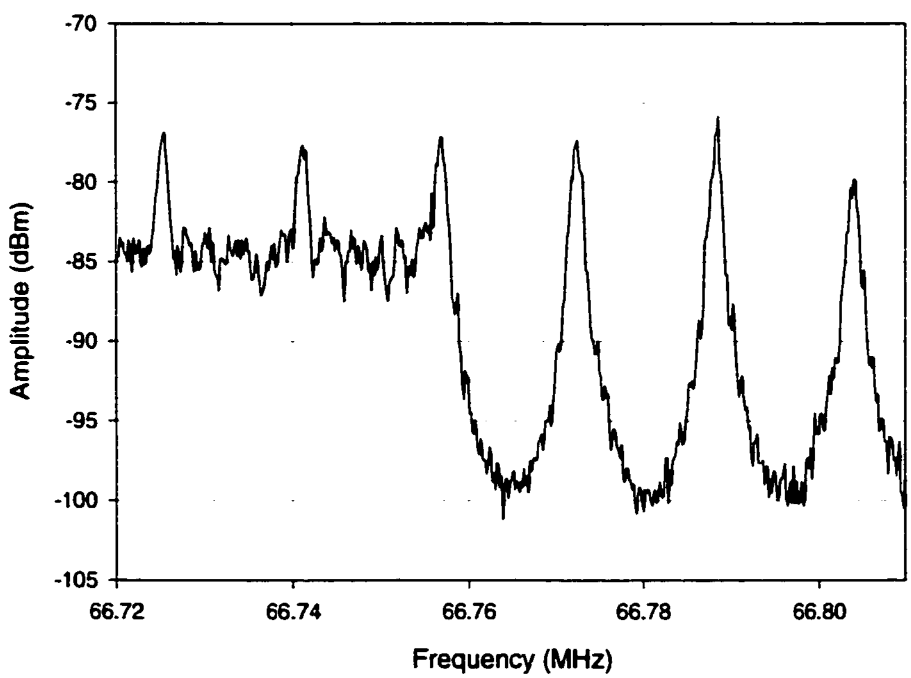

Figure 4-5: Sum of the NTSC and OFDM carriers spectrum.

4.2.3 Data Broadcasting System Block Diagram

To implement the in-band data broadcasting system, an important parameter needs to be defined: the carrier spacing. Carrier spacing is defined as the difference between 2 points at the input of the IFFT. This section provides the definition of the carrier spacing and indicates the number of data carriers that can be inserted within a 15.75 kHz interval.

The block diagram of the system is shown in Figure 4 -6. The data source produces a series of bits, and the multilevel data encoder encodes these bits into m-ary data symbols. A spectral shaping component ensures that the notches are properly positioned within the spectrum of the data signal and transforms the data symbols into data carriers. The IFFT transforms the data carriers into OFDM symbols. At the output of the IFFT block, the OFDM symbol is combined within the vestigial sideband of the television signal and transmitted over the transmission channel.

At the receiver, the tuner downconverts the TV signal and separates the OFDM symbol from the video and audio signals. The FFT transforms the OFDM symbol into data carriers and the filtering block further transforms the data carriers into data symbols. The last block, the multilevel decoder, decodes the symbol into the original data bits.

In this thesis, the implementation of the system does not include a guard interval to mitigate multipaths or forward error correction (FEC) to reduce the transmission errors caused by the transmission channel.

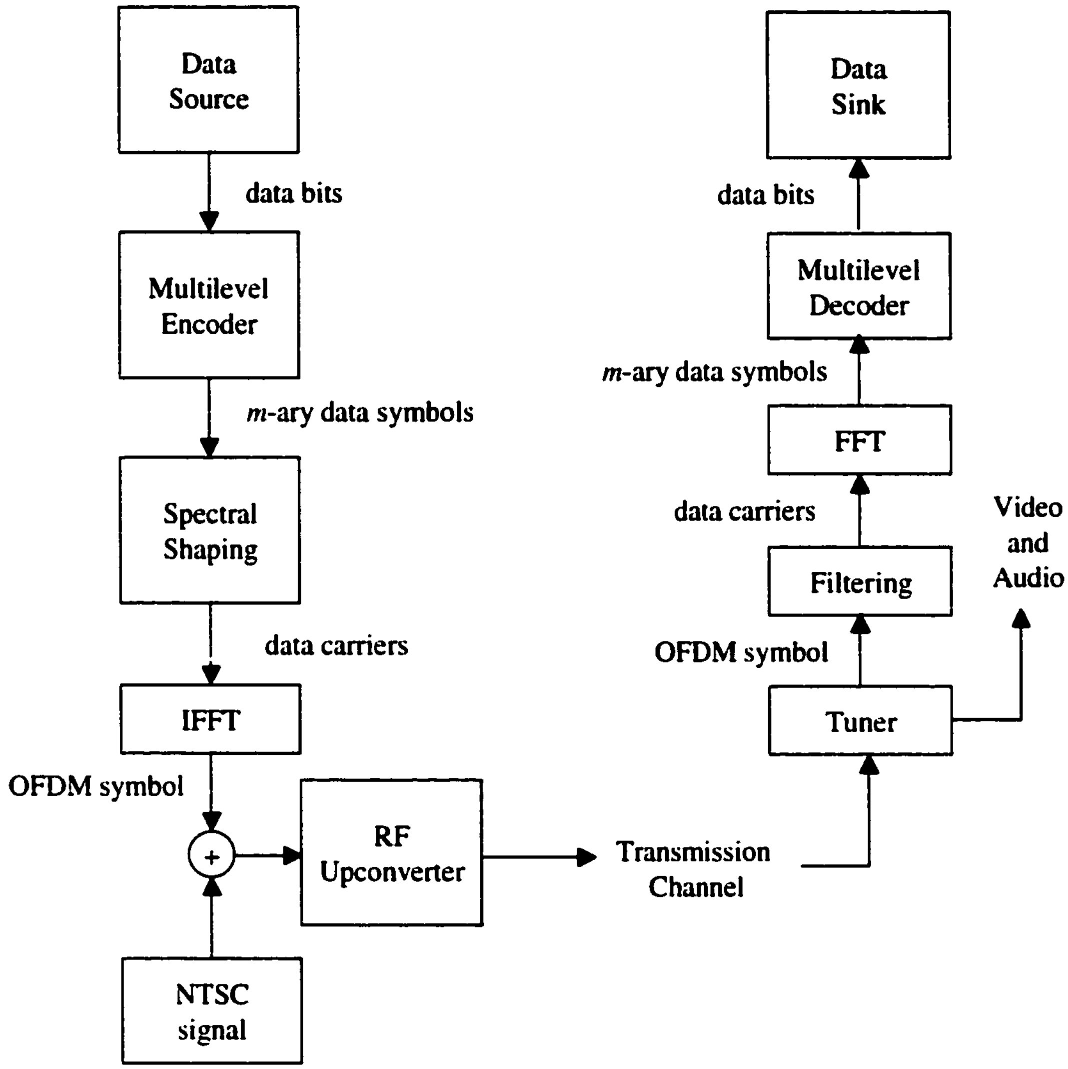

Figure 4-6: Data broadcasting system block diagram.

4.3 Determination of the OFDM Parameters

4.3.1 Carrier Spacing of the OFDM Symbol

For the implementation of the simulated system, a value must be allocated to each bin or point at the input of the IFFT. The carrier spacing between any two points at the input of the IFFT is called the carrier spacing Δf and is defined by the ratio of the sampling rate f_s, to N, the size of the Fourier transform:

$$\Delta f = \frac{f_s}{N} \qquad (4.1)$$

The size of the Fourier transform is limited to values that are powers of 2 (i.e. 512, 1024, 2048, 4096,...). The choice of the sampling rate is limited by two important criteria: first, the sampling rate must meet Nyquist's criterion, and second, for the purpose of the simulation, the symbol must share the same sampling rate as the sampled NTSC signal used as a source of interference. Table 4-1 lists the values of the carrier spacing for different values of f_s and N.

Table 4-1: Carrier spacing for multicarrier system.

	Size of Fourier Transform (*N*)					
f_s	512	1024	2048	4096	8192	16384
2 MHz	3.91 kH	1.95 kH	977 H	488 H	244 H	122 H
5 MHz	9.77 kH	4.88 kH	2.44 kH	1.22 kH	610 H	305 H
6.45 MH	12.6 kH	6.30 kH	3.15 kH	1.58 kH	788 H	394 H
10 MH	19.5 kH	9.77 kH	4.88 kH	2.44 kH	1.22 kH	610 H
12.9 MH	25.2 kH	12.6 kH	6.30 kH	3.15 kH	1.58 kH	788 H
20 MH	39.1 kH	19.5 kH	9.77 kH	4.88 kH	2.44 kH	1.22 kH

With the carrier spacing defined, it i s possible to determine the number of data carriers that can be inserted within the 15.75 kHz spectrum interval. The number of intervals that the data carriers span determines the total bandwidth of the data signal.

4.3.2 Number of Carriers per 15.75 kHz Interval

The number of data carriers, N_c, within a 15.75 kHz interval is computed by the following equation.

$$N_c = \frac{15.75\ \text{kHz}}{\Delta f} \qquad (4.2)$$

Table 4-2 list the number of carriers (or points) within a 15.75 kHz interval of spectrum, for different values of f_s and N. It must be noted that not all of the carriers can be used to transmit data information since some of the carriers are set to zero in order to create notches in the data spectrum.

Table 4-2: Number of carriers per 15.75 kHz spectrum interval.

	Size of Fourier Transform (*N*)					
f_s	512	1024	2048	4096	8192	16384
2 MHz	4.0	8.1	16.1	32.3	64.5	129.0
5 MHz	1.6	3.2	6.5	12.9	25.8	51.6
6.45 MH	1.3	2.5	5	10	20	40
10 MH	0.8	1.6	3.2	6.5	12.9	25.8
12.9 MH	0.6	1.3	2.5	5	10	20
20 MH	0.4	0.8	1.6	3.2	6.5	12.9

The results in Table 4-2 show that for a given sampling rate, increasing the size of the Fourier transform also increases the number of data points per 15.75 kHz interval. For a fixed value of *N*, increasing the sampling rate reduces the number of points per interval because this also increases the carrier spacing and leaves less points available for a fixed interval. The sampling rates of 6.49 MHz and 12.9 MHz are shown to demonstrate the possibility of designing a system with an integer number of carriers per interval.

To ease the computing requirements, an FFT size of 8192 points was chosen. Due to a limitation of the sampling and acquisition hardware used in this thesis, only integer values of sampling rates are available. In this case, a sampling rate of 10 MHz is chosen in order to limit the number of samples required to reconstruct the NTSC signal. By using these two values, the carrier separation is defined as 1.22 kHz and the number of carriers per 15.75 kHz interval is 12.9.

4.4 NTSC Acquisition

Since the simulations require that the sampled television signal and the OFDM symbols be combined in the computer model, a common sampling rate must be used. This section describes the process by which the NTSC television signal was sampled and the spectral analysis of the sampled NTSC signal.

4.4.1 Laboratory Setup

The spectrum of interest in the video signal is the vestigial sideband and the video carrier of the television signal. For this reason, it is the only portion of the video signal that was sampled. This section describes the laboratory procedure by which the signal was downconverted and sampled.

The block diagram of the laboratory setup is shown in Figure 4 -5. A rooftop log-periodic antenna picked up the off-air signal. A bandpass filter (channel 13 at 210 to 216 MHz) eliminated RF signals from antenna feed, except for the channel of interest. Since the television equipment uses a 75 Ω impedance and the measurement and laboratory equipment uses a 50 Ω impedance, a minimum loss pad is connected from the bandpass filter to a variable bandpass filter to eliminate the mismatches that might occur on the transmission line.

A variable bandpass filter centred at 206.5 MHz and with a bandwidth of 10.33 MHz, filtered out the spectrum above the video carrier and kept the vestigial sideband. A signal generator (208.796 MHz, -7.0 dBm) and a mixer performed the downconversion of the vestigial sideband from the frequency band of 210 to 211.25 MHz to the frequency band located between 1.204 and 2.454 MHz.

The low pass filter removed the harmonics and other intermodulation products resulting from the downconversion. This ensured that the signal was bandlimited and met the Nyquist criterion before the sampling process. The combination of a 25 dB amplifier and a 10 dB attenuator ensured that the signal power was optimal for the dynamic range of the 10-bit analogue to digital converter. The signal was stored on a computer for later processing with the simulation.

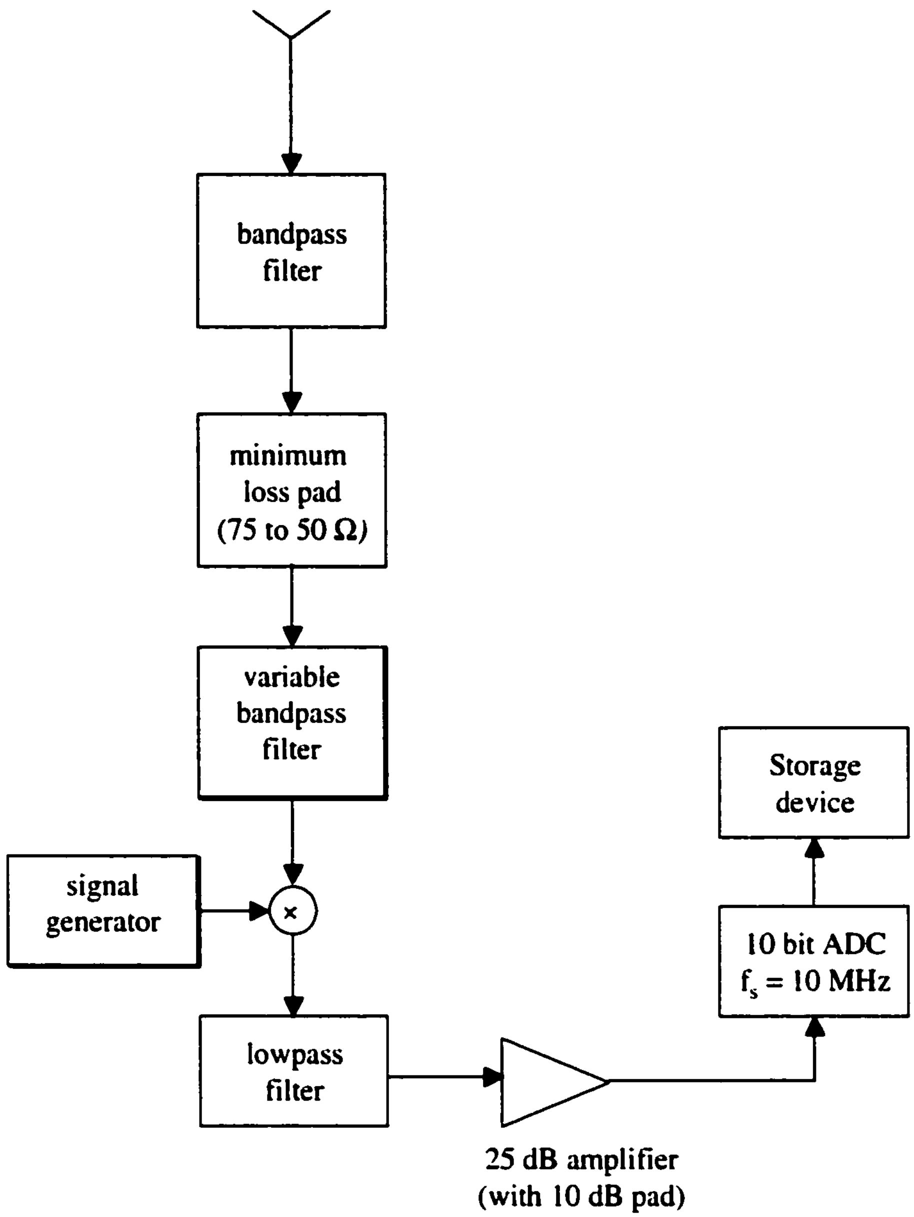

Figure 4-7: Laboratory setup for the acquisition of the NTSC signal.

4.4.2 Spectral Analysis

The sampled signal stored approximately three million real samples of the NTSC signal, which represents about 3 seconds of a video stream. To determine which bins at the input of the IFFT would carry data and which would be turned off, the host NTSC signal was analysed in the frequency domain. Figure 4-8 shows the spectrum of the sampled NTSC signal (0 to $f_s/2$), where

f_s= 10 MHz. The video frequency was located at 2.5 MHz or bin 2020 after the 8192-point FFT and the start of the NTSC channel is approximately located at 1.2 MHz.

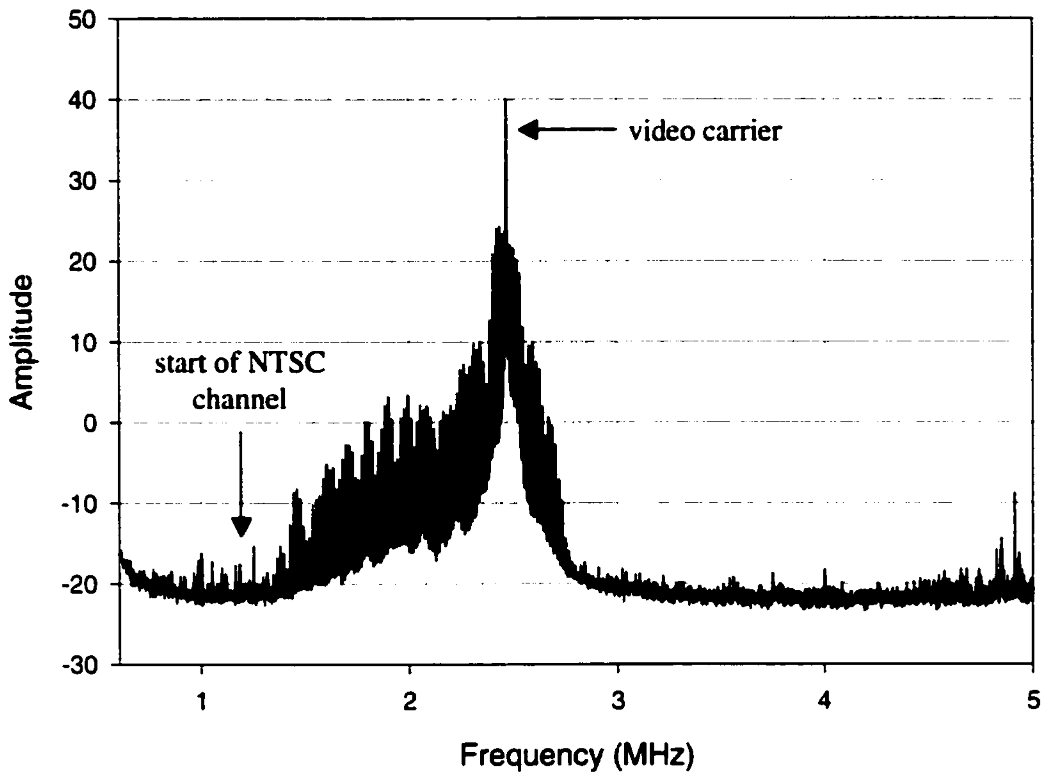

Figure 4-8: Spectrum of sampled NTSC signal.

4.5 System Parameters

4.5.1 Overview

The location of the data carriers in the vestigial sideband must ensure that there is no out of band emissions in the lower adjacent channel. The selected start frequency is set 1.1 MHz below the video carrier, where there is 150 kHz of spectral isolation between the data signal and the edge of the lower adjacent channel. The start frequency is equivalent to bin 1119 on the 8192-point FFT.

Using a carrier spacing (or simulation resolution) of 1.22 kHz per point, allows 12.9 data points per 15.75 kHz interval. Given that the simulation requires an integer number of points, 13 points were used in the Matlab simulation. Since this value would eventually cause an offset in the desired location of the data carriers, some intervals were shortened to 12 points (see Table 4-4).

4.5.2 System Definition

The data broadcasting system is tested with three different bandwidths: 300 kHz, 450 kHz and 600 kHz. To determine the effect of the notches in the spectrum, notches of different widths were inserted in the spectrum: 1.2 kHz (1 point), 3.7 kHz (3 points), and 6.1 kHz (5 points). Table 4-3 lists the system parameters used for each combination of bandwidths and notch widths. The bit rate is based on a spectral efficiency of 2 b/s/Hz per data carrier. Each 8192 block has a symbol duration of 819.2 μs.

The number of spectral components spanned by each bandwidth of 300, 450 and 600 kHz is 18, 28, and 38, respectively.

Table 4-3: System parameters.

Data bandwidth (kHz)	Notch width (kHz)	Number of carriers	Bit rate (kbps)
300	1.2	270	659.18
300	3.7	208	507.81
300	6.1	166	405.27
450	1.2	356	868.64
450	3.7	296	722.24
450	6.1	236	575.84
600	1.2	464	1132.16
600	3.7	386	941.84
600	6.1	308	751.52

Table 4-4 lists the bin number for spectral components that are spanned for each system bandwidth.

Table 4-4: Location of NTSC spectral components.

Number of 15.75 kHz intervals	Bin number of spectral components	Comments
	1119	Start location for all systems
1	1130	
2	1143	
3	1156	
4	1169	
5	1182	
6	1195	
7	1208	
8	1221	Delta of 12 between
9	1233	interval 8 and 9
10	1246	
11	1259	
12	1272	
13	1285	
14	1298	
15	1311	
16	1324	
17	1337	Delta of 12 between
18	1349	interval 17 and 18
19	1362	End 300 kHz system
20	1375	
21	1388	
22	1401	
23	1414	
24	1427	
25	1440	
26	1453	Delta of 12 between
27	1465	interval 26 and 27
28	1478	
29	1491	End 450 kHz system
30	1504	
31	1517	
32	1530	
33	1543	
34	1556	
35	1569	
36	1582	
37	1595	Delta of 12 between
38	1607	interval 37 and 38
39	1620	End 600 kHz system

4.6 Summary

Given the available technology, the proposed in-band data broadcasting system could be easil implemented by a television broadcaster. A basic configuration would include a network server to route the data from a storage device or the Internet to the input of the multicarrier encoder. At the broadcaster's headend, the multicarri er data signal is upconverted to the IF (intermediate frequency) and inserted in the vestigial sideband of the video carrier. After the insertion, the combined video and data signals are upconverted to the broadcaster's RF frequency and transmitted over the air.

At the receiver, a splitter would feed both the data decoder and the NTSC decoder. The data signal is lowpass filtered, decoded by the OFDM demodulator and sent to a data sink. As for the video signal, it would be processed by the NTSC decoder and displayed on the screen.

In order for such a system to be approved by broadcasters, the system must first demonstrate that it is capable of delivering data at a reasonable rate and not cause any noticeable degradation to the host video signal. The evaluation of this multicarrier system is described in chapter 5 and 6.

Chapter 5 discusses our objective performance evaluations, which include BER measurements computed by a computer simulation using QPSK carriers at the input of the IFFT. During the simulation, the ratio of the video carrier amplitude to the data carrier amplitude is varied in order to obtain different test conditions.

Chapter 6 reports the results of the subjective assessment where the impairment of the video signal is characterised whe n the data signal is inserted in the vestigial sideband of the video carrier. The impaired video signal is displayed on a television screen receiver and viewers were asked to describe the impact on the quality of the signal. During the tests, the amplitu de of the data signal was increased until the threshold of visibility was achieved and then increased until the conditions of slightly annoying and annoying were also observed.

5 Computer Simulation Results

5.1 *Overview*

This chapter describes the Matlab simulation used to model the interference the NTSC television signal would have on the multicarrier data broadcasting signal. Section 5.2 describes how the simulation was implemented using the MATLAB programming environment. Section 5.3 discusses the results from the computer simulations. The source code for the simulation is provided in Appendix A.

5.2 Simulation Description

The block diagram shown in Figure 4-6 served as a basis for the Matlab model used to simulate the multicarrier data broadcasting system. Figure 5-1 shows the block diagram used in the simulation of the multicarrier modulation data broadcasting system.

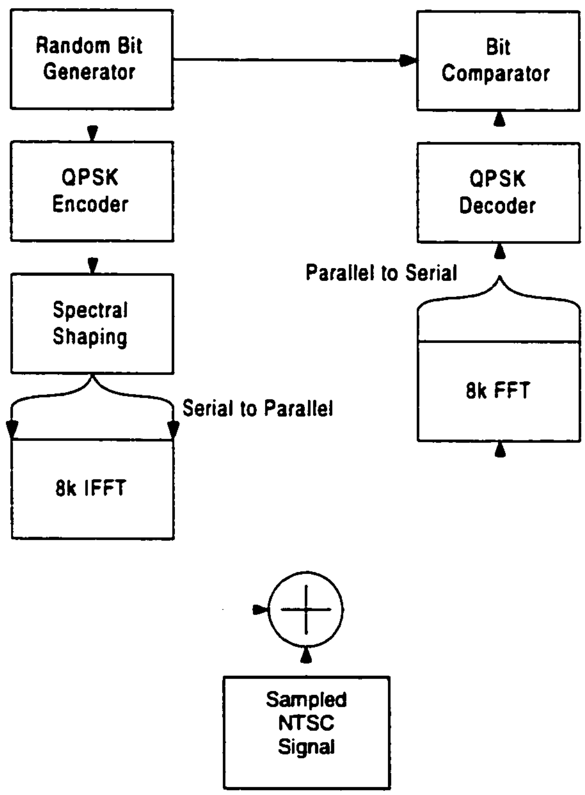

Figure 5-1: Data broadcasting system block diagram.

The first block generates a series of random bits as a source to the encoder. These bits are then encoded by a QPSK encoder following the complex signal constellation depicted in Figure 5-2.

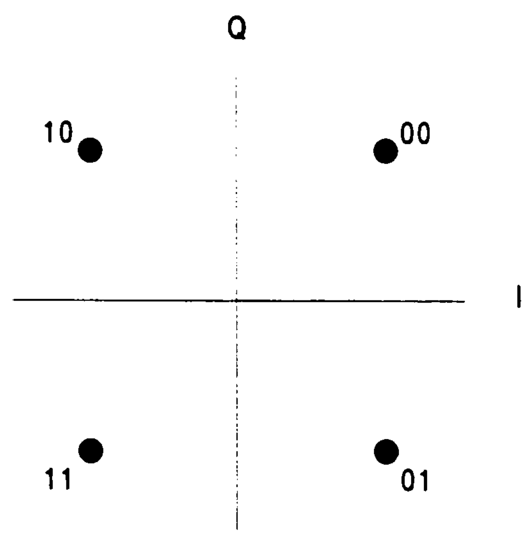

Figure 5-2: QPSK signal constellation.

The spectral shaping block assigns the QPSK symbols, or data carriers, to their pre -determined bins at the input of the IFFT and sets the other carriers to zero to create the notches in the spectrum. The 8192-point array is then processed by the IFFT. The OFDM symbol at the output of the IFFT is then combined with an 8192 -point sample of the NTSC signal. Note that the sampling of the NTSC signal is done only for the computer simulations: in real life implementations, the NTSC signal would not be sampled.

At the receiver, the demodulation is performed by an 8192-point FFT: it decodes the OFDM symbol by transforming the time domain block into QPSK carriers. The output of the FFT is then filtered to remove the notches, and the QPSK decoder decodes the symbols. Finally, a bit comparator determines the bit error rate (BER), by comparing the received bit sequence with the original bit sequence.

The varying parameter considered for the simulation is the desired to undesired ratio (D/U ratio), where D is the amplitude of the video carrier and U is the amplitude of the data carrier. The D/U ratio is utilised to compare the amplitude of two different signals. During the simulations, OFDM symbols were generated, one at a time, and combined with the NTSC signal until 100 bit errors were recorded. After the desired number of errors was recorded, the simulation was repeated with an increased D/U ratio. Reducing the amplitude of the data carriers, relative to the video carrier, increased the D/U ratio. This was achieved by scaling the data carriers by the different scaling factors listed in Table 5-1.

Since the coding is designed to minimize the impact each signal would have on each other, the NTSC signal does not have to be removed from the data carriers before they are decoded. Just as the data carriers do not need to be removed from the video signal before it is decoded.

Table 5-1: Scaling factors for computer simulation.

Scaling factor	D/U ratio (dB)
2.83	28
2.00	31
1.41	34
1.00	37
0.707	40
0.5	43
0.35	46
0.25	49
0.18	52
0.12	55
0.099	56.99

The variation in D/U ratio allowed the computation of a BER curve from 10^{-2} to 10^{-5}. The simulations were repeated for the signal with no notches in the spectrum and with notches of 1.2 kHz, 3.7 kHz, and 6.1 kHz. The source code for the simulation is listed in Appendix A.

5.3 Simulation Results

The following section discusses the results obtained from the computer simulations.

During the analysis of the results from section 5.3.1, it was observed that some of the carriers were severely corrupted. These errors were due to harmonics caused by the downconversion process. Using the flexibility of the encoding scheme, the width of some of the notches were widened to mitigate the impact from the interference. The definition of the modified system, labelled System II, is given in section 5.3.2.

In general, the results demonstrate that there is a gain to be achieved by increasing the width of the notches in the spectrum.

5.3.1 Data Insertion with Uniform Spectral Notch Widths (System I)

Table 5-2 lists the parameters of System I used for the simulations.

Table 5-2: Parameters for System I.

System bandwidth (kHz)	Notch width (kHz)	Number of carriers	Bit rate (kbps)
300	0	256	625.0
300	1.2	237	578.6
300	3.7	197	481.0
300	6.1	157	383.3
450	0	385	939.9
450	1.2	356	869.1
450	3.7	296	727.7
450	6.1	236	576.2
600	0	501	1223.1
600	1.2	463	1130.4
600	3.7	385	939.9
600	6.1	307	749.5

Tables 5-3 through 5-5 list the bit error rate (BER) measurements for the different values of the D/U ratios and Figures 5-3 through 5-5 graphically illustrate these results.

The source of interference for the simulation is a fixed length sample of an NTSC signal. Only 3364 8192-point samples were available for the simulation. This means that time duration for the different trials of the simulation was constant, but the number of bits transmitted depended on the number of bits under the different conditions (system bandwidth and notch width). This is demonstrated in the following tables, where the number of bits transmitted varies under the different conditions.

Table 5-3: BER measurement for 300 kHz (System I).

D/U (dB)	No notches	Notches = 1.2 kHz	Notches = 3.7 kHz	Notches = 6.1 kHz
56.99	1.52E-01	1.29E-01	1.07E-01	9.32E-02
55	1.02E-01	8.30E-02	6.09E-02	6.21E-02
52	4.00E-02	3.09E-02	3.11E-02	2.52E-02
49	2.28E-02	1.38E-02	9.12E-03	6.25E-03
46	1.10E-02	4.50E-03	3.17E-03	2.82E-03
43	4.02E-03	1.23E-03	5.47E-04	5.88E-04
40	9.86E-04	3.82E-04	2.81E-04	3.52E-04
37	2.23E-04	4.38E-05 [1]	4.09E-05 [2]	4.61E-05 [3]
34	1.28E-05 [4]	no errors [5]	no errors [6]	no errors [7]

[1] 76 errors in 1,736,736 bits transmitted.
[2] 59 errors in 1,443,616 bits transmitted.
[3] 53 errors in 1,150,496 bits transmitted.
[4] 24 errors in 1,875,968 bits transmitted.
[5] less than 1 error in 1,736,736 bits transmitted.
[6] less than 1 error in 1,443,616 bits transmitted.
[7] less than 1 error in 1,150,496 bits transmitted.

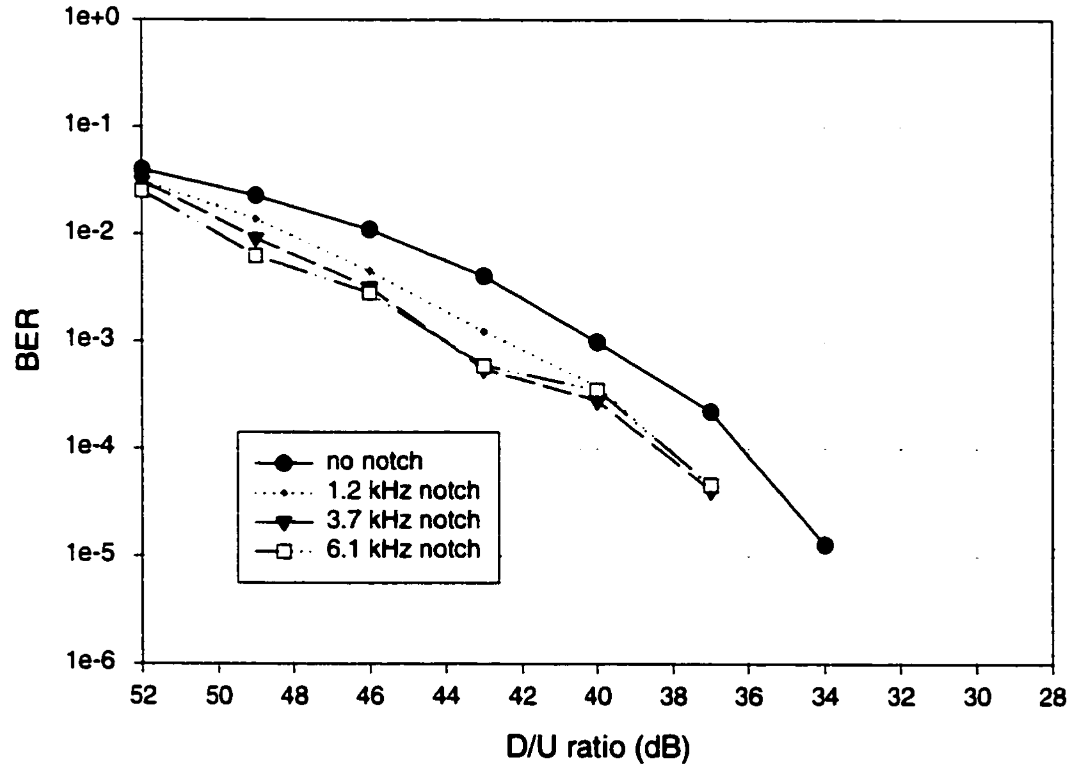

Figure 5-3: BER measurement for 300 kHz (System I).

Table 5-4: BER measurement for 450 kHz (System I).

D/U (dB)	No notches	Notches = 1.2 kHz	Notches = 3.7 kHz	Notches = 6.1 kHz
56.99	2.14E-01	1.99E-01	1.45E-01	0.153602
55	1.45E-01	1.12E-01	1.01E-01	8.62E-02
52	8.18E-02	5.06E-02	3.10E-02	3.18E-02
49	2.99E-02	2.07E-02	1.41E-02	7.74E-03
46	1.77E-02	9.17E-03	3.44E-03	2.71E-03
43	8.74E-03	2.70E-03	6.86E-04	5.07E-04
40	3.86E-03	1.11E-03	3.06E-04	3.66E-04
37	9.62E-04	2.49E-04	1.67E-04	2.24E-04
34	1.84E-04	3.37E-05 [1]	2.58E-05 [2]	3.12E-05 [3]
31	8.60E-05	no errors [4]	no errors [5]	no errors [6]

[1] 88 errors in 2,821,280 bits transmitted.
[2] 56 errors in 2,169,088 bits transmitted.
[3] 54 errors in 1,729,408 bits transmitted.
[4] less than 1 error in 2,821,280 bits transmitted.
[5] less than 1 error in 2,169,088 bits transmitted.
[6] less than 1 error in 1,729,408 bits transmitted.

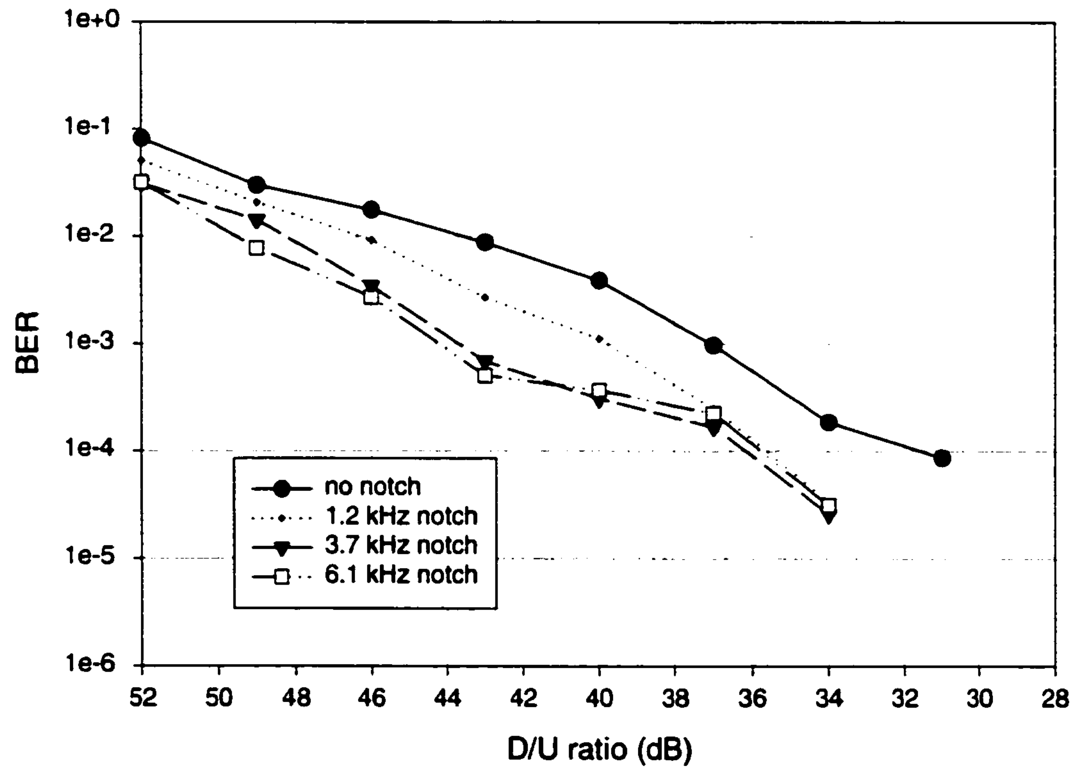

Figure 5-4: BER measurement for 450 kHz (System I).

Table 5-5: BER measurement for 600 kHz (System I).

D/U (dB)	No notches	Notches = 1.2 kHz	Notches = 3.7 kHz	Notches = 6.1 kHz
56.99	2.08E-01	1.90E-01	1.65E-01	1.73E-01
55	1.77E-01	1.43E-01	1.27E-01	1.25E-01
52	1.03E-01	8.69E-02	6.82E-02	4.07E-02
49	5.39E-02	3.05E-02	1.86E-02	1.85E-02
46	2.28E-02	1.38E-02	5.25E-03	5.23E-03
43	1.31E-02	4.91E-03	2.12E-03	2.03E-03
40	6.22E-03	1.89E-03	7.00E-04	5.58E-04
37	2.22E-03	4.35E-04	2.03E-04	2.27E-04
34	6.20E-04	1.35E-04	2.59E-05 [1]	3.16E-05 [2]
31	7.94E-05	6.19E-06 [3]	no errors [4]	no errors [5]

[1] 73 errors in 2,821,280 bits transmitted.
[2] 71 errors in 2,224,696 bits transmitted.
[3] 21 errors in 3,392,864 bits transmitted.
[4] less than 1 error in 2,821,280 bits transmitted.
[5] less than 1 error in 2,224,696 bits transmitted.

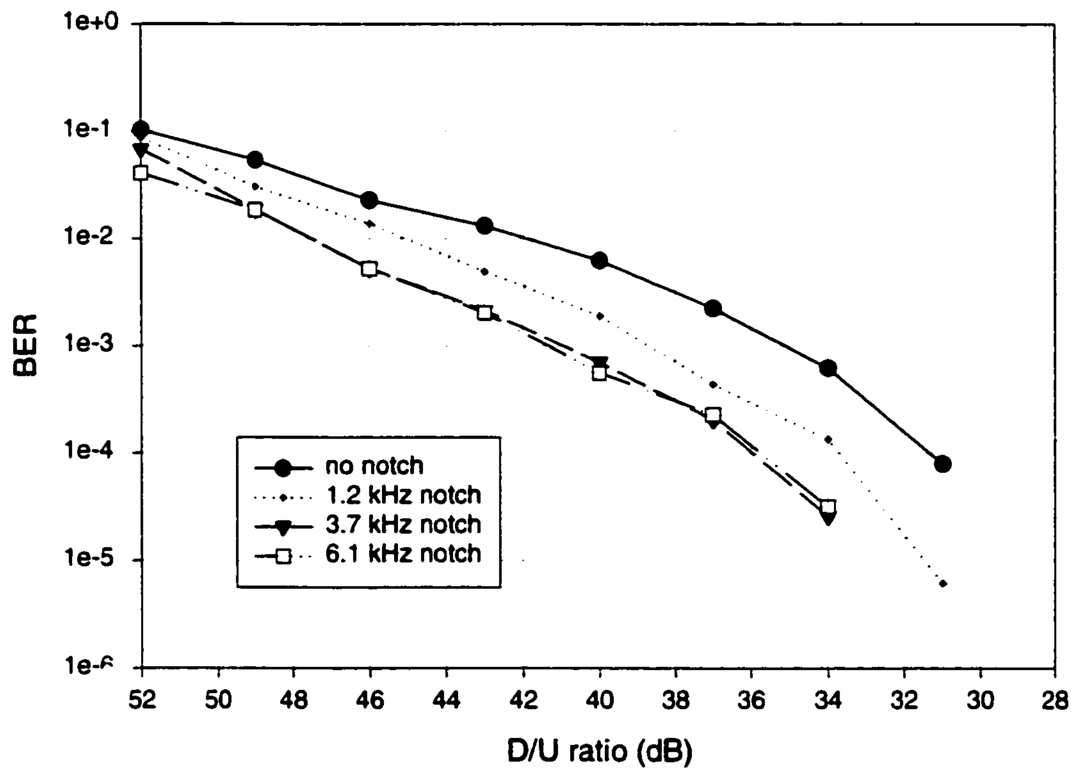

Figure 5-5: BER measurement for 600 kHz (System I).

When the notches of 1.2 kHz are inserted in the spectrum of the data signal, for the case of the 300 kHz system bandwidth, the average BER reduction is 45.8%. By increasing the notch width to 3.7 kHz, the incremental reduction in BER is 24.4% while an extra opening of the notches up to 6.1 kHz, offers an incremental reduction in the BER of only 3.4%. As the width of the notches increases, the issue becomes a problem of diminishing return: the bit error rate reduction is not worth the decrease in data capacity. Table 5-6 lists the BER reduction for each increment in the width of the notches.

Table 5-6: Bit error reduction for increased notch widths (System I).

Signal bandwidth (kHz)	No notches to 1.2 kHz	1.2 kHz to 3.7 kHz	3.7 kHz to 6.1 kHz
300	45.8 %	24.4 %	3.4 %
450	49.2 %	41.5 %	2.7 %
600	46.4 %	44.5 %	3.2 %

Table 5-7 lists the reduction in the data capacity, expressed as a percentage of the lost number of data carriers in increasing the width of the notches. The results demonstrate the decline in data capacity when the width of the notches is increased, whereas the Table 5-6 shows the improvement in BER when the width of the notches increases.

Table 5-7: Reduction in the number of carriers for increased notch width (System I).

Signal bandwidth (kHz)	No notches to 1.2 kHz	1.2 kHz to 3.7 kHz	3.7 kHz to 6.1 kHz
300	7.4 %	15.1 %	17.8 %
450	7.5 %	15.7 %	18.6 %
600	7.6 %	16.8 %	20.1 %

5.3.2 Data Insertion with Optimised Spectral Notch Widths (System II)

System II is based on the parameters of System I, the only change is the width of the some of the notches. The width of some of the notches was widened by inserting more zeros between the data carriers. Table 5-8 lists the parameters of System II including the reduction in the number of data carriers compared to System I.

Table 5-8: Parameters for System II.

Signal bandwidth (kHz)	Average width of notches (kHz)	Number of carriers	Bit rate (kbps)	Reduction in the number of carriers compared to system I
300	0	256	625.0	not applicable
300	3.5	192	468.8	45
300	5.4	162	395.5	35
300	7.3	132	322.2	25
450	0	385	939.9	not applicable
450	4.7	260	634.8	96
450	6.5	220	537.1	76
450	8.0	184	449.2	52
600	0	501	1223.1	not applicable
600	4.7	344	839.8	119
600	6.2	298	727.5	87
600	7.7	252	615.2	55

Tables 5-9 through 5-11 and Figures 5-6 through 5-8 present the BER measurements from the computer simulation using the system parameter listed in Table 5-8.

It can be seen that the highest reduction in bit rate is always for the case where the width of the notches is the smallest.

Table 5-9: BER measurement for 300 kHz (System II).

D/U (dB)	No notches	Notches = 3.5 kHz	Notches = 5.4 kHz	Notches = 7.3 kHz
52	4.26E-02	2.37E-02	2.75E-02	1.86E-02
46	1.07E-02	4.41E-03	2.25E-03	1.55E-03
40	7.88E-04	3.02E-04	6.65E-05 [1]	7.55E-05 [2]
34	1.23E-05 [3]	2.13E-06 [4]	no errors [5]	no errors [6]

[1] 79 errors in 1,187,136 bits transmitted.
[2] 73 errors in 967,296 bits transmitted.
[3] 23 errors in 1,875,986 bits transmitted.
[4] 3 errors in 1,406,976 bits transmitted.
[5] less than 1 error in 1,187,136 bits transmitted.
[6] less than 1 error in 967,296 bits transmitted.

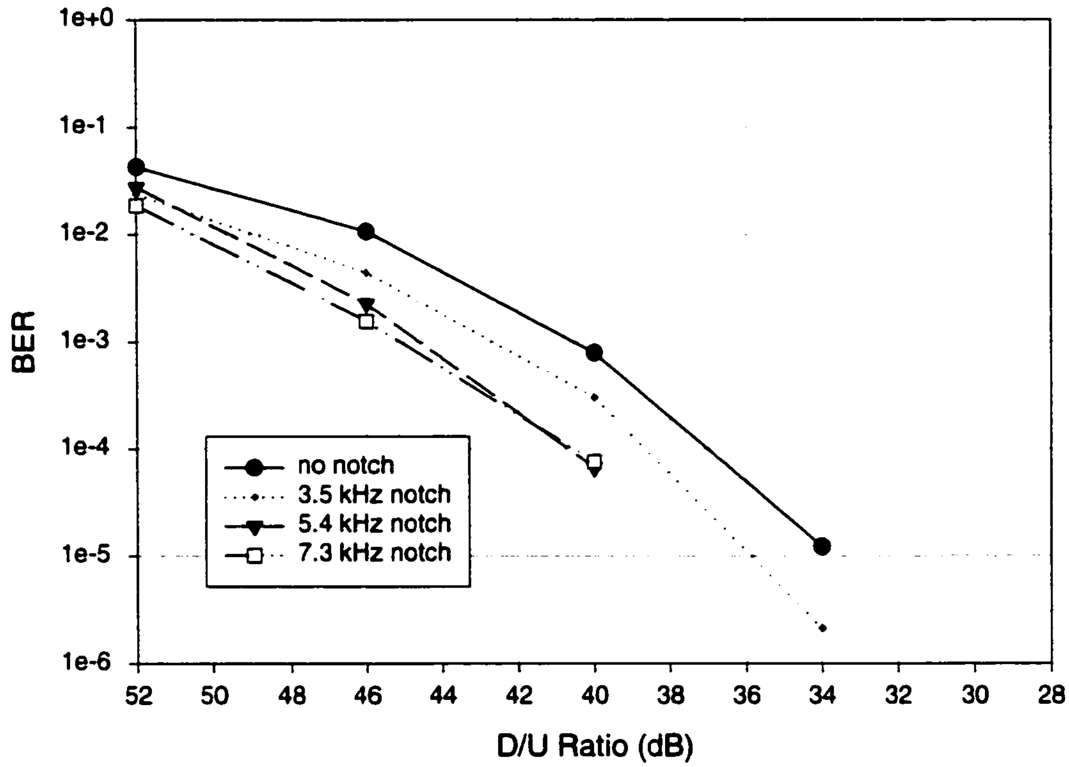

Figure 5-6: BER measurement for 300 kHz (System II).

Table 5-10: BER measurement for 450 kHz (System II).

D/U (dB)	No notches	Notches = 4.7 kHz	Notches = 6.5 kHz	Notches = 8.0 kHz
52	7.66E-02	3.21E-02	2.68E-02	2.94E-02
46	1.93E-02	3.92E-03	3.14E-03	3.04E-03
40	3.79E-03	4.10E-04	2.75E-04	3.25E-04
37	1.29E-03	7.53E-05	3.04E-05 [1]	2.97E-05 [2]
34	1.78E-04	5.25E-06 [3]	no errors [4]	no errors [5]
31	8.73E-05	no errors [7]	no errors [4]	no errors [5]
28	1.06E-05 [6]	no errors [7]	no errors [4]	no errors [5]

[1] 49 errors in 1,612,160 bits transmitted.
[2] 40 errors in 1,348,352 bits transmitted.
[3] 10 errors in 1,905,280 bits transmitted.
[4] less than 1 error in 1,612,160 bits transmitted.
[5] less than 1 error in 1,348,352 bits transmitted.
[6] 30 errors in 2,821,280 bits transmitted.
[7] less than 1 error in 1,905,280 bits transmitted.

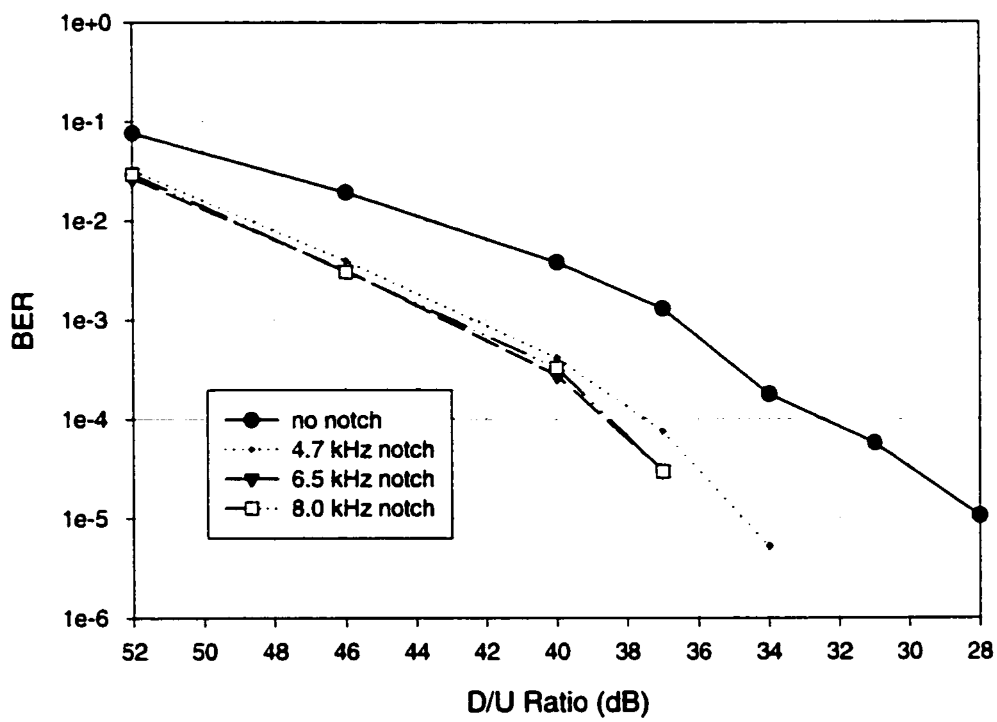

Figure 5-7: BER measurement for 450 kHz (System II).

Table 5-11: BER measurement for 600 kHz (System II).

D/U (dB)	No notches	Notches = 1.0 kHz	Notches = 6.2 kHz	Notches = 7.7 kHz
52	1.18E-01	7.56E-02	3.69E-02	4.09E-02
46	2.42E-02	9.18E-03	5.66E-03	4.31E-03
40	5.87E-03	1.01E-03	4.90E-04	4.88E-04
37	2.08E-03	2.26E-04	1.84E-04	1.88E-04
34	5.79E-04	1.94E-05 [1]	1.01E-05 [2]	1.19E-05 [3]
31	7.77E-05	1.59E-06 [4]	no errors [5]	no errors [6]
28	8.99E-06 [7]	no errors [8]	no errors [5]	no errors [6]

[1] 49 errors in 2,520,832 bits transmitted.
[2] 22 errors in 2,183,744 bits trans itted.
[3] 22 errors in 1,846,656 bits transmitted.
[4] 4 errors in 2,520,832 bits transmitted.
[5] less than 1 error in 2,183,744 bits transmitted.
[6] less than 1 error in 1,846,656 bits transmitted.
[7] 33 errors in 3,671,328 bits transmitted.
[7] less than 1 error in 2,520,832 bits transmitted.

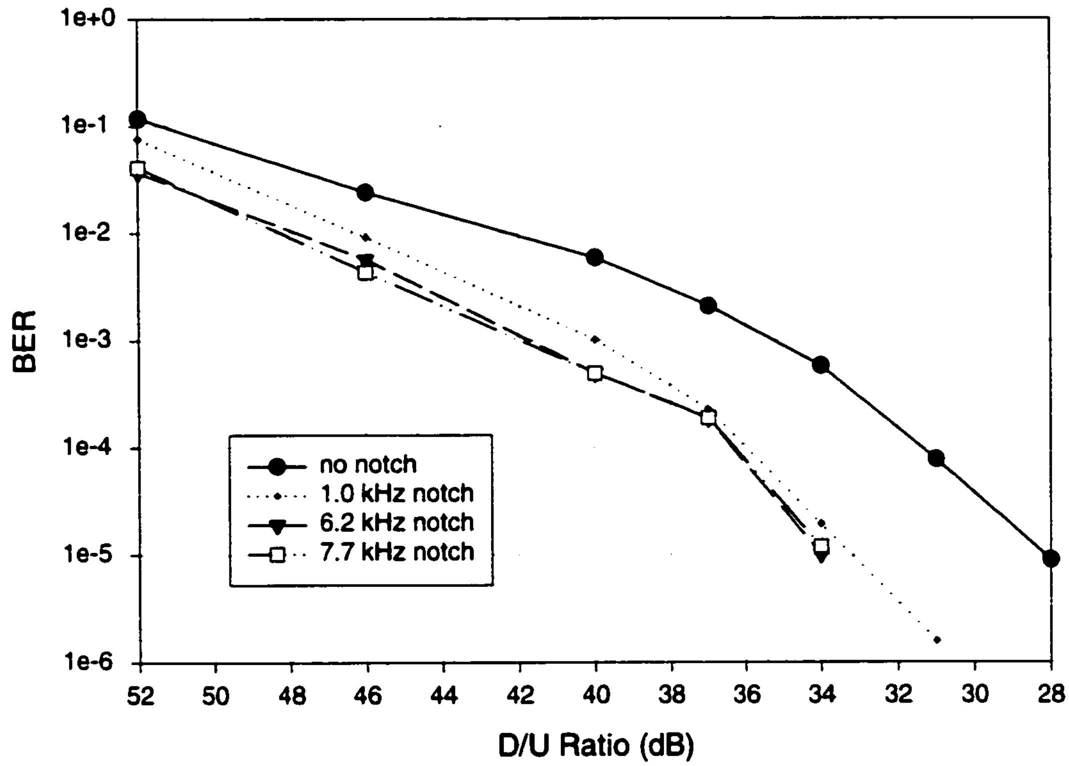

Figure 5-8: BER measurement for 600 kHz (System II).

The results for the 300 kHz bandwidth in Figure 5 -6 demonstrate that the optimum gain is achieved after the notches are widen to approximately 5.4 kHz. In Figure 5 -7 more interesting results demonstrate that for the System II with a 450 kHz bandwidth, the optimum gain in BER reduction is obtained after widening the notches to 4.7 kHz. Thi s characteristic indicates that there are no spectral components affecting the BER performance, only the noise floor of the NTSC signal.

For the 300 kHz signal, for a D/U ratio of 52 to 44 dB, there is a gradual reduction in BER as the width of the notche s increases, with the increase diminishing when the D/U ratio approaches 40 dB. For the 450 kHz signal, the results are as expected, which means that the width in the notches is wide enough to eliminate all of the errors, except for the errors due to the noise floor. Finally, the 600 kHz signal exhibits the worst performance, because the power of the video carrier has the most impact on a wide data signal.

5.4 Summary

The results of the computer simulations have demonstrated how the flexibility in shaping t he spectrum can have an impact on the performance (BER). For the system with a uniform notch width across the band, for a given bandwidth, the performance improves as the width of the notches increases.

The results in Figure 5-7 demonstrate that if the o ptimal width for the notches is chosen, the notches reduce the effect that the insertion of the video spectral components can have on the data signal. Operating with optimised notch widths offers the optimum data capacity with optimum data protection. At this point, increasing the notch widths reduces the data capacity of the system.

Due to limitation in the laboratory, only a one dimensional interference signal was combined with the data symbols. While an analysis with a complex interference signal wou ld produce slightly different BER measurements, this simulation represents the worst case scenario for the BER performance. The goal of the simulation was to demonstrate the trend in BER as the width of the notches and the bandwidth of the data signal are varied.

6 Subjective Assessment

6.1 Overview

This chapter covers the subjective assessment used to characterise the impact of the data signal on picture quality. Section 6.2 describes the method used to perform the subjective assessment. Two series of tests were performed, the first, described in section 6.3 covers the subjective assessment when a single tone is inserted in the video carrier. Section 6.4 describes the results from the second test when the influence of the multicarrier data broadcasting signal on the image quality is characterised. Finally, section 6.5 presents an analysis of the results obtained.

6.2 Subjective Evaluation

The International Telecommunication Union -Radiocommunication (ITU-R) sector has a recommendation called ITU -R Rec. 500 that defines guidelines for use when conducting subjective assessments of picture quality in television systems. The evaluation performed in this research project followed this recommendation for the use of an impairment scale, viewing distance and lighting condition.

In most cases, subjective assessments are carried out with non-expert viewers, where non-expert viewers are viewers that are not trained to detect impairments in the video quality. Since studies with non-expert viewers require a large number of participants to produce meaningful results, this study was performed with two separate tests. The first test was performed with one expert viewer and the second with three non-expert viewers.

An important aspect of subjective assessment is the choice of material that is shown to the viewers. In a study of perceived video quality, the material must be carefully chosen since some video sequences have the ability to mask the interference, while others allow the artifact to be readily noticeable. For these tests, the chosen video sequence included a variety of camera angles (i.e. close-ups, wide shots and pans) and scenes with various image content.

6.2.1 Laboratory Set-Up

The laboratory set-up used for this evaluation is shown in Figure 6-1. The source video was a composite video signal from a DVD player, playing a video sequence in a loop. The video signal was modulated to channel 12 (204-210 MHz) and combined with the signal generator. The output of the combiner was fed to a professional grade video monitor for subjective assessments and to a spectrum analyser for measurements.

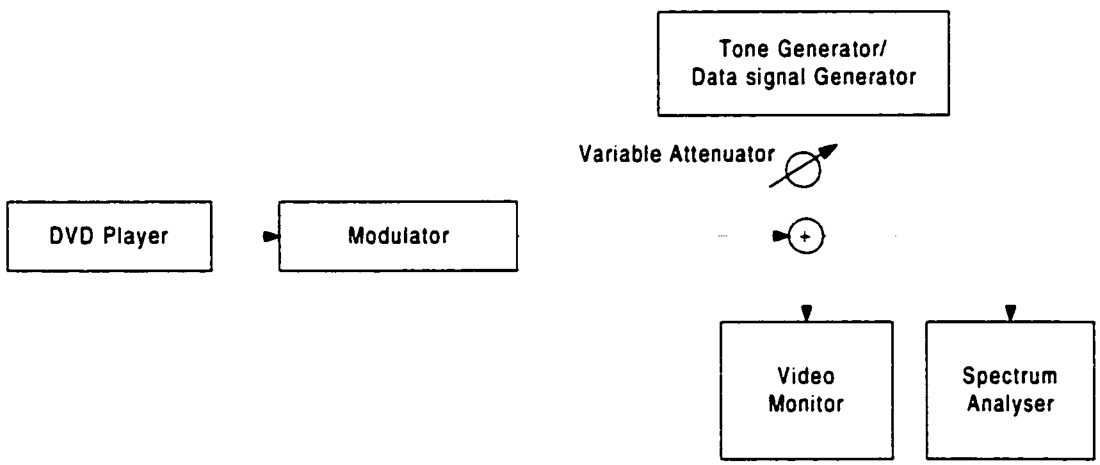

Figure 6-1: Laboratory set-up for subjective assessment.

6.2.2 Laboratory Calibration

A professional grade CRT monitor was used for expert viewing. The contrast was adjusted such that a peak white windowed signal yielded 120cd/m^2, in accordance with SMPTE Recommended Practice RP -167-1995. The brightness was adjusted using the PLUGE (Picture Lineup Generating Equipment) within the SMPTE colour bar, under low ambient lighting conditions of 5 to 6 lux. The focus, the purity, the geometry, the convergence and the overscan settings of the video monitor were verified. The chrominance amplitude and phase were adjus ted using the blue-channel-only technique. Greyscale tracking was also verified, and found to be within 5% of the optimal D6500 standard. Internal video monitor settings were such that the comb filtering was enabled and no aperture correction was applied.

6.2.3 Test Procedure

During the tests, the viewers were seated at a distance of 4H from the screen, where H represents the height of the television screen. The viewers were then asked to rate the perceptibility of the impairment in the video signal based on the ITU-R impairment scale shown in Table 6-1.

Table 6-1: ITU-R Impairment Scale.

Rating	Impairment
5	Imperceptible
4	Perceptible, but not annoying (TOV)
3	Slightly annoying
2	Annoying
1	Very annoying

To begin the test, the video sequence was shown to the viewers without interference. After an initial time period, the level of the interference signal was gradually increased until the different levels of impairment were obtained. The data points colle cted by the expert observer were threshold of visibility (TOV), slightly annoying, and annoying, while the non -expert viewers recorded TOV and annoying.

For each data point collected, the desired to undesired signal ratio (D/U) was calculated, where D is the amplitude of the interfering signal and U is the amplitude of the video carrier.

6.3 Single Carrier Wave (CW) Interference Test

The single carrier wave (CW) interference test consisted of determining the impact a single tone inserted in the vestigial sid eband would have on the picture quality. The signal generator produced a CW and swept the carrier frequency across the vestigial sideband of the video carrier.

Two separate tests were performed. The first test was conducted with the CW located between two spectral components, as in Figure 6-2 and the second test was with the CW colocated with a spectral component of the video signal, as in Figure 6 -3. For each frequency, the power of the

CW was increased until the expert viewer observed TOV and slightl   annoying impairment conditions. For each measurement, the D/U ratio was calculated.

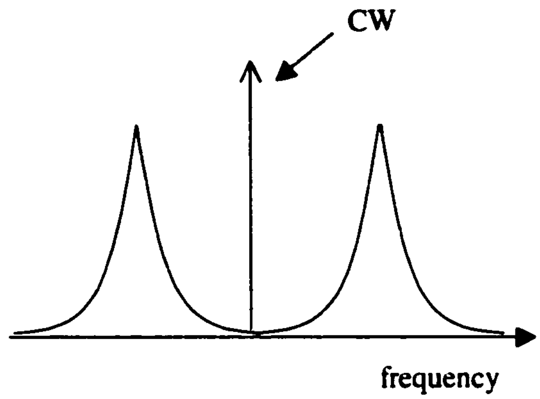

Figure 6-2: CW located between two spectral components.

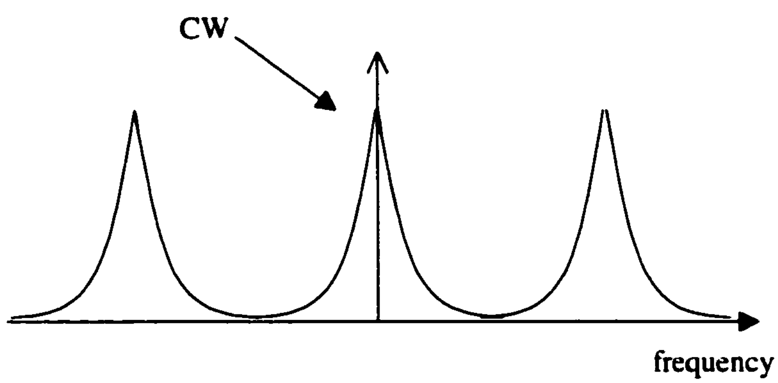

Figure 6-3: CW colocated with a spectral component.

6.3.1 Test Results

The values of D/U for the CW tone located between two spectral components are listed in Table 6-2. The values of D/U for the CW tone colocated with an NTSC spectral component are listed in Table 6-3. The results are graphically presented in Figure 6-4 and Figure 6-5 for case of the CW located between two spectral components and colocated with an NTSC spectral component respectively.

Table 6-2: D/U for CW Located Between Two Spectral Components.

Frequency (MHz)	Frequency offset from video carrier (kHz)	D/U @ TOV (dB)	D/U @ slightly annoying (dB)
204.0035	1246.5	-26.9	-13.9
204.0837	1166.3	-29.9	-18.9
204.1612	1088.8	-23.9	-17.9
204.2076	1042.4	-24.9	-13.9
204.3962	853.80	-29.9	-20.9
204.6008	649.20	-25.9	-22.9
204.8054	444.60	-37.9	-24.9
205.0097	240.30	-32.9	-27.9
205.1039	146.10	-36.9	-23.9

Table 6-3: D/U for CW Colocated with an NTSC Spectral Component.

Frequency (MHz)	Frequency offset from video carrier (kHz)	D/U @ TOV (dB)	D/U @ slightly annoying (dB)
204.0110	1239.00	-31.9	-28.9
204.0762	1173.80	-39.9	-33.9
204.1687	1081.30	-39.9	-25.9
204.2151	1034.90	-40.9	-30.9
204.4037	846.30	-39.9	-31.9
204.6083	641.70	-53.9	-42.9
204.8129	437.10	-54.9	-41.9
205.0172	232.80	-56.9	-50.9
205.1114	138.60	-52.9	-37.9

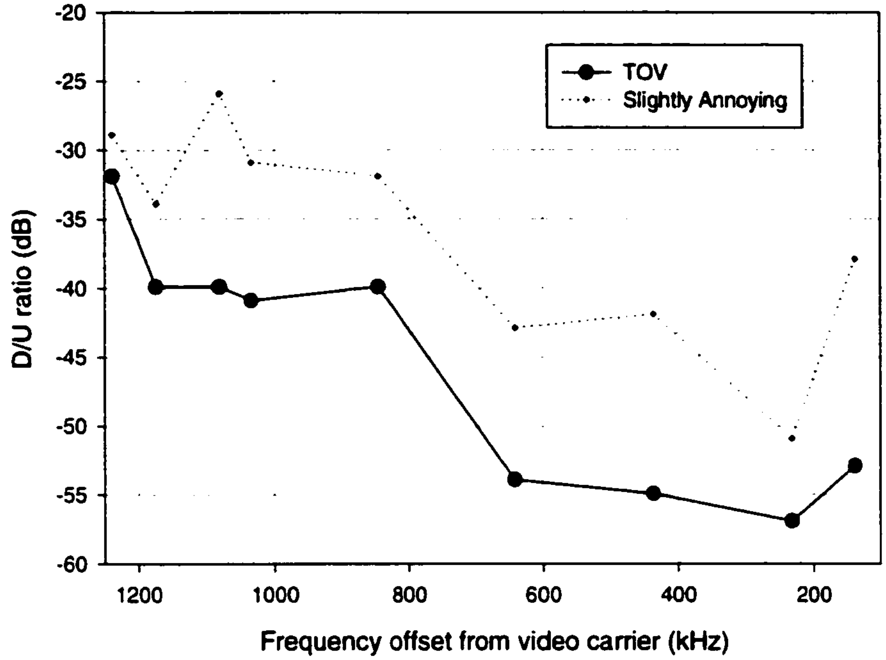

Figure 6-4: D/U for CW Located Between Two Spectral Components.

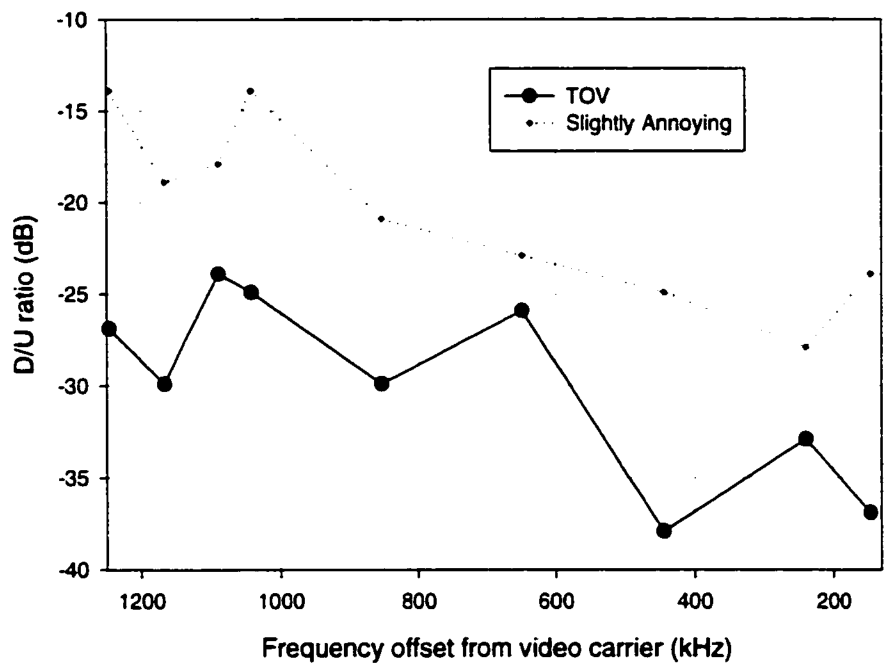

Figure 6-5: D/U for CW Colocated with an NTSC Spectral Component.

6.3.2 Observations

Figures 6-4 and 6-5 demonstrate that as the interference approaches the vi deo carrier, the D/U ratio must be increased in order to preserve the quality of the picture at the same rating. For the results in Figure 6-4, the averaged difference between the TOV and the slightly annoying rating was 9.33 dB, while in Figure 6-5, the averaged difference between the TOV and the slightl annoying rating was 9.55 dB. Which represents a constant 9 dB difference in D/U between the two impairment levels regardless of the location of the CW. The curves in Figure 6 -5 are approximately 10 dB higher than those in Figure 6-4, which shows the need for added protection when the CW overlaps a spectral component of the NTSC signal.

The interference into the NTSC is mostly manifested as stripes and lines across the picture. The characteristics that changed, when the frequency of the CW varied, were the slope and frequenc of the lines on the screen. At some frequencies, the impairment was readily visible while at others it was less perceptible.

6.4 Subjective Assessment of Data Signal into NTSC

6.4.1 Overview

The goal of this test was the same as in the previous section, except that the source of interference is now a multicarrier data signal generated by an arbitrary waveform generator. All 12 systems defined in Tables 4-1 to 4-3 are evaluated.

The OFDM data signals were generated in Matlab, saved in a file and transferred to a programmable waveform generator. The output of the generator was upconverted using a signal generator. The laboratory set-up was identical to the one described in section 6.2.1 and shown in Figure 6-1, except that the signal generator was now programmed to produce a multicarrier signal. The software code that generated the OFDM symbols for the programmable waveform generator is listed in Appendix B.

For these measurements, the amplitude of the video carrier was set to -24 dBm at the input of the receiver, and the variable attenuator controlled the amplitude of the data signal.

6.4.2 Expert Viewer

The following tables present the D/U measurements for the expert viewer. Tables 6-4 through 6-6 list the values of D/U ratios for the 300 kHz, 450 kHz and 600 kHz signals respectively.

Table 6-4: Results from 300 kHz system (expert observer).

Width of nulls (kHz)	D/U @ TOV (dB)	D/U @ slightly annoying (dB)	D/U @ annoying (dB)
0	42.40	35.40	29.40
1.2	41.40	35.40	29.40
3.7	40.40	32.40	28.40
6.1	39.40	32.40	29.40

Table 6-5: Results from 450 kHz system (expert observer).

Width of nulls (kHz)	D/U @ TOV (dB)	D/U @ slightly annoying (dB)	D/U @ annoying (dB)
0	52.40	41.40	34.40
1.2	51.40	39.40	31.40
3.7	47.40	41.40	31.40
6.1	47.40	36.40	30.40

Table 6-6: Results from 600 kHz system (expert observer).

Width of nulls (kHz)	D/U @ TOV (dB)	D/U @ slightly annoying (dB)	D/U @ annoying (dB)
0	50.40	43.40	34.40
1.2	44.40	39.40	34.40
3.7	45.40	37.40	34.40
6.1	44.40	36.40	33.40

Figures 6-6 through 6-8 illustrate the results from the above tables.

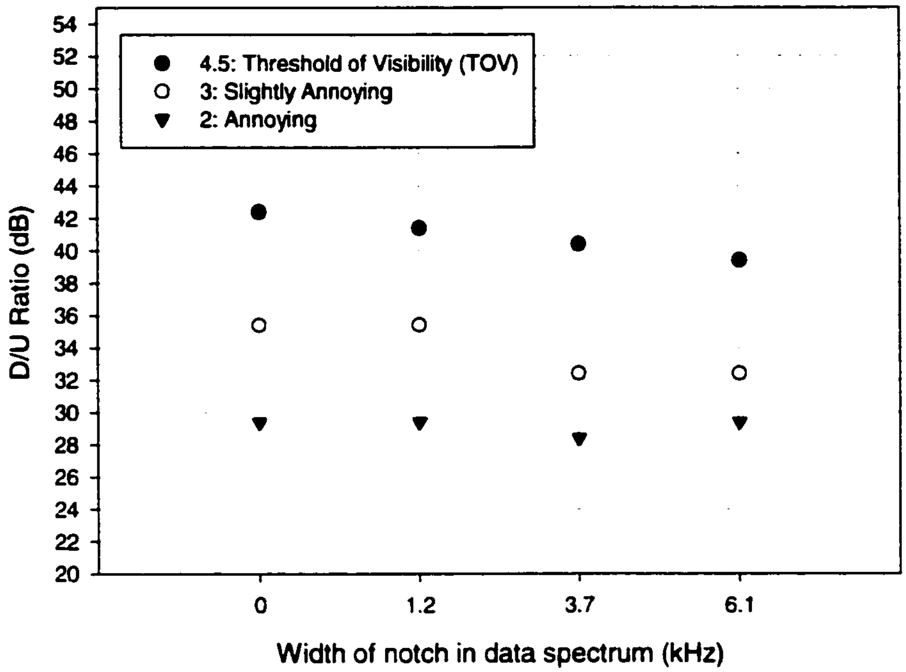

Figure 6-6: Results from 300 kHz system (expert observer).

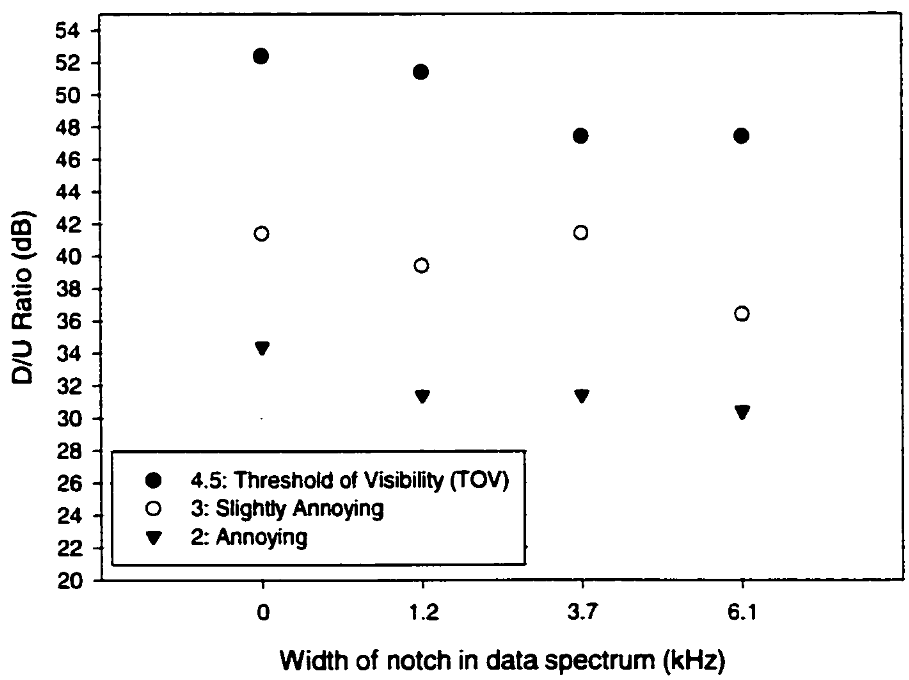

Figure 6-7: Results from 450 kHz system (expert viewer).

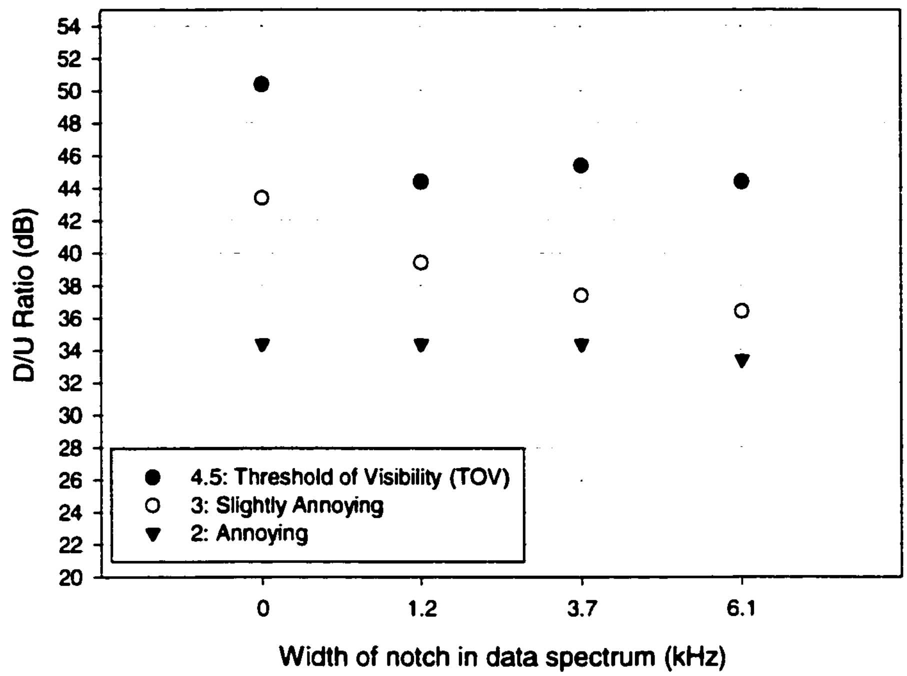

Figure 6-8: Results from 600 kHz system (expert viewer).

All of the expert viewer results express a reduction in the D/U ratio as the width of the notch increases. This indicates that by reducing the number of data carriers there is less inter ference into the video signal. In Figures 6 -6 and 6-7, the reduction in D/U ratio is almost linear for the grading of TOV and slightly annoying as the width of the notches increases, while the D/U ratios for the grading of annoying is relatively stable. This means that the degradation becomes annoying at the same level, regardless of the signal being injected in the video signal.

The results in Figure 6 -8, demonstrates the greatest change in D/U ratio, almost 6 dB, occurs when the transition from a signal with no notches to a signal with notches is encountered. There is also very little variation in the D/U measurements for TOV observations. This indicates that the 600 kHz signal is too close to the video carrier, and is the most perceptible among the three signals.

6.4.3 Non-Expert Viewers

The following results are from the same test except three non-expert viewers were used to rate the picture quality. Statistically speaking, a conclusion cannot be drawn from these results, but they are shown to demonstrate how a small sample of non-expert viewers rate a picture quality compared to an expert viewer.

Tables 6-7 through 6-9 present the numerical results and Figures 6-9 to 6-11 illustrate them. Due to the difference in expertise between the non -experts and expert viewers, no rating of slightl annoying was recorded from the non-expert viewers.

Table 6-7: Results from 300 kHz system (non-expert viewers).

Width of nulls (kHz)	D/U @ TOV (dB)	D/U @ Annoying (dB)
0	26.80	13.80
1.2	27.90	14.90
3.7	27.60	12.60

Table 6-8: Results from 450 kHz system (non-expert viewers).

Width of nulls (kHz)	D/U @ TOV (dB)	D/U @ Annoying (dB)
0	32.00	17.00
1.2	28.40	15.40
3.7	31.00	12.00

Table 6-9: Results from 600 kHz system (non-expert viewers).

Width of nulls (kHz)	D/U @ TOV (dB)	D/U @ Annoying (dB)
0	31.60	18.60
1.2	33.70	16.70
3.7	31.60	13.60

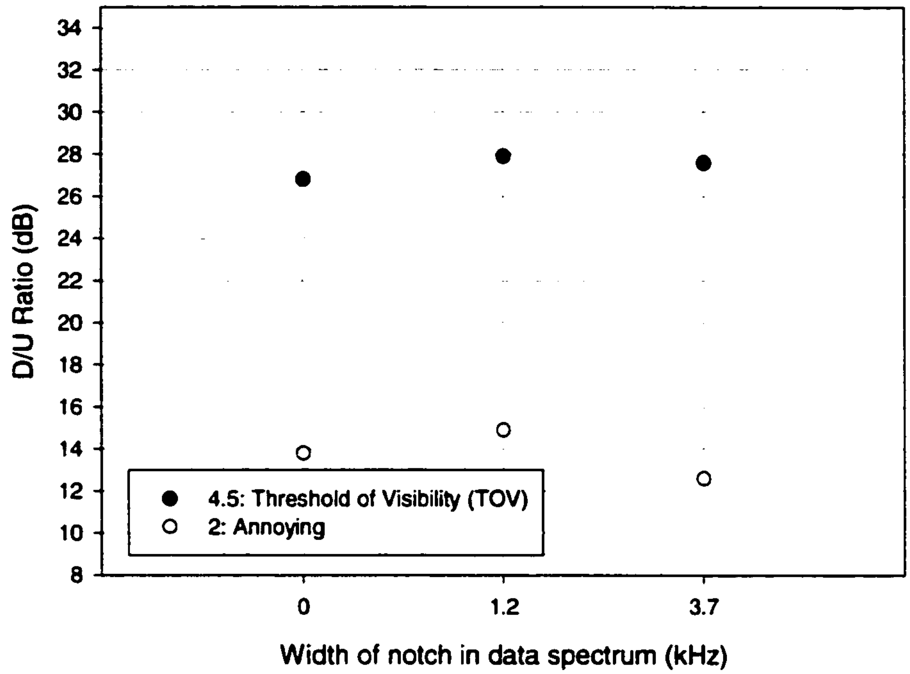

Figure 6-9: Results from 300 kHz system (non expert viewers).

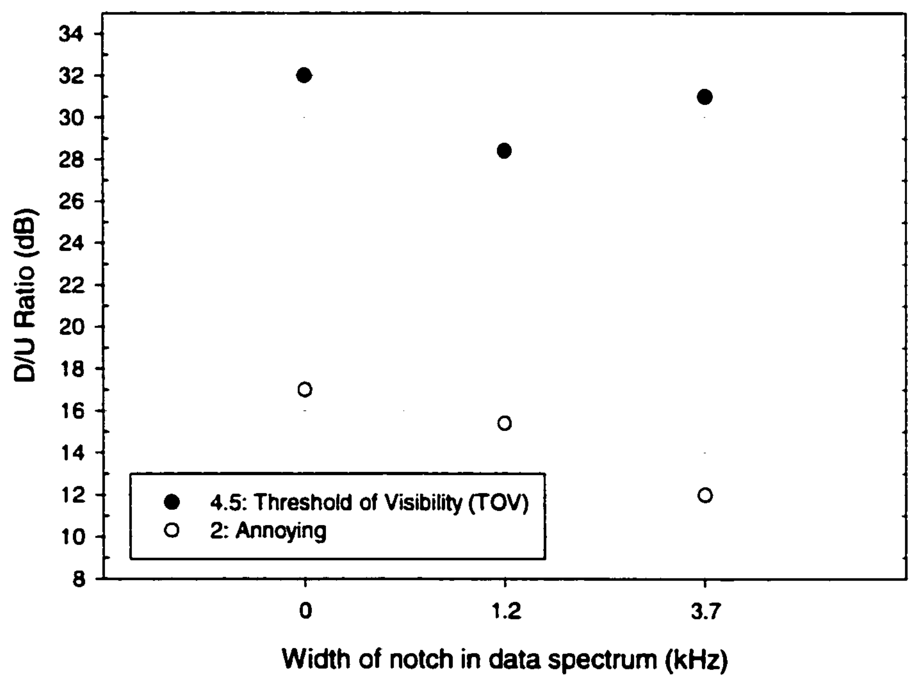

Figure 6-10: Results from 450 kHz system (non-expert viewers).

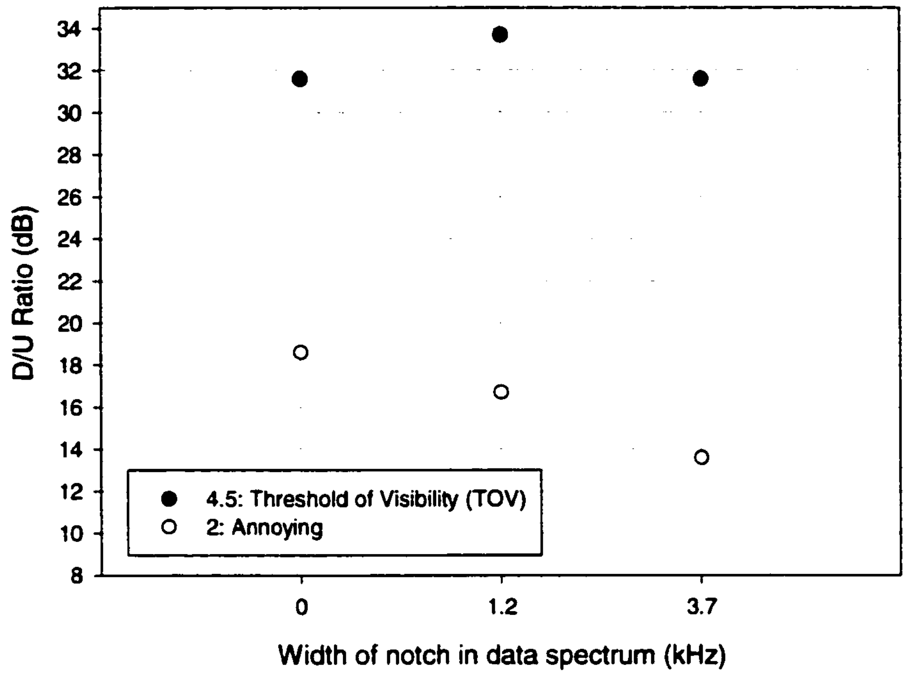

Figure 6-11: Results from 600 kHz system (non-expert viewers).

6.4.4 Observations

The results from the non-expert viewers did not demonstrate the same decreasing trend in D/U ratio as for the expert viewers. This is because non -expert viewers are not as discriminating in observing picture degradation as expert viewers are. On average, most results were within a ± 3 dB variation.

The average value for D/U @ TOV is 16.1 dB below than for the expert viewer while the value for the slightly annoying level was 17 dB below.

6.5 Analysis of Results

The subjective assessment has demonstrated two important points. The first is that inserting notches in the spectrum of the data signal, reduces the required D/U ratio for a given impairment rating and the second is that increasing the bandwidth of the data signal requires a greater D/U ratio to maintain a constant impairment rating.

To operate a system with a rating of TOV, based on an expert viewer, the average D/U ratio for the 300 kHz, 450 kHz and 600 kHz systems are 40.4 dB, 48.7 dB and 44.7 dB, respectively.

To compare with the non-expert viewers, the D/U ratios at TOV are 27.4 dB, 30.0 dB and 32.3 dB for the system bandwidth of 300 kHz, 450 kHz and 600 kHz. The trend in the non -expert viewer's results demonstrates that as the b andwidth of the signal increases, so does the requirement in D/U ratio.

7 Conclusion

The concept of an in-band multicarrier data broadcasting system for the NTSC standard has been introduced and evaluated by means of a computer simulations and subjective assessments. This chapter summarises the findings of the thesis, highlights the contributions made by the work of the thesis and describes examples of future work that would enhance the performance of the multicarrier data broadcasting system.

7.1 Summary

The two objectives set in chapter 1 have been met through computer simulations and subjective assessments. A multicarrier system can offer data rates that are higher than traditional data broadcasting techniques with a limited impact on the video quality. The multicarrier coding scheme proposed allows the system parameters to be very flexible.

The computer simulation results presented in chapter 5 demonstrate that as the bandwidth of the data signal increases, the BER performance degrades, that is, there is more power of the NTSC video carrier that is affecting the data carriers. In section 5.3.1, it is observed that for the system with no notches in the spectrum operating at a BER of 10^{-4}, the 300 kHz system has a D/U ratio of 36 dB while the 600 kHz system has a D/U ratio of 31 dB, leading to a 5 dB degradation.

To demonstrate how the D/U ratios vary under the different interference conditions and varying parameters, the approximate D/U values for a BER of 10^{-4} are given in Table 7-1. From these results, it can be observed that the required D/U ratio increases as the width of the notches is widened, which means there is less impact into the video signal.

Table 7-1: Required D/U for a BER of 10^{-4}.

Notch width	300 kHz		450 kHz		600 kHz	
	System I	System II	System I	System II	System I	System II
0 kHz	36 dB	35 dB	34 dB	34 dB	31 dB	31 dB
1.2 kHz	39 dB	38 dB	36 dB	38 dB	34 dB	36 dB
3.7 kHz	39 dB	41 dB	37 dB	39 dB	36 dB	36 dB
6.1 kHz	39 dB	41 dB	36 dB	39 dB	36 dB	36 dB

Tables 7-2 through 7-4 lists the impairment rating for the expert viewer for a BER of 10^{-4}. The results for the implementation with no notches (notch width = 0 kHz) show that the level of impairment degrades as the bandwidth of the data signal in creases. In addition the results demonstrate that the impairment rating improves as the width of the notches increases, demonstrating that inserting notches in the spectrum of the data offers additional protection to the video signal.

Table 7-2: Impairment rating (expert viewer) of 300 kHz system for a BER of 10^{-4}.

Notch width (kHz)	System I	Notch width (kHz)	System II
0	slightly annoying	0	slightly annoying
1.2	TOV	3.5	TOV - slightly annoying
3.7	TOV	5.4	better than TOV
6.1	TOV	7.3	better than TOV

Table 7-3: Impairment rating (expert viewer) of 450 kHz system for a BER of 10^{-4}.

Notch width (kHz)	System I	Notch width (kHz)	System II
0	annoying	0	annoying
1.2	slightly annoying - annoying	4.7	slightly annoying
3.7	slightly annoying	6.5	slightly annoying
6.1	slightly annoying	8.0	slightly annoying

Table 7-4: Impairment rating (expert viewer) of 600 kHz system for a BER of 10^{-4}.

Notch width (kHz)	System I	Notch width (kHz)	System II
0	worst than annoying	0	worst than annoying
1.2	annoying	1.0	slightly annoying - annoying
3.7	slightly annoying - annoying	6.2	slightly annoying
6.1	slightly annoying	7.7	slightghtl annoying

Overall, the 300 kHz system offers a better performance in picture quality, since the smaller bandwidth has less of an impact on the video carrier. A system operating with an impairment rating of TOV or better would offer a bit rate between 395 and 581 kbps, offering data rates that already match the current technologies.

An impairment that is slightly annoying to an expert viewer could be considered as imperceptible to non-expert viewers. Since most television viewers are considered non -expert viewers, a television broadcaster could choose to transmit a data with a higher bandwidth. Based on the results where the expert viewer rated the degradation as only slightly annoying, it would be possible to achieve data rates between 598 kbps and 920 kbps. Nearly doubling the data capacit of the Digideck system. The system could also operate in parallel with the WavePhore system and with all of the VBI data transmission schemes except for Teletext.

These observations performed at 10^{-4} are conservative since the errors are generated by video interference and are thereby very distributed. Unlike random noise, there is no risk of burst errors in this system, when the NTSC signal is the major source of errors. It could be possible to operate the system with a BER of 10^{-3} and use a forward error correction code that performs well in an environment with no burst of errors and reduce the error rate to an acceptable level. B observing the simulation results, the change in operating point from 10^{-4} to 10^{-3} offers an additional margin of 4 to 5 dB. Taking into account an implementation margin of 1 to 2 dB, this would leave a margin of 2 to 3 dB for system operation.

7.2 Thesis Contributions

Two major contributions were made in the study of this project. Th e first is that multicarrier modulation using the IFFT, as an encoder is a viable coding scheme for inserting data carriers within the unused portion in the vestigial sideband of the NTSC video carrier. The second contribution is the demonstration that using notches in the data spectrum mitigates the impact of the data carriers on the video quality.

The results from section 6.3 are well founded based on the information on the Digideck system. The amplitude of the data carrier in the Digideck [Jur97] system is 30 dB below the video carrier, which is exactly the same result the CW interference test obtained when the CW was about 1 MHz below the video carrier.

The coding scheme introduced in chapter 4 encodes the data in an innovative approach, since the transmission band is in essence corrupted by tone interference. By taking advantage of the coding scheme, the spectral components of the video carrier do not cause any impact on the reliability of the transmission system.

In chapter 5, the results have demonstrated that as the width of the notches in the data spectrum is widened, the performance of the communication system increases at a loss of data throughput. By observing which data carriers are affected by the spectral components, it is possible to set the width of the notches in the data spectrum to optimise the system, maximum data throughput with a minimum impact from the NTSC signal.

The results from chapter 6, summarised in Tables 7-2 through 7-4 demonstrate that for the most part, operating with a BER of 10^{-4}, produces an impairment in the video signal that would be acceptable to non-expert viewers: non -expert viewers being not as sensitive to picture qualit degradation as expert viewers. For the 300 kHz bandwidth, System II produced an impairment rating that is better than TOV.

7.3 Suggested Work for Future Research

In this section research areas are described that could merit further study in the improvement of the in-band multicarrier data broadcasting system. The objective is always to improv e the data capacity of the system without degrading the video quality of the NTSC television signal.

In this thesis, the OFDM modulation was implemented with data carrier of constant amplitude across the bandwidth of the data spectrum. Figure 7 -1 illustrates the data spectrum with data carriers of constant amplitude inserted within the vestigial sideband of the video carrier. It can be observed, in this configuration, that the noise floor of the data carrier closer to the video carrier is not as large as the noise floor at the start of the spectrum. This means that the tail end of the spectrum is more susceptible to interference from the video carrier.

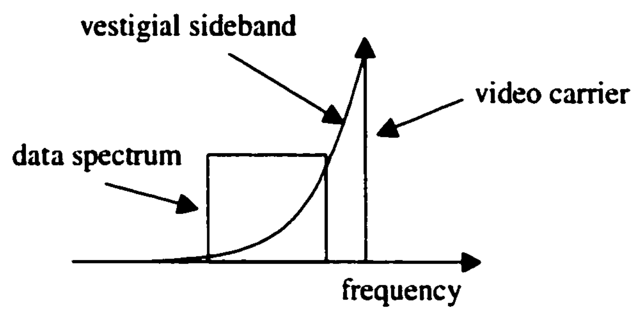

Figure 7-1: Data spectrum with constant amplitude.

To improve the performance in this situation, the shape of the spectrum could be changed to correlate with the spectrum of the video carrier. Figure 7 -2 illustrates an example where the power allocated to the data carrier at the end of the spectrum is gre ater than at the start of the spectrum. The increased noise margin should also increase the noise performance of the system. Further investigations would be needed to confirm the optimal number of carriers per 15.75 kHz interval, as the data carriers approach the video carrier frequency.

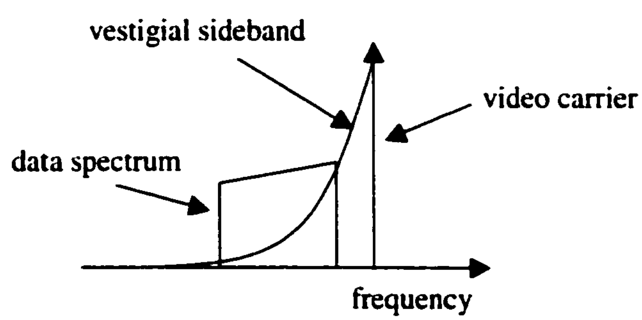

Figure 7-2: Data spectrum with varying amplitude.

A second improvement consists in increasing the spectral efficiency of the data carriers. Since this criterion is set at the input of the IFFT, it is possible to modify the data carriers on a per carrier basis. Instead of assigning the same spectral efficiency to all data carriers, as is the case in this thesis, the carriers located in the middle of the NTSC nulls, coul d have a higher spectral efficiency.

Figure 7-3 illustrates the frequency span covering three NTSC spectral components and two NTSC nulls. In each of the nulls five data carriers are inserted, the first and the fifth are QPSK carriers, while the centre c arriers can be of a higher order, for instance 8PSK or perhaps 16 QAM. The spectrum of the video carrier naturally has a lower noise floor in the middle of the nulls and this type of configuration would take advantage of this characteristic.

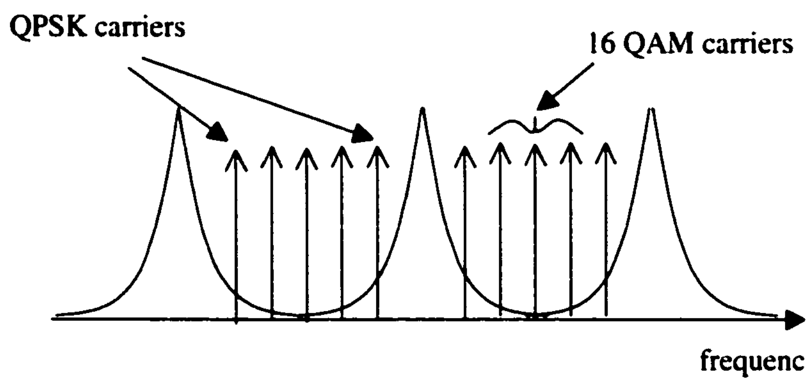

Figure 7-3: Carriers with different spectral efficiency.

Another simulation study would be to verify the robustness of the system over a transmission channel. The performance of the system should be evaluated against random noise, multipath and impulse noise.

These changes could be implemented within the MATLAB environment. The results of these new simulations could demonstrate if it would be possible to increase the data capacity of the data broadcasting system and maintain its performance. The next step in the matter of objective measurements would be to build a hardware prototype of the encoder and decoder. The evaluation of the prototype in the laboratory would confirm the computer simulation results. Another study would be to determine the robustness of the system: to study its performance under AWGN and multipath conditions.

To study in more details the issue of the subjective assessments, a series of tests could be completed with non-expert viewers. Typica lly a subjective assessment study requires 20 different subjects in order for the test results to be statistically reliable.

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Appendix A: Matlab Simulation Source Code

This appendix describes the different routines used in the MATLAB simulations of chapter 5.

A.1 LOOP_MAIN.M
A.2 MAIN.M
A.3 GEN_BIN.M
A.4 QPSK_ENC.M
A.5 G_IFFT.M
A.6 ADD_NTSC.M
A.7 G_FFT.M
A.8 QPSK_DEC.M

The control of the simulation is controlled by LOOP_MAIN.M. It defines the 12 different sets of parameters and for each set of parameters executes the MAIN.M function which is the core of the simulation. Within MAIN.M, a vector of binary symbols is generated by GEN_BIN.M. The binary symbols are encoded into QPSK carriers by the QPSK_ENC.M function. The G_IFFT.M function assigns the data carriers to the correct bin at the input of the IFFT and generates the OFDM symbol by computing an 8192-point IFFT. The OFDM symbol is scaled and combined with an 8192-point sample of the NTSC signal in the ADD_NTSC.M function.

At the receiver, the G_FFT.M function decodes the OFDM symbol into QPSK carriers. The QPSK carriers are decoded into data bits by the QPSK_DEC.M function. The MAIN.M function then computes the bit error rate by comparing the receive d bit sequence to the original bit sequence. The result is stored in an array and repeated until 100 bit errors are recorded.

A.1 Source Code for "LOOP_MAIN.M"

Function: defines the parameters for the simulation and loops the simulation program for the different symbol combination and the different bandwidths

Input:

- none

Output:

-Save results in result_data array.

Variables:

- para: array containing bandwidth, number of nulls and number of data carriers
- l: index to loop through the 12 combinations of the para arra
- h: number of notches in data spectrum
- bw: bandwidth of data spectrum
- num_of_cara: number of data carriers

```
para(1,1)=300; para(1,2)=0; para(1,3)=256;
para(2,1)=300; para(2,2)=1; para(2,3)=192;
para(3,1)=300; para(3,2)=3; para(3,3)=162;
para(4,1)=300; para(4,2)=5; para(4,3)=132;

para(5,1)=450; para(5,2)=0; para(5,3)=385;
para(6,1)=450; para(6,2)=1; para(6,3)=260;
para(7,1)=450; para(7,2)=3; para(7,3)=220;
para(8,1)=450; para(8,2)=5; para(8,3)=184;

para(9,1)=600; para(9,2)=0; para(9,3)=501;
para(10,1)=600; para(10,2)=1; para(10,3)=344;
para(11,1)=600; para(11,2)=3; para(11,3)=298;
para(12,1)=600; para(12,2)=5; para(12,3)=252;

for l =1:12
        bw = para(l,1);
        h = para(l,2);
        num_of_car r= para(l,3);
        main;
        eval(sprintf('save result_data %i_%i.txt result -ascii',h,bw))
end
```

A.2 Source Code for "MAIN.M"

Function: the simulation program
Input:
- none

Output:
- Save results in result_data array.

Variables:
- FFT: size of the Fourier transform
- offset: frequency offset for location of data carriers
- count_limit: maximum number of iteration that can be computed, due to limit in sampled NTSC signal
- err_loc_index :
- err_ind:
- fn: filename where the carrier location is recorded
- data_index: location of the data carriers
- noisefact: factor by which the data signal is multiplied before being added to the NTSC signal
- loop_count: number of current iteration
- num_err
- num_of_carr : number of data carriers at the input of the IFFT
- s1: vector of source data bits
- s2: vector of source QPSK carriers
- s3: OFDM symbol
- s4: sum of OFDM symbol and NTSC signal
- s5: vector of received QPSK carriers
- s6: vector of received data bits

```
FFT = 8192;
fs=10;
offset=0;
count_limit = 3663; % max number of loops
err_loc_index = 0;
err_ind =1;
eval(sprintf('fn="sys%i_%i";',bw,h)); % filename with carrier location
eval(sprintf('load %s.txt',fn));
eval(sprintf('data_index = %s;',fn))
eval(sprintf('clear %s',fn));
noisefact=[2,2.83,1.41,1.0,0.707,0.35,0.176]% scaling factor for desired D/U ratio
for p=1:(length(noisefact))
        noise = noisefact(p);
        loop_count = 0 ;
        num_err = 0;
        while (num_err < 100)
```

```
        s1 = gen_bin(2*num_of_carr);          % generate the bits for the symbol
        s2 = qpsk_enc(s1);                    % encode the bits onto QPSK
        s3 = g_ifft(s2,fs,FFT,data_index,offset);
        s4 = add_ntsc(s3,noise,loop_count+1);
        if (loop_count ==-1)
                n_data= s3*noise;
                c=pow(n_data);
        end
        s5 = g_fft(s4,8192,data_index,offset);
        s6 = qpsk_dec(s5);
        num_err = num_err + sum(xor(s6,s1));
        if (sum(xor(s6,s1)) ~= 0)
                err_loc(err_ind,:)=xor(s6,s1);
                err_loc_index(err_ind,:)= loop_count+1;
                err_ind = err_ind+1;
        end
        loop_count=loop_count+1;
        if loop_count > count_limit
                break;
        end
        num_err;
        disp(loop_count)
    end
    ber = num_err/(loop_count*length(s1));
    result(p,1) = noise;
    result(p,2) = ber;
    result(p,3) = num_err;
    result(p,4) = loop_count;
    save result.mat result
    save result.txt result -ascii
    if loop_count > count_limit
            break;
    end
end
```

A.3 Source Code for "GEN_BIN.M"

Function: generates a vector of random binary digits of length len
Input:
- length of vector

Output:
- vector of random bits

Variable:
- none

```
function bin=gen_bin(len)
bin=fix(2*rand(1,len));
```

A.4 Source Code for "QPSK_ENC.M"

Function: generates QPSK symbols from a vector of binary digits
Input:
- vector of binary digits

Output:
- vector of QPSK symbols

Variables:
- num: number of bits in input vector
- lngth: number of samples for QPSK vector
- S1_I: real component of QPSK symbol
- S1_q: imaginary component of QPSK symbol
- ctr: counter of symbols generated
- ptr: pointer to locate bits in input vector
- lp: local pointer between the 2 bits
- bits: vector of two bits
- -vali = value of the encoded I component
- -valq = value of the encoded Q component
- -symbols: vector of QPSK symbols

```
function symbols = qpsk_enc(bits)
num = length(bits);
lngth = length(bits)/2;
s1_i=1:z_lngth;
s1_q=1:z_lngth;
ctr=0;
% Encoding begins
while ctr-1 < ((num/(2))-1)  % times 2 because QPSK
        ptr = ctr*nb_pts*(2)+1; % times 2 because QPSK
        for lp=0:1
                bits(lp+1) = bits(ptr + lp);
        end
        vali = (-2*bits(1))+1;  % convert 2-bit word for I to decimal
        valq = (-2*bits(2))+1;
        s1_i(ctr+1) = vali;
        s1_q(ctr+1) = valq;
        ctr = ctr+1;
end
symbols = s1_i+j*s1_q;
```

A.5 Source Code for "G_IFFT.M"

Function: generates an OFDM symbol
Input:

- data: vector of QPSK carriers
- fs : sampling rate
- FFT_size : size of Fourier transform
- data_index:
- offset: offset in the position of the carriers at the input of the IFFT

Output:

- ofdm: OFDM symbol

Variables:

- inp: vector of zeros
- len:
- I
- Index

```
function ofdm = g_ifft(data,fs, FFT_size,data_index,offset)

fs = fs*1e6;
data_index = data_index + offset;
inp=zeros(1,FFT_size);
len=length(data_index(:,1));
i=1;
for index = 1:len
        for m = data_index(index,1):data_index(index,2)
                inp(m)=data(i);
                i=i+1;
        end
end
ofdm = ifft(inp);
```

A.6 Source Code for "ADD_NTSC.M"

Function: adds NTSC and OFDM symbol

Input:

- data: OFDM symbol
- gain: value by which the symbol is multiplied before combining
- l: pointer in the NTSC vectors

Output:

- summ: sum of the NTSC and OFDM symbol

Variables:

- ntsc: 8192 sample of the NTSC signal
- xa:product of the gain and the data signal

```
function summ=add_ntsc(data,gain,l)

cd cjoh\mat
eval(sprintf('load ntsc_%i',l))
cd ..\..
eval(sprintf('ntsc=ntsc_%i;',l))
xa=data*gain; % reduce amplitude of the data
summ = xa+ntsc';
```

A.7 Source Code for "G_FFT.M"

Function: decodes the OFDM symbol
Input:

- ofdm: OFDM symbol
- FFT_size: size of the Fourier transform
- data_index: vector with the location of the data carriers
- offset:offset in the location of the data carriers

Output:

- data: vector of QPSK carriers

Variables:

- post: FFT of the input OFDM symbol
- len: number of data carriers to be recovered
- I: index for the number of QPSK carriers
- Index
- M: index of the number of interval

```
function data = g_fft_var(ofdm, FFT_size,data_index,offset)
post=fft(ofdm);
data_index = data_index + offset;
len = length(data_index(:,1));
i = 1;
for index =1:len
        for m = data_index(index,1):data_index(index,2)
                data(i)=post(m);
                i=i+1;
        end
end
```

A.8 Source Code for "QPSK_DEC.M"

Function: decodes the QPSK carriers

Input:

- symbols: vector of QPSK symbol

Output:

- bits: vector of bits

Variables:

- i_channel: real component of QPSK symbol
- q_channel: imaginary component of QPSK symbol
- l: bit counter
- b: symbol counter

```
function bits = qpsk_dec(symbols)

i_channel = real(symbols);
q_channel = imag(symbols);
l=1;
for b = 1:length(symbols)
	bits(l) = ((i_channel(b)-1)/(-2));
	% slicer
	if (bits(l) <=0.5)
		bits(l) = 0;
	else
		bits(l) = 1;
	end
	bits(l+1) = ((q_channel(b)-1)/(-2));
	% slicer
	if (bits(l+1) <=0.5)
		bits(l+1) = 0;
	else
		bits(l+1) = 1;
	end
	l=l+2;
end
```

Appendix B: Matlab Source Code for Generating OFDM Signals

This appendix describes the different routines used in the MATLAB simulations of chapter 6.

B.1 MAIN_AWG.M

For the subjective assessments, the source of the signal was an programmable waveform generator programmed to output the OFDM signal. The source code listed in section B.1, was used to generate the 12 different combinations of signal bandwidth and notch widths. Before running this code, the selection of bandwidth and width of the notches had to be chosen. The process generated a vect or of bits (GEN_BIN.M), which was encoded by a QPSK encoder (QPSK_ENC.M). The QPSK symbols were then placed at the input of a 16384 -point IFFT to produce an OFDM symbol. The sampling rate of the AWG was set to 17.2032 MHz which produced a carrier spacing (Δf) of 1.05 kHz per point, the closest match to the system parameter in listed in Chapter 4. The OFDM symbol is saved to file in ASCII format and the software uses a routine to transform the ASCII file into a binary file that the AWG can read.

B.1 Source Code for "MAIN_AWG.M"

Function: generates OFDM symbols for the programmable waveform generator
Input:

-none

Output:

- OFDM symbol in a binary file format

Variables:

- null: number of nulls
- ind: index to determine bandwidth of data signal
- bw_fn: bandwidth for filename
- num_symb: number of symbols to generate
- start: start bin for the data at the input of the IFFT
- stop: stop bin for the data at the input of the IFFT
- num_of_carriers: number of data carriers
- inp: input vector to IFFT
- s1: binary data
- s2: QPSK symbol
- s3: IFFT output
- s6_1: real vector of IFFT symbol
- s6_2: imaginary vector of IFFT symbol

```
% Make your choice
% 1) width of notches: 0,1, 2 or 3
% 2) ind = index for stop, determines the BW
%       1 = 300 kHz, 2 = 450 kHz, 3 = 600 kHz, 4 = 1000 kHz

null=0;
ind=3; % bw index
bw_fn = 600; % for the filename
num_symb = 2;
start = 2857;           %start point for all signals
stop(1) = 3143;         %stop for 300 kHz wide signal
stop(2) = 3286;         %stop for 450 kHz wide signal
stop(3) = 3429;         %stop for 600 kHz wide signal
stop(4) = 3809;         %stop for 1000 kHz wide signal
res= 1050; % resolution per point fs/FFT, FFT = 16k, Fs= 17.2032 MHz

num_of_carriers = stop(ind)-start+1
s1=gen_bin(2*num_of_carriers*num_symb);
s2=qpsk_enc(s1);

for symb=1:num_symb
        inp=zeros(1,16384);
```

```
        start1 = start+null;
        stop1 = stop(ind);
        start2 = 1+(symb-1)*(num_of_carriers);
        stop2 = (symb)*(num_of_carriers);
        inp(start1:stop1)=s2(start2:stop2);
        s3= ifft(inp);

        s6_1=real(s3);
        s6_2=imag(s3);
        save s6_1.asc s6_1 -ascii -double
        save s6_2.asc s6_2 -ascii -double
% convert ASCII file to AWG binary file format
        disp('asc2wfm channel 1')
        eval(sprintf('!asc2wfm s6_1.asc %i_%i%ia.wfm',bw_fn,null,symb))
        disp('asc2wfm channel 2')
        eval(sprintf('!asc2wfm s6_1.asc %i_%i%ib.wfm',bw_fn,null,symb))
end
```