Satellite DVB versus S-UMTS for multicast/broadcast

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Abstract

Future mobile phone systems may include multicast and broadcast services to complement current terrestrial voice and data full duplex services. Due to their wide area coverage and point to multipoint capability, satellites are seen as an ideal form of delivery.

Candidate systems for satellite transmission to mobiles of multicast and broadcast services are based on DVB-S, S-UMTS, DAB-S and the DARS system, which use coherent QPSK, W-CDMA(QPSK and 16QAM), COFDM(pi/4DQPSK) and coherent QPSK respectively.

Two key technical aspects involved in the design of such a system, are the effects on the transmission by the satellite high power amplifier and by the propagation channel.

For each scheme, HPA spectral regrowth and link BER shall be simulated for various amounts of OBO in the HPA. In addition, link BER shall be simulated for satellite and terrestrial paths using narrowband and wideband channel models. Finally, the combined effect of the HPA non-linearity and the channel shall be simulated.

A comparison between the candidate systems based on their performances through the HPA and channel shall be made by using a detailed link budget using the simulation results above as inputs, culminating in a recommendation for multicast/broadcast. Other factors including cost and viability shall be discussed.

Abbreviations

3G	Third generation
ACPR	Adjacent channel power ratio
ACTS	Advanced communications technologies and services
AM	Amplitude modulation
ARQ	Automatic repeat request
AWGN	Additive white Gaussian noise
BER	Bit error rate
BGAN	Broadband global area network
BPSK	Binary phase shift keying
BRAN	Broadband radio access networks
CCSR	Centre for Communication Systems Research
CD	Compact disc
CDMA	Code division multiple access
COFDM	Coded orthogonal frequency division multiplex
CONUS	Continental United States
dB	DeciBels
DAB	Digital audio broadcast
DARS	Digital audio radio service
DC	Direct current
DCS	Digital mobile communication system
DPSK	Differential phase shift keying
DQPSK	Differential quadtature phase shift keying
DRM	Digital radio mondiale
DTH	Direct to home
DVB	Digital video broadcast
DVB-RCS	Digital video broadcast return channel for satellites
Eb/No	Energy per bit divided by noise power spectral density
EDGE	Enhanced data rates for GSM evolution
FDD	Frequency division duplex
FDMA	Frequency division multiple access
FFT	Fast Fourier transform
FM	Frequency modulation
G/T	Antenna gain to system noise temperature ratio
GAN	Global area network
GEO	Geostationary Earth orbit
GEOCAST	Multicast over geostationary satellite
GMSK	Gaussian minimum shift keying
GPRS	General packet radio systems
GSM	Global system for mobile communications, Groupe Speciale Mobile
HEO	Highly elliptical orbit
HF	High frequency
HIPERLAN	High performance radio LAN
HPA	High power amplifier
IBO	Input backoff
ICI	Inter-carrier interference
IEEE	Institution of electrical and electronic engineers
IFFT	Inverse fast Fourier transform

IP	Internet protocol
IQ	Inphase/Quadrature
IS-95	Interim standard 95
ISDN	Integrated services digital network
ISI	Inter-symbol interference
IST	Information Society Technologie
LAN	Local area network
LEO	Low Earth orbit
LOS	Line of sight
MEO	Medium Earth orbit
MP3	MPEG2 layer 3
MPE	Multi-protocol encapsulation
MPEG	Motion pictures expert group
OBO	Output backoff
OFDM	Orthogonal frequency division multiplex
OQPSK	Offset quaternary phase shift keying
OVSF	Orthogonal variable spreading factor
PCS	Personal communications system
PM	Phase modulation
PN	Pseudo noise
PSK	Phase shift keying
PSTN	Public switched telephone network
RELP	Residual excited linear predictive coding
RF	Radio frequency
RRC	Root raised cosing
Q	Quality factor
QAM	Quadrature amplitude modulation
QPSK	Quadrature phase shift keying
SATIN	Satellite-UMTS IP-based network
SCPC	Single channel per carrier
S-UMTS	Satellite-UMTS
SSPA	Solid state power amplifier
TDD	Time division duplex
TDM	Time division multiplex
TDMA	Time division multiple access
TV	Television
TWTA	Travelling wave tube amplifier
UHF	Ultra high frequency
UMTS	Universal mobile telecommunications systems
UK	United Kingdom
US	United States
VHF	Very high frequency
W-CDMA	Wideband-CDMA
WLAN	Wireless LAN
xDSL	x Digital subscriber line, where x is A for asymmetric and V for very high bit-rate for example

List of Figures

List of Tables

Contents

1 Introduction

Future mobile phones shall offer a vast portfolio of revenue generating multimedia applications, many of which shall require highly asymmetric data. In order to deliver these services, 3G operators will have to use very small cell sizes to meet the downlink capacity demand whilst the uplink capacity may be under-utilised. This inefficient network use is expensive and 3G mobile operators should consider using broadcast technology to complement their network. Satellite broadcasting can save on network traffic by not having to distribute network traffic to every base station and increase spectrum efficiency by not tying up an RF channel in every cell.

Although mobile-satellite communications has not always been successful, broadcasting and multicasting to mobiles is seen as an ideal application for satellites due to their wide area coverage and strengths in point to multipoint communications.

To complement terrestrial UMTS, satellite UMTS is being developed to provide seamless global UMTS coverage. S-UMTS is also being considered for multicasting. However, S-UMTS may not be the optimum form of delivery for broadcast and multicast services and systems based on DVB-S, DAB-S and the American DARS are being considered.

Most satellite broadcasting technology today uses quaternary phase shift keying modulation because it is less susceptible to the effects from the non-linear satellite power amplifier and the power amplifier can be operated efficiently near saturation. However S-UMTS uses spread spectrum code division multiple access with QPSK modulation, which is more susceptible than quaternary phase shift keying to these non-linear effects, and the satellite power amplifier has to be operated backed off. Also, DAB-S, which uses orthogonal frequency division multiplex modulated by pi/4 DQPSK is highly susceptible to the satellite non-linearity and has to be backed off. These non-linear satellite power amplifier effects cause spectral regrowth causing interference to adjacent channels and increases in BER.

The first half of this project is to investigate the differences between quaternary phase shift keying, code division multiple access and orthogonal frequency division multiplex schemes when transmitted through a non-linear satellite power amplifier.

Delivery of the transmission from the satellite to the mobile can be direct or, where the signal is not strong enough, can be boosted by a terrestrial repeater. The mobile-satellite propagation channel is modelled by taking path loss, Rayleigh plus shadowing or Ricean fading, Doppler shift, delay, noise and interference into account. When the transmission bandwidth is small compared to the channel coherence bandwidth, a narrowband channel model can be used; otherwise, a wideband channel

is used. The repeater-mobile propagation channel is modelled by taking path loss, shadowing, Rayleigh fading, Doppler shift, noise and interference into account. Again, narrowband and wideband models are applied depending on the transmission bandwidth.

The second half of this project is to investigate the differences between quaternary phase shift keying, code division multiple access and orthogonal frequency division multiplex modulation schemes when transmitted through these channels. The ways in which each modulation scheme overcomes wideband channel impairments shall be investigated by simulation. Ways to mitigate the resulting narrowband fading shall be discussed. The combined effects from the HPA and channel combined shall then be simulated.

To make a recommendation for multicast/broadcast, a comprehensive forward path link budget shall be presented using the simulation results as inputs. It will then be possible to establish which system is best from a link margin/availability viewpoint. After discussing other factors including cost and viability, a recommendation for satellite multicast/broadcast shall be made.

The rest of this project report is split into six main sections. First, all the background reading is presented in summary, where current mobile and broadcast systems are explained and the need for mobile operator and broadcaster convergence is highlighted. This leads up to the ideal role satellites can play in the picture for mobile broadcast and multicast. Then, each candidate modulation technique shall be described giving details of the simulation test benches and results in an AWGN channel. Thirdly, the satellite high power amplifier simulations are presented showing output backoff requirements to achieve the same adjacent channel power and BER versus Eb/No curves for each backoff. Then the channel models are described before presenting the channel simulation results. Next, the combined effect of HPA non-linearity and the propagation channel shall be given. Finally, each system shall be compared using a detailed link budget.

2 Project Background

2.1 Introduction

There are currently many highly successful terrestrial mobile and satellite broadcast systems available today in addition to traditional analogue terrestrial broadcast systems. There have been many attempts at creating a business using satellite mobile and digital terrestrial broadcast systems that have not fared as well.

In the UK, there are five 3G licence holders, with Hutchison, a new player planning terrestrial 3G mobile services for availability in Sept 2002. Although ideal for many applications, these UMTS systems may struggle with high bit-rate high-quality audio and video broadcasting and many satellite and terrestrial broadcasting companies are suggesting complementing terrestrial UMTS with DVB and/or DAB broadcasting technology. In addition, satellites are being proposed for multicast/broadcast due to their wide area coverage and suitability for point to multipoint communications.

This chapter starts by giving brief descriptions of the current systems available offering mobile and broadcast services via terrestrial and satellite means, then describes the likely applications and services including multicasting and broadcasting. The ideal and likely convergence of broadcast and mobile systems shall then be discussed before detailing an optimum use of satellites - to broadcast and multicast to mobiles. The current research in this area will be discussed paying attention to those investigating satellite broadcast / multicast services. This poses many technical challenges, two of which will be investigated in depth in this project – the mobile-satellite channel and the effect of satellite HPA non-linearity.

2.2 Survey of Mobile and Broadcast Wireless Systems

2.2.1 Terrestrial Mobile Communications

2G Systems: GSM

The highly successful GSM system has generated large revenues for mobile telecommunication operators worldwide in its various forms of GSM900, DCS1800 and PCS1900 for over ten years. It was designed to supplement the traditional telephony architecture and is therefore primarily a circuit switched service designed for voice traffic and full-duplex symmetrical data up to 14.4kbps. The system uses FDD/TDMA modulated with GMSK with one timeslot allocated to each user in each direction. With the massive interest in the Internet since 1995, mobile operators aimed to exploit the demand for data by offering higher bit rates to a mobile terminal. [2]

2.5G Systems: GPRS, EDGE

GPRS offers customers increased data rate using a new mobile terminal without the operator requiring a completely new network or a new frequency spectrum licence. GPRS works by allocating more than one timeslot to each user – typically four downlink timeslots and two for uplink. The maximum throughput per user is 115.2kbps although 30kbps is expected on average. EDGE uses 8-PSK modulation filtered so the spectrum remains in the GSM channel mask. This has a maximum throughput of 384kbps and an expected average throughput of 50-80kbps. Both GPRS and EDGE is packet switched. [2]

3G Systems: UMTS and CDMA2000

CDMA2000 is the American 3G standard and UMTS the European. UMTS offers large potential increases in data rate offering multimedia/Internet access to mobile terminals. High capacity bi-directional data implies very small cell sizes in densely populated areas. Maximum throughput is 144-2000kbps depending on speed and average throughput is expected to be 30-300kbps. The system uses W-CDMA between 1900-2160MHz and requires a new spectrum licence. In the UK in 2000, five operators purchased spectrum from the government costing £22 billion total. For example mmO2 is licensed to use one 10MHz band in each direction for FDD services in addition to a 5MHz band for TDD services. Although UMTS terminals will be ideal for Internet and short video clip traffic for example, it will not be possible to provide high quality audio and television services requiring consistent high bit-rate asymmetric data transport. To compete with new services like wireless local area networks, the 3G standard now incorporates a high speed channel using 16QAM effectively doubling the user data rate. [2]

Wireless LANs

Wireless LANs offer the ability to achieve high data rate communications from a laptop to a computer network saving costs associated with wiring and rewiring buildings. In addition, wireless LANs are seen as strong competition to 3G operators for the mobile business sector market and British Telecom are already trialling wireless LAN service access points in areas like hotels and airports. High data rates are achievable due to the low channel multipath delay spread found in these picocells.

At present, most WLANs are specified to the IEEE 802.11 standard but high-performance radio LAN (HIPERLAN) equipment is shortly becoming available. HIPERLAN is similar to IEEE 802.11 but with an Ethernet-like protocol and provides a fully decentralized system suitable for ad hoc networking. In addition to a spread spectrum air interface offering data rates up to 2Mbit/s, the IEEE 802.11 standard offers a high-speed extension. This enables 11Mbit/s at 2.4GHz using direct sequence spread spectrum (IEEE 802.11B) or 24Mbit/s at 5GHz using orthogonal frequency division multiplexing (IEEE 802.11A). Although OFDM mitigates wideband fading, timing and frequency synchronisation are crucial and their optimisation is in

development. Even higher data rates of 25Mbit/s plus are proposed by IEEE 802.16 and ETSI broadband radio access networks (BRANs) known as HIPERACCESS. Further details about WLANs can be found in [45].

2.2.2 Satellite Mobile Communications

Inmarsat

Inmarsat now offers voice and data services for maritime, aeronautical and land users via its own fleet of satellites. INMARSAT-A, now obsolete, offered circuit switched telephony and telex between the PSTN and ships using FM/FDMA/SCPC for voice and BPSK/FDMA/TDM (shore to ship) and BPSK/FDMA/TDMA (ship to shore) for data.

INMARSAT-B, effectively a digital equivalent of System A, provides voice (16kbps) and data (2.4kbps) using OQPSK/FDMA/SCPC for voice and OQPSK/FDMA/TDM (shore to ship) and OQPSK/TDMA/FDMA (ship to shore) for data. A 64kbps high-speed channel is also now available on System B.

INMARSAT-C, now used for land mobile use as well as maritime, in addition to System B type services, offers low speed (1200bps), store and forward, two-way messaging services for mobiles with very low G/T receivers, making the terminals cheaper and available to a wider market.

INMARSAT-M offers circuit switched, medium quality voice and full duplex medium rate data using OQPSK/FDMA/SCPC at 8kbit/s. Mobile terminals, requiring a G/T of –10dB/K, are available in maritime and land transportable forms. The land antenna, the size of a small briefcase is manually pointed but the maritime antenna is actively stabilized.

INMARSAT-Aero provides communications between an aeronautical earth station and a ground earth station using a low gain (0dBi) or high gain (12dBi) aircraft antenna. Low rate data (600bit/s) using DPSK/TDM and voice (9.6kbit/s RELP vocoder) using OQPSK/FDMA/SCPC services are provided. Due to the aircraft motion, Doppler frequencies as high as 1.5kHz are possible and compensation is required.

INMARSAT-GAN provides a global area network of IP/ISDN services at 64kbit/s using 16QAM with turbo coding. Satellite spotbeams ensures connectivity to a laptop terminal with 45cm antenna.

INMARSAT-BGAN, in development, offers up to 144kbit/s to a multimedia personal communicator. Also in development are 432kbit/s services to Palmtop using Inmarsat-4 satellite. [21], [31]

Iridium
Developed over 11 years by Motorola, filed Chapter 11 in 1999, now used by US military, Iridium offered voice, fax, data at 2.4 and 4.8kbps via its constellation of 66 satellites in LEO polar orbit. The air interface used TD-TDMA/FDMA with four slots at 50kbps with hard handover and no satellite diversity. Satellites had part regenerative payloads and four inter-satellite links at 25Mbps. [32]

Globalstar
Although now filed Chapter 11, Globalstar offered voice, fax, data at 2.4, 4.8 and 9.6kbps via its constellation of 48 satellites in LEO inclined orbit optimised for 50º latitude (over US and China). The air interface used CDMA similar to US IS95 with soft handover and Rake receivers were used to combine diversity – good dual diversity is visible between 20º-60º latitude from non-regenerative payload satellites. [25]

ICO
A similar system offering voice, fax, data at 2.4(data), 4.8kbps(voice) via its constellation of 10 satellites in MEO. The air interface uses TDMA with six slots at 36kbps using QPSK with a roll-off of 0.4 and satellite diversity used from non-regenerative payloads. [30]

Aces
Offering 3.6kbps(voice), fax, data, standard GSM features, high penetrating alert from one then later two geostationary satellites covering Asia, Eastern Europe and North Africa. The air interface is at L-band and the mobile transmit power is reduced by using more FDMA and less TDMA channels in the reverse channel. [3]

Thuraya
Offering voice, fax, data at 2.4, 4.8 and 9.6kbps plus standard GSM features and value added services via two geostationary satellites over Middle East, parts of Europe, North Africa and East India. The air interface is at L-band and is GSM adapted with 31.25kHz channelization and TDMA frames period of 40ms. Terminal can switch to standard GSM where available and GPS can locate terminal to 100m accuracy. [60]

S-UMTS
Worldwide, 30MHz has been allocated for satellite UMTS in both uplink and downlink. S-UMTS offers similar data rates to terrestrial UMTS and is therefore a possible candidate for multicast/broadcast. There are currently several S-UMTS proposals: ICO RTT(ICO), SW-CDMA(ESA), Iridium(Motorola), SW-C/TDMA(ESA), SAT-CDMA(TTA, S.Koria) and Horizon(Inmarsat). Only Horizon is considering geostationary orbit satellites. There are several ACTS/IST projects contributing to the field (SINUS, SUMO, SATIN, etc).
[2], [15]

2.2.3 Terrestrial Broadcast Systems

DVB-T

Digital Video Broadcasting (DVB) is a consortium of around 300 companies (broadcasters, manufacturers, network operations and regulatory bodies) from 35 countries that have agreed a common standard for digital television broadcasting. Terrestrial DVB uses OFDM modulation to mitigate multipath fading and broadcast in the VHF and UHF bands. From May 1998, a consortium of 17 companies launched the MOTIVATE project that has investigated the practical and theoretical performance limits of DVB-T for mobile reception. [13], [8]

DAB

The Digital Audio Broadcasting (DAB) system originated from the European Collaborative Research Project called Eureka 147 and was standardized by the World DAB Forum. DAB provides reliable, multi-service digital sound broadcasting for reception by mobile, portable and fixed receivers using an omnidirectional antenna. The DAB standard allows for terrestrial, satellite, cable and hybrid broadcast networks although it has not yet been used via satellite due to its high modulation peak-to-mean factor. Each channel is multiplexed in time and the 1.5Mbps multiplex is modulated using COFDM into a 1.5MHz bandwidth. In the UK, it is broadcast at 220-228MHz and 1440-1504MHz. [62], [8]

Digital Radio Mondiale

Digital Radio Mondiale aims to re-invigorate broadcasting below 30MHz by using digital techniques to overcome poor signal to noise, frequency selective fading and improve spectrum efficiency. Existing transmitting stations, designed for constant envelope AM must remain usable for DRM with minor alterations. COFDM has been chosen to mitigate multipath fading and enable a single frequency network. The HF fading environment can have long deep fades, path delay spreads of a few milliseconds and large Doppler. Therefore advanced forward error correction with deep interleaving is required, in addition to a large guard interval for multipath and large carrier spacings to reduce inter carrier interference due to Doppler shift. The operator can switch between 16QAM and 64QAM depending on data rate requirements and ruggedness to the channel. [12], [58]

2.2.4 Satellite Broadcast Systems

DVB-S

Satellite DVB broadcasts at 11/12GHz providing direct to home (DTH) television broadcasting. Video from each channel is compressed using MPEG2 and these packets are multiplexed onto one transport stream. Serial concatenated coding is

added before being modulated using QPSK with roll-off of 0.35 typically into a 36MHz transponder bandwidth. [13]

Sirius Satellite Radio

The Sirius Radio System was conceived to provide DAB services directly to vehicles across Continental United States (CONUS) region via satellite. Sirius has alliances with Ford, Chrysler, BMW, Mercedes, Mazda, Jaguar, Volvo, Freightliner and Sterling vehicles to install three-band (AM/FM/SAT) radios provided by numerous manufacturers. The Sirius system uses three satellites in elliptical orbit with two satellites visible at any time. The satellites transmit in S-band (2320-2332.5MHz). This 12.5MHz is split into three bands; the upper and lower 4.2MHz sub-bands are assigned to two satellites providing diversity, and the middle 4.1MHz sub-band is used for terrestrial repeaters. Each channel is multiplexed using TDM and after serial concatenated coding, OQPSK modulation is used which allows more efficient transmission through the satellite HPA. The terrestrial repeaters use TDM/OFDM. [54]

XM radio

The XM radio offers a similar DARS system covering the CONUS region using two geostationary satellites. Each satellite has two bent pipe transponders with sixteen 216 Watt TWTA power amplifiers operating in parallel providing a peak eirp of 68dBW between 2332.5 and 2345MHz. Each channel is combined using TDM and transmitted using QPSK. A network of terrestrial repeaters using COFDM modulation ensures reliable coverage. Each satellite broadcasts the same information enabling time and space diversity. [64]

WorldSpace

Offering 50-200 radio channels per beam (three per satellite) to portable radios over developing countries using three geostationary satellites transmitting in L-band. Each channel is MPEG2 layer III (MP3) coded and multiplexed using TDM, then serial concatenated channel coded before being broadcast from satellite using QPSK. Terrestrial repeaters using OFDM improve availability in dense urban areas. [63]

Global Radio

Currently in development, Global Radio aims to provide radio broadcasting, infotainment and telematics to vehicles over Europe using three HEO satellites. Spotbeam technology ensures low G/T receivers with terrestrial DAB offering coverage when LOS path is not available. The terrestrial return link is proposed for interactivity. [24]

2.3 Potential Future Mobile Communication Systems

2.3.1 The Requirement: Services and Applications

The previous section has shown mobile communications and broadcasting systems working independently and having both reached an advanced stage of their respective industries. Before the reason why mobile communications and broadcasting should converge is discussed, the anticipated services and applications shall be described. Joint usage of these two complementary technologies can provide new value added services that each technology cannot provide individually and more efficient use of the spectrum.

Services and Applications can be grouped from the point of view of the user, the network and the mobility. For example, telephony is required on demand (user view), requiring real-time, low delay, symmetrical, fixed bit-rate data (network view) and could be moving at fixed, pedestrian, vehicle or train speed (mobility view). Whereas mobile television and radio broadcasting is required by pressing a button (user view), requiring real-time, high bit-rate, asymmetric data (network view) and could be requested at fixed, pedestrian, vehicle or train speed (mobility view) although likely only to be practical at fixed or pedestrian speeds. While business and e-commerce is required on demand (user view), requiring low BER, non real-time, moderate bit-rate data (network view) at fixed, pedestrian, vehicle and train speeds (mobility view).

Many services and applications could be available in the near future. These include general information services like telephony, visiophony, browsing the Internet, interactive shopping, e-commerce, newspapers and location based services. Entertainment services include television, radio, programme-related services, online streaming video events, audio/video/games on demand and interactive TV. Business services include mobile office (Web, email, connection to computer network at place of work), share price information, video-conferencing, file transfer, ordering tickets and travel information. Road transport services include travel, traffic information, automatic vehicle environment including software updates and remote diagnosis, public transportation passenger infotainment, fleet management and toll and emergency transmission.

Each of these services could be transported to the mobile optimally by using one of either current broadcasting or mobile communication systems. In addition, some of these services are better supported by the wide area coverage and broadcast capability of satellites, which offers the most efficient cost-effective solution.

2.3.2 Convergence of Broadcast and Mobile Systems

There are many scenarios how terrestrial and satellite mobile and broadcasting/ multicasting technologies could complement each other. The diagram below shows just one possible scenario. Here we show the mobile terminal able to communicate with terrestrial GSM, GPRS, EDGE and/or UMTS mobile communication networks in addition to terrestrial DVB-T, DAB and satellite DVB networks for broadcasting applications, with satellite UMTS providing UMTS support in rural and open areas. In addition, satellites are ideal for broadcasting and multicasting to all outdoor cells types.

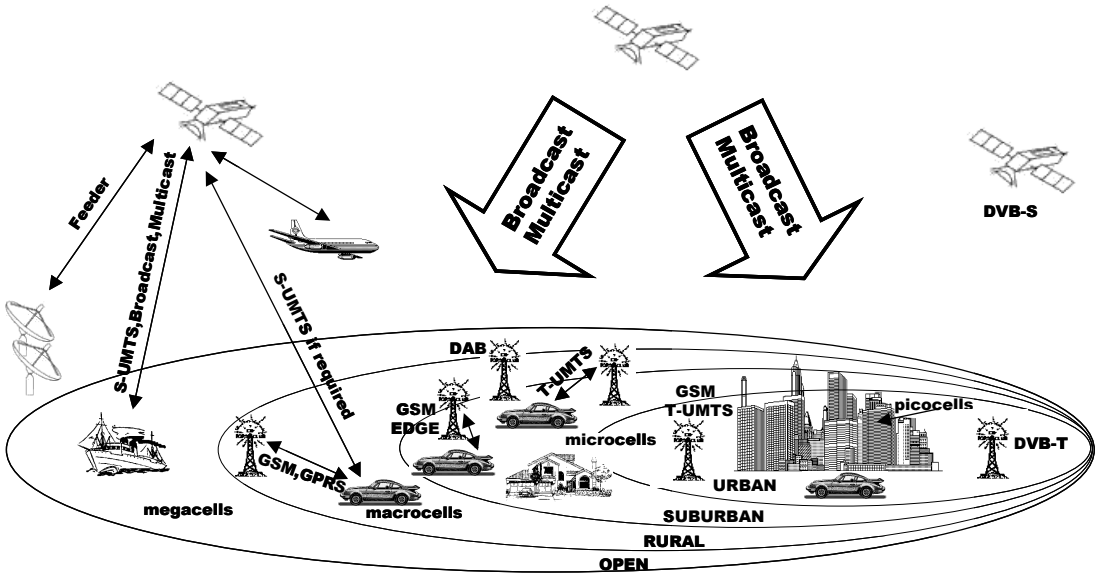


Figure 2.1 Future mobile scenario

So, what are the business drivers? Broadcast consumer choice has increased enormously in recent years and broadcasters have to offer interactive multimedia services as demand and competition from technology such as xDSL rises. Broadcasting is however predominantly a unidirectional service although satellite television currently uses the PSTN for the return channel. Even though the DVB return channel has been standardised (DVB-RCS), broadcasters see that having access to the UMTS network would greatly assist their ability to deliver personalized multimedia services in addition to broadcasting to millions.

The mobile communication operators would ideally like to use 3G to provide all the services to the mobile and increase their customer base and revenues. However, to use the 3G network for broadcasting to millions would require extremely small cells and hence the network would be highly expensive. In addition, they could find their downlink capacity highly congested whilst their uplink capacity is under-utilised. Unfortunately, it is unlikely that broadcasters and mobile communications operators will join forces until it is commercially better for both parties to do so.

2.3.3 Broadcast and Multicast to Mobile via Satellite

Satellite mobile systems are highly effective for delivering broadcast and multicast data due to their wide area coverage. The potential market for broadcasting to mobiles in Europe is up to 100 million subscribers. A broadcast service comprising a multiplex of CD quality audio or low-rate video (MPEG 4) channels typically requires up to 1.2Mbps transport data.

Multicasting like broadcasting is a point to multipoint topology but refers to non real time services sent to a defined group. Mobiles would download streams of data from satellite into local memory using ARQ for example providing reliable data. Users can then browse information at any time. For example, the user could subscribe to a financial service and have near continuous share price updates. There is much research underway looking at satellite delivery of broadcast and multicast services including the following related projects:

BRAHMS: Broadband Access for High-speed Multimedia via Satellite
http://brahms/telecomitalialab.com

FRAMES: Future Radio Wideband Multiple Access Schemes
http://www.infowin.org/ACTS/RUS/PROJECTS/FRAMES/index.html

GAUSS: Galileo and UMTS synergetic system
http://www.galileo.cs.telespazio.it/gauss

GEOCAST: Multicast over geostationary satellite
http://www.geocast-satellite.com

INSURED: Integrated S-UMTS Real Environment Demonstrator
http://www.cordis.lu/infowin/acts/rus/projects/ac229.htm

SATIN: Satellite UMTS IP based Network
http://www.ee.surrey.ac.uk/satin

SINUS: Satellite UMTS air interfaces
http://www.ee.surrey.ac.uk/CCSR/ACTS/Sinus

SUITED: Design and validation of an integrated terrestrial/satellite broadband infrastructure.
http://www.ist-suited.com

SUMO: Resolving interoperability between satellite and terrestrial networks
http://www.ee.surrey.ac.uk/CCSR/ACTS/Sumo

TOMAS: Testbed for mobile applications of satellite communications
http://www.cordis.lu/infowin/acts/rus/projects/ac201.htm

VIRTUOUS: Virtual home UMTS on satellite
http://www.ebanet.it/virtuous.htm

2.4 Options for Multicasting and Broadcasting via Satellite

Multicasting and broadcasting to mobiles via satellite may be able to adopt the use of existing infrastructure like direct to home DVB-S services, systems in development like S-UMTS, systems based on the American DARS systems, systems based on the DAB-S system or a completely new system could be designed. This chapter shall discuss some of the choices to be made in the delivery of multicast and broadcast services.

2.4.1 Air interface

For multicast and broadcast applications, it is not necessary to have a return link, although a return link would add interactivity and allow ARQ for more accurate transmission. For a cheaper system, the multicast and broadcast transmissions may be able to ride on the back of DTH DVB-S services like those offered by SkyDigital in the UK. By subscribing to certain multicast and broadcast services via the mobile terrestrial network or by landline telephone, the operator could decrypt those services by updating a smart card in the mobile. Multicast/broadcast transmission could also use a DARS or DAB-S system with a terrestrial network for the return path. S-UMTS on the other hand is a full duplex system being developed for full global UMTS coverage and could therefore add better interactivity and error control.

2.4.2 Terminals

Key factors in the success of a mobile system are the cost of the mobile terminal and delivering the services, applications and functionality the customer wants. A major problem with current WAP phones offering pseudo Internet services has been the display size; future handheld phones must therefore provide a large screen area. Also, terminals are likely to be multi-mode offering a combination of S-UMTS, T-UMTS, GSM, GPRS systems since the older technologies like GSM offer near guaranteed connection at lower speeds whilst the newer technologies like UMTS provide much higher speeds but a full network rollout will take many years. A benefit of using S-UMTS for multicast/broadcast is that the terminal would have a lot in common with a standard T-UMTS terminal reducing cost, size and battery drain.

In addition to handheld mobile devices, nomadic terminals have been proposed for S-UMTS similar to that used for Inmarsat's Mini-M. A laptop PC with built in RF section including integrated antenna could be developed. Or a RF subsystem with PCMCIA card could be marketed. Alternatively, the antenna could be designed into the roof of a vehicle providing it with a range of in-car infotainment.

Unfortunately, the expected G/T of the handheld is only about –26dB/K and that of the nomadic terminal is approximately –20dB/K. Therefore, mobiles are unlikely to

be able to use a DTH DVB-S system for multicast/broadcast without the use of a terrestrial repeater.

2.4.3 Terrestrial Repeaters

Terrestrial repeaters also known as gapfillers pick up the transmission from the satellite, boost the signal and then retransmit similar to a terrestrial basestation. Care must be taken with frequency planning when using repeaters. Alternatively, the incoming transmission from the satellite is demodulated and retransmitted using a modulation scheme better able to cope with larger multipath, like OFDM. It is also possible to transmit QPSK, ideal for the LOS mobile-satellite link and OFDM, ideal for dealing with multipath interference, from the satellite. At the terrestrial repeater, the OFDM signal is boosted and retransmitted without any need for transmodulation.

Repeaters can be situated on an aeroplane, ship, train, road vehicle or be fixed like a terrestrial basestation, where they could be jointly located. Different channel models would apply to each repeater scenario. In this project, simulations assume the repeater is of terrestrial fixed type.

2.4.4 Satellite Orbit

There are many decisions to be made when choosing the orbit including cost, lifetime, regulatory issues, as well as those factors that affect satellite communications. The table below compares each type of orbit from the communications point of view.

Parameter	GSO	HEO	MEO	LEO	Units
Altitude	36000	1250-39105[1]	5000-10000	500-1500	km
Free space loss at 2GHz	190	160-190	172-178	152-162	dB
Propagation delay (max)	280	200-310	80-120	20-60	ms
Satellite handover	unlikely	4-8	2	10 mins	hours
Delay jump on handover	none	12	24	4	ms
Doppler shift	± 1	± 50	± 100	± 200	kHz
Doppler jump on handover	none	100	200	400	kHz
Multipath delay spread	200	<100	200	200	ns
Multipath fade margin	5-10	2	5-10	10-15	dB
Orbit period	24	8-24	6-12	1.5	hours
Number of gateways[2]	10	10	10	50	
Elevation range	> 10	> 40	> 10	> 10	degrees
Number of satellites[2]	3	5-12	10-15	> 48	

Notes:

1. For 'MOLNYA' 12 hour orbit. (For 'TUNDRA' 24 hour orbit, perigee=25231km, apogee=46340km.)
2. For near global coverage.

Table 2.1 Comparison of satellite orbits

2.4.5 Payload

The main requirement from the satellite payload for multicast and broadcast is that the signal is transmitted with enough eirp in order for a mobile with low G/T to be suitable. This means a lattice of spotbeams is required so that the satellite antenna gain is high. Although a regenerative payload offers the ability to separate the up and down links when performing a link budget and would allow smaller delay in a single hop peer-to-peer voice connection for example, they are more costly, difficult to adapt to other future uses and not required for multicast and broadcast services. Operators are more likely to be able to lease bent-pipe transponder bandwidth for lower initial costs. A transparent (bent-pipe) architecture is therefore often preferable for multicast and broadcast services.

Another aspect of the payload design is the HPA saturated power and linearity. Each modulation has different envelope characteristics that require a different output backoff, therefore affecting the efficiency of the HPA. This subject is dealt with in detail later.

2.4.6 Modulation and Coding

The aim of the combined modulation and coding scheme is to maximize spectral efficiency whilst decreasing power usage, which are normally opposing goals. Maximizing spectral efficiency involves using higher order modulation schemes. However, higher order modulation has a larger peak-to-mean signal envelope and is more prone to intermodulation effects in the non-linear satellite HPA. Ideally, to obtain maximum efficiency from the HPA, the transmitted signal needs to operate as near to saturated level as possible. However, higher order modulation would cause too much interference in adjacent channels when operated near saturation so the power has to be backed off. This is why many systems use QPSK or OQPSK because of the low peak-to-mean value. (OQPSK ensures the envelope is never zero and there is reduced tendency for spectral regrowth than QPSK.) CDMA and OFDM have much higher peak-to-mean than QPSK and has to be backed off at the satellite HPA reducing efficiency.

2.4.7 The Propagation Channel

When choosing a modulation scheme, it is necessary to consider the effect of the channel on BER. Different schemes provide certain properties to deal with fast fading and wideband channels. For example, both CDMA and OFDM offers some resilience towards wideband channels.

3 System Description including modelling approach

Simulations could have been performed using SystemView, SPW, ADS, C/C++, or Matlab. Matlab was chosen due to its accessibility in the computer lab. The quickest solution would be to use SystemView with its channel model libraries but this was unavailable. Using Matlab has also given the author valuable insight into the modelling process and much modelling experience.

3.1 QPSK (DVB-S)

The DVB-S system provides a generic transport medium for unicast, multicast and broadcast services. A typical 36MHz transponder can carry one of the following or any combination making up the bandwidth: 4-8 standard TV channels, 2 high definition channels, 150 radio programmes, 550 64kbps ISDN type channels or a variety of other high and low data rate channels. Multicast and broadcast services could therefore be introduced gradually by using some of a transport stream as and when required.

The DVB specification suggests data can be carried using data piping, data streaming, multi-protocol encapsulation (MPE), data carousels or object carousels. With a suitable interaction channel, MPE has been provided for the transport of IP packets.

After multiplexing the services, the transport ensemble is transmitted using the following channel coding and modulation. Initially the MPEG2 188 byte data packets are scrambled before serial concatenated coding is applied and then coherent QPSK modulation is used as shown below:

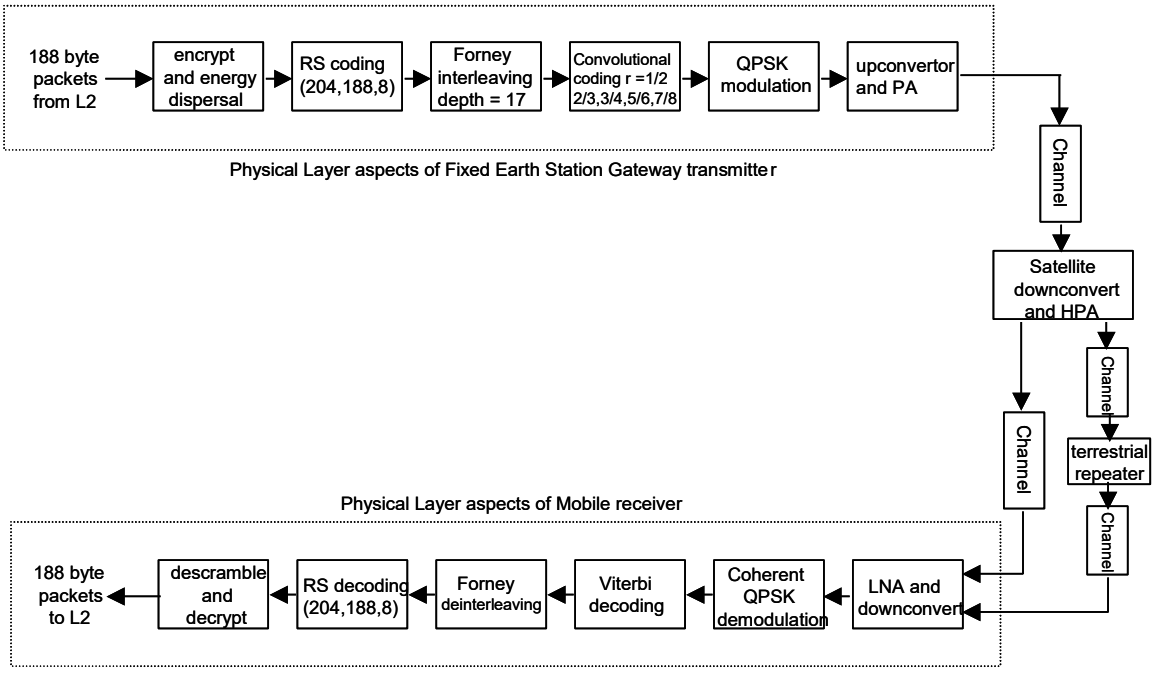


Figure 3.1 Coding and modulation for DVB-S

To simulate the performance of coherent QPSK, the channel coding has been omitted and hard decisions have been made at the demodulator output.

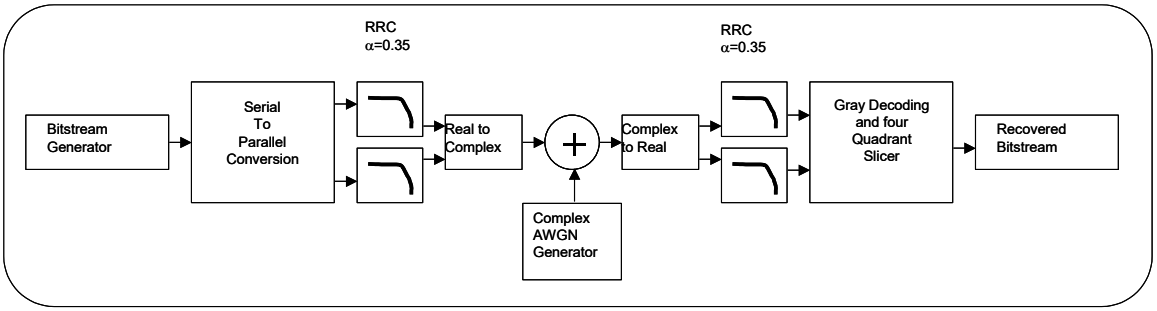


Figure 3.2 DVB-S simulation test bench

The following plots show the QPSK modulated signal in the complex IQ and frequency domains.

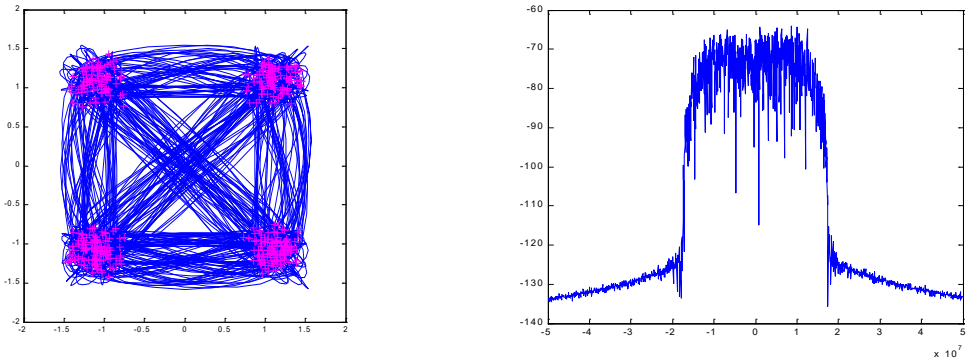
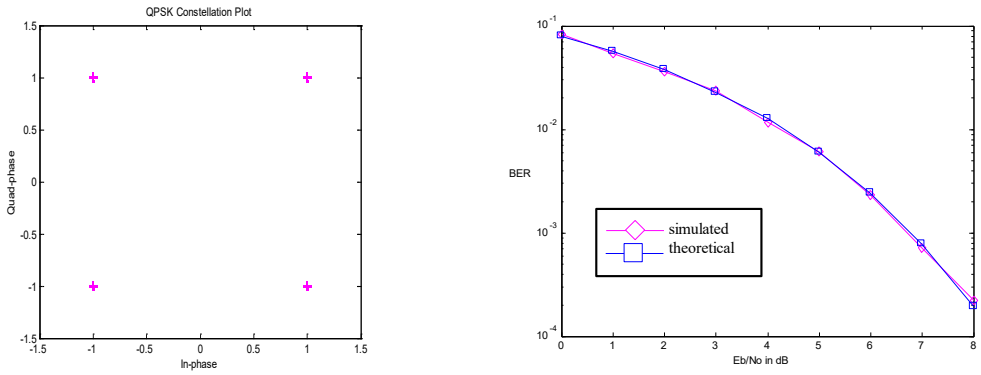


Figure 3.3 Output of DVB-S modulator

The plot (below left) shows the received constellation in a noiseless channel and the plot (below right) shows the theoretical and simulated BER curves in an AWGN channel. The theoretical performance equation of QPSK is given in chapter 5.1.



QPSK constellation QPSK BER curves

Figure 3.4 End-to-end link simulation results

3.2 W-CDMA/QPSK (S-UMTS)

As discussed earlier, S-UMTS is being developed to complement T-UMTS by offering services where no terrestrial network is available and offer multicast/ broadcast services to all mobiles. In addition to S-UMTS, which is largely in development, much can also be learned from T-UMTS on which it is based. This section will start by describing how CDMA works paying specific attention to the W-CDMA forward link physical layer design. Attention will be paid to power control, Rake receivers, overcoming channel impairments and the peak-to-mean ratio. The simulation test bench shall then be introduced along with BER curves in an AWGN channel.

Unlike FDMA where users are separated by frequency, and TDMA where users are separated by time, in CDMA, users are separated by code. Each user occupies the same frequency and is transmitted at the same time. It is possible to differentiate between users because each code is orthogonal.

Consider the following orthogonal matrix:

$$H_4 = \begin{bmatrix} -1 & -1 & -1 & -1 \\ -1 & 1 & -1 & 1 \\ -1 & -1 & 1 & 1 \\ -1 & 1 & 1 & -1 \end{bmatrix} \qquad \textbf{Equation 3.1}$$

Each user is assigned a row in this matrix. The first row is assigned to the pilot channel. Suppose two users are simultaneously transmitting using row 2 and 3, as shown below:

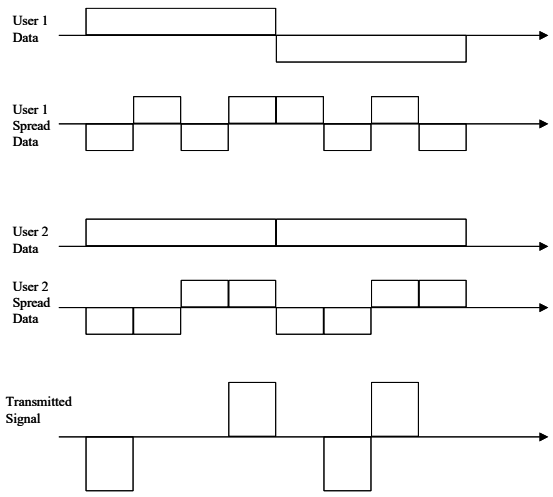


Figure 3.5 CDMA coding process

The transmitted signal is recovered at the demodulator. The receiver multiplies the received composite signal by the code and integrates over one bit period. The sign after integration gives the recovered data.

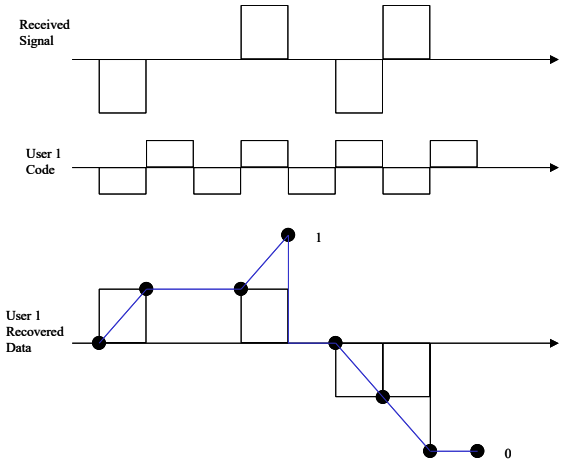


Figure 3.6 CDMA decoding process

It is crucial that the receiver is synchronized to the transmission. To demonstrate this, suppose the code has slipped by half a chip in the above example:

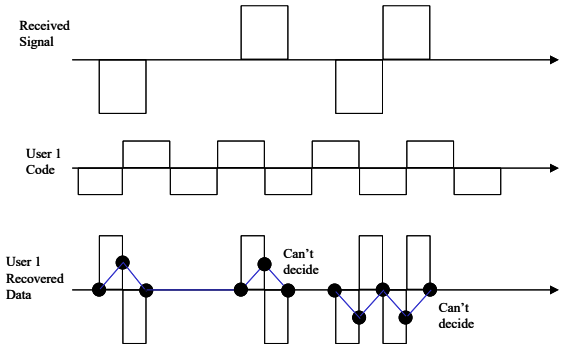


Figure 3.7 CDMA decoding errors

Here, the correlator output integrates to near zero and it would be easy for the QPSK slicer to make the wrong decision, especially with noise and channel impairments present.

It is interesting to note that spreading the data bit over four chips provides a spreading gain equal to 10log4 = 6.02dB. This can be added to the link budget. However, spreading gain is not for free and is at the expense of increasing the bandwidth. Much larger spreading gains are achievable. A gain of 24dB is achieved with a spreading factor of 256, which provides a usable bit rate for speech communications.

UMTS uses wideband direct-sequence code division multiple access, with a 3.84Mcps chip rate, where the user information bits are spread over a 5MHz carrier bandwidth by multiplying the user data by these quasi-random bits (known as chips) derived from CDMA spreading codes.

The following schematic shows the W-CDMA forward link modulator:

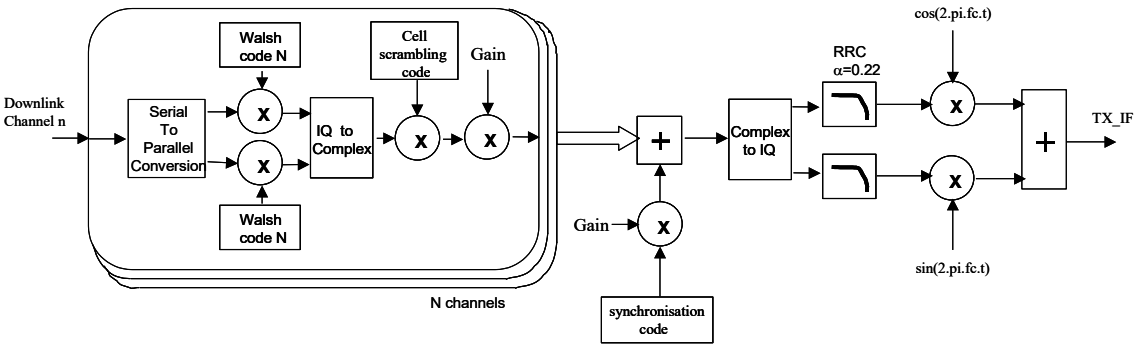


Figure 3.8 W-CDMA modulator

The incoming channel coded traffic and control data are split into an IQ stream where the same real OVSF code is applied to both I and Q streams. These orthogonal codes are used to separate data to different users and separate data to the same user and shall be discussed in the next section. The complex data stream is then scrambled using a Gold sequence. As well as providing a cell identity to the transmission, these codes ensure the signal has good autocorrelation properties essential for Rake operation in a wideband channel. (The OVSF codes have good crosscorrelation properties but poor autocorrelation properties.) They also scramble the signal to ensure reasonably flat signal power spectral density across the carrier bandwidth.

Since each channel shares the same bandwidth, each channel is scaled so that just enough power is transmitted for reception at the required bit error rate. The pilot channel, which just transmits the cell scrambling code, is usually given more power because successful reception is essential in the receiver for synchronization purposes.

Each channel, up to 512 in the forward link, is then added before being applied to a QPSK modulator with root raised cosine filters with roll-off factor of 0.22. The IF signal is then filtered, upconverted, amplified and applied to the gateway transmitting station.

In the mobile receiver, after synchronization, a Rake receiver maximizes the energy from a number of parallel correlators (known as fingers) tuned to each multipath component before applying the recovered IQ signals to a coherent QPSK demodulator. A Rake receiver has little benefit in a satellite-mobile wideband channel due to the fact that the first path is dominant.

The reader is referred to [29] and [65] for additional details of the CDMA process and capacity equations.

The spreading codes make use of Orthogonal Variable Spreading Factor codes. These codes enable the spreading factor to be changed whilst retaining orthogonality

between different spreading codes of different lengths. These codes are also known as Walsh codes. Whilst the forward link uses Walsh codes, the reverse link, which cannot guarantee synchronisation between every mobile, uses pseudorandom noise (PN) codes for channelization. Walsh codes are generated by the Hadamard matrix shown below:

$$H_{2N} = \begin{bmatrix} H_N & H_N \\ H_N & \overline{H_N} \end{bmatrix} \qquad \textbf{Equation 3.2}$$

The seed matrix is:

$$H_2 = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} \qquad \textbf{Equation 3.3}$$

Each row in the Walsh matrix is orthogonal provided they are synchronised in time. This is why they are only used in the forward path since all codes are derived from a common clock. Being orthogonal means that they can be used for channelization – during the correlation process in the demodulator, every code apart from the wanted channel, correlates to zero provided the cross correlation of the synchronised codes is zero or very small. Other conditions of orthogonality are that there are equal numbers of +1s and –1s (or they differ at most by one), and that the scalar dot product of each code is equal to 1. In W-CDMA, the spreading code row lengths range from 4 to 512. By inspection, it can be seen that row 1 is uncoded and is used for the pilot signal.

In all the CDMA simulations, the 384kbit/s data rate class shall be assumed, which uses the H_{16} spreading matrix. Whereas OVSF codes have good crosscorrelation properties but poor autocorrelation properties, PN codes have good autocorrelation properties but not so good crosscorrelation properties. The basic PN codes, known as m-sequences, are generated by a maximal length shift register. The PN sequence has an autocorrelation function of the following form:

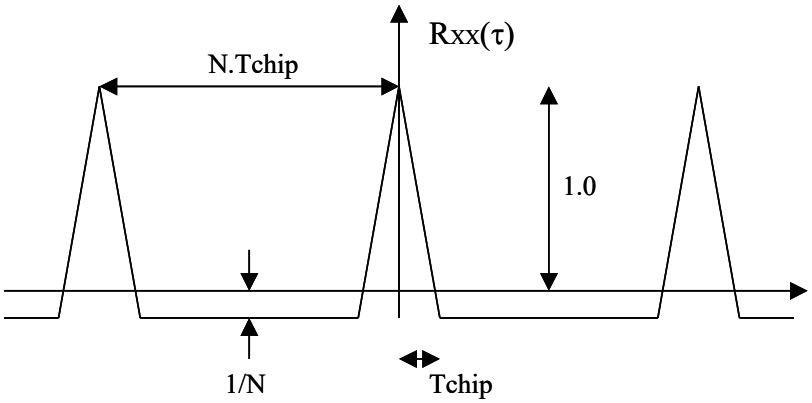


Figure 3.9 Autocorrelation of PN sequence

This peak makes it easy for the receiver to locate and synchronise with the pilot signal which is PN coded. Although PN sequences have good autocorrelation properties, their crosscorrelation is poor which makes it difficult for the receiver to separate different basestations or satellite spotbeams. It is also impossible to calculate the crosscorrelation of m-sequences except by brute force, which can be time consuming because the codes can be long. Gold proposed a solution to these problems by EX-OR'ing two m-sequences. Gold codes have good autocorrelation and crosscorrelation properties and are therefore used for the forward link scrambling code in W-CDMA. These complex Gold codes are produced in W-CDMA with the following code generator:

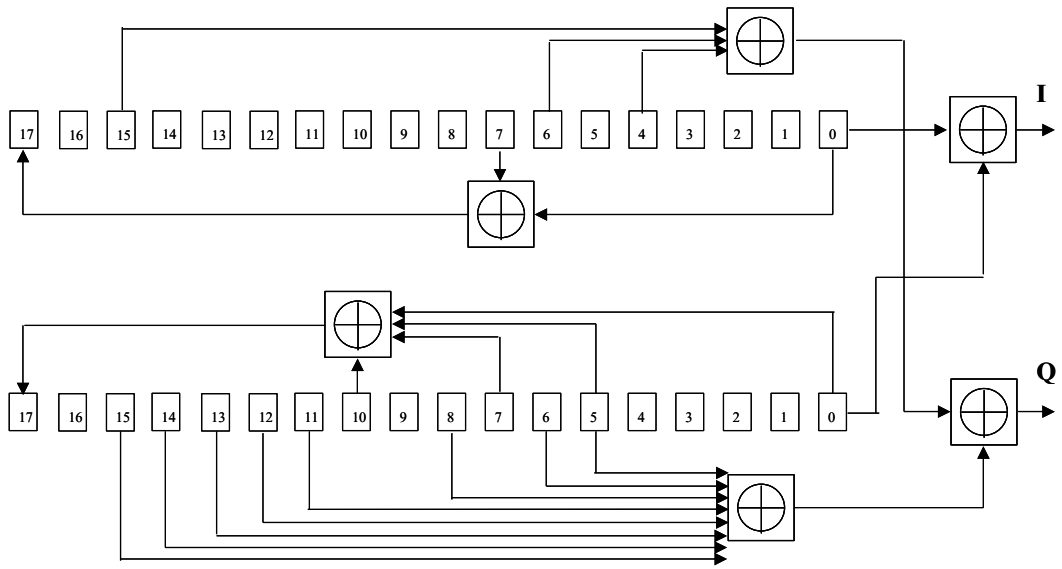


Figure 3.10 Complex Gold code generator

W-CDMA provides a number of advantages when used in a channel. As discussed later the satellite-mobile channel is modelled using a Lutz model operating in the good state only and the repeater-mobile channel is modeled as a 6-tap wideband model with each tap Rayleigh faded. The Lutz model in good state is modelled as Ricean with K varying from 5 to 15dB. For the satellite-mobile channel, the rms delay spread is approximately 50 to 100ns. This is small compared to the chip duration of 260ns and therefore this channel can be accurately modelled as flat fading. However the terrestrial channel can have rms delays ranging from 1 to 2us in urban and suburban areas to 20us or more in hilly areas.

This is where W-CDMA becomes advantageous. Firstly, CDMA offers resistance to multipath due to the fact that delayed versions of the transmitted signal will have low correlation with the original and will therefore appear as another uncorrelated user and ignored by the receiver in the correlation process, provided the codes have good autocorrelation properties. As well as being multipath resistant, they can also take

advantage of it. Provided each path is delayed more than 260ns, they can be separately demodulated using a correlator and combined using maximal ratio combining to take advantage of the multipaths. This form of multipath diversity is achieved using a Rake receiver. If a delayed component traverses into the next bit, then it cannot be resolved and produces interference. This is more likely with smaller spreading codes. The performance of a Rake receiver degrades with smaller spreading codes or higher bit-rates because the autocorrelation properties are not as good. Also the benefit of multiple correlators is only advantageous when the delayed paths have significant energy.

The receiver has to cope with deep fades as high as 40dB from the Rayleigh process. These are generally countered by using multipath diversity from the Rake receiver and strong coding, interleaving and retransmission protocols are adopted. For the terrestrial system, fast power control can mitigate signal fading. Unfortunately in a satellite system, the power control update rate is not enough to track fast fading, but can be used to track slow fading. Even with power control there is still random phase variation that is corrected by a phase rotator in the Rake receiver. Both the rate of change of this phasor and signal power is increased at higher Doppler frequencies or higher speeds.

Although in general a narrowband Ricean model can be used for the satellite-mobile channel using W-CDMA, applying a wideband model can test the properties of the codes. This can be modelled with a Ricean first and second tap followed by Rayleigh taps. The first Ricean tap is usually much greater than the delayed taps and therefore there is little signal energy to be obtained from the delayed taps.

Power control plays an essential part in a CDMA system for two main reasons. Firstly, it is used in the reverse link so that all mobiles transmit at a power that maintains equal received powers at the gateway receiver. Secondly, in a terrestrial W-CDMA system, power control is updated at 1500 times a second to track the Rayleigh fading environment. Reiterating, in a satellite system, due to the round trip delay, power control is unable to track fast fading, but can still be used to track slow fading.

The Rake receiver is used to provide multipath diversity in a multipath environment where each path delay is greater than a chip duration and less than a bit duration. Each path, varying in delay, can be viewed as a rotating phasor, where the amplitude distribution is Rayleigh or Ricean and the phase angle is uniformly random over 2π radians. The Rake receiver has to lock onto each delayed path, synchronize using the pilot, correlate, rotate in phase until all phasors are coherent and scale using maximal ratio techniques. It is essential that the unwanted paths in each correlator integrate to near zero and this requires careful selection of the type of Gold codes. A Rake receiver is not required for the satellite-mobile path as the paths greater than one chip,

which can be resolved, are much lower in power than the main signal. However for a system where the satellite transmission is repeated terrestrially, it is essential. Also, a Rake receiver simplifies reception from multiple satellites in diversity systems and is useful during spotbeam handover. The following diagram shows the functionality of a Rake receiver:

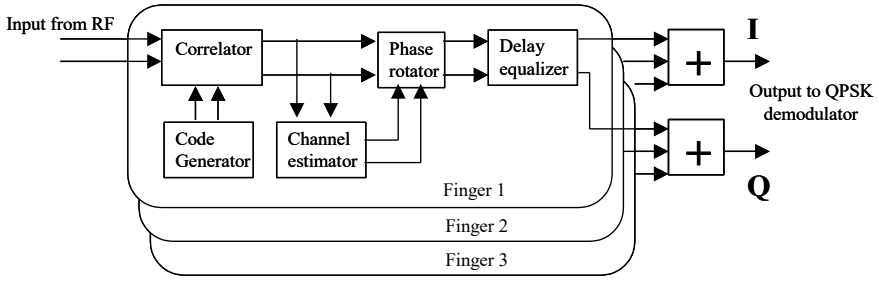


Figure 3.11 Rake receiver architecture

Another advantage of CDMA is that of frequency re-use. Each spot beam can occupy the same frequency, therefore reducing spectrum licence costs. The mobile knows which cell it is in by investigating the cell scrambling code. However, where there is spotbeam overlap, some additional interference occurs, worsening the bit error rate.

Bandwidth-on-demand is well supported with W-CDMA by using variable bit-rates. The following table details typical user bit-rates available for each spreading factor:

Spreading Factor	Channel Symbol rate (kbit/s)	Channel Bit rate (kbit/s)	Data channel Bit rate range (kbit/s)	Maximum user rate with ½-rate coding (kbit/s)
512	7.5	15	3-6	1-3
256	15	30	12-24	6-12
128	30	60	42-51	20-24
64	60	120	90	45
32	120	240	210	105
16	240	480	432	215
8	480	960	912	456
4	960	1920	1872	936
4, 3 parallel codes	2880	5760	5616	2300

Figure 3.12 W-CDMA spreading factors and bit rates

The peak-to-mean is especially important in the satellite HPA. This is because of the limited power available on the satellite and the need to operate as near to saturated power as possible, which improves efficiency. Although W-CDMA can have up to 512 channels occupying the 5MHz bandwidth, for multicast and broadcast applications, the user bit-rates are likely to be upwards of 64kbit/s. To simplify and manage the vast possible array of simulations that could be carried out in this project,

a spreading factor of 16 has been used throughout. This is known as the 384kbit/s class. In the next chapter, the statistics of the envelope shall be plotted and the required output backoff for a specific ACPR and link BER shall be obtained.

The following diagram shows the test bench used to evaluate W-CDMA / QPSK.

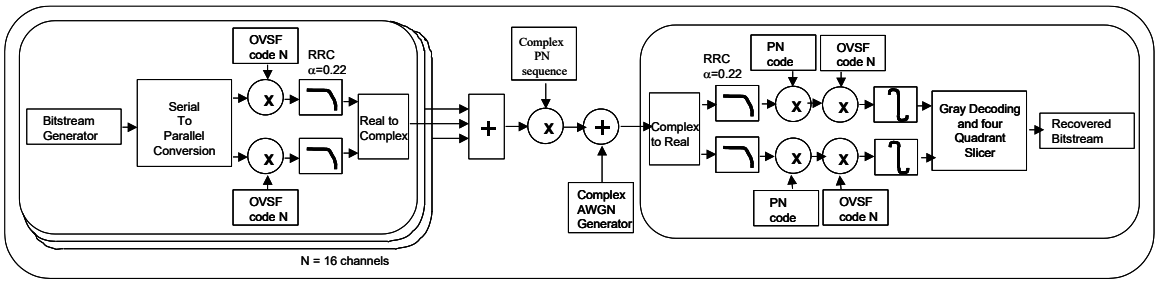


Figure 3.13 W-CDMA simulation test bench

Sixteen equal power channels were used, each multiplied by the following orthogonal Walsh matrix:

$$H_{16} = \begin{bmatrix}
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&1&0&1&0&1&0&1&0&1&0&1&0&1&0&1\\
0&0&1&1&0&0&1&1&0&0&1&1&0&0&1&1\\
0&1&1&0&0&1&1&0&0&1&1&0&0&1&1&0\\
0&0&0&0&1&1&1&1&0&0&0&0&1&1&1&1\\
0&1&0&1&1&0&1&0&0&1&0&1&1&0&1&0\\
0&0&1&1&1&1&0&0&0&0&1&1&1&1&0&0\\
0&1&1&0&1&0&0&1&0&1&1&0&1&0&0&1\\
0&0&0&0&0&0&0&0&1&1&1&1&1&1&1&1\\
0&1&0&1&0&1&0&1&1&0&1&0&1&0&1&0\\
0&0&1&1&0&0&1&1&1&1&0&0&1&1&0&0\\
0&1&1&0&0&1&1&0&1&0&0&1&1&0&0&1\\
0&0&0&0&1&1&1&1&1&1&1&1&0&0&0&0\\
0&1&0&1&1&0&1&0&1&0&1&0&0&1&0&1\\
0&0&1&1&1&1&0&0&1&1&0&0&0&0&1&1\\
0&1&1&0&1&0&0&1&1&0&0&1&0&1&1&0
\end{bmatrix}$$

Figure 3.14 Walsh matrix used in simulations

The composite signal was multiplied by a PN sequence to improve the autocorrelation properties. This helps the correlator integrate the unwanted paths in the wideband channel model to noise. The following plots show the W-CDMA modulated signal in the complex IQ and frequency domains.

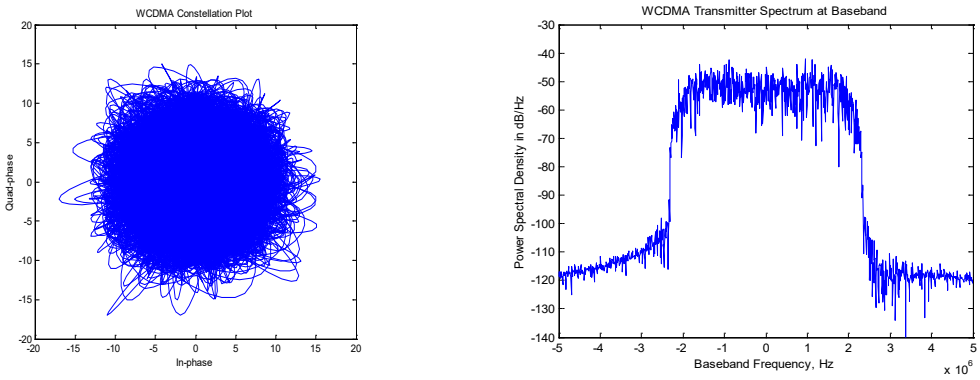
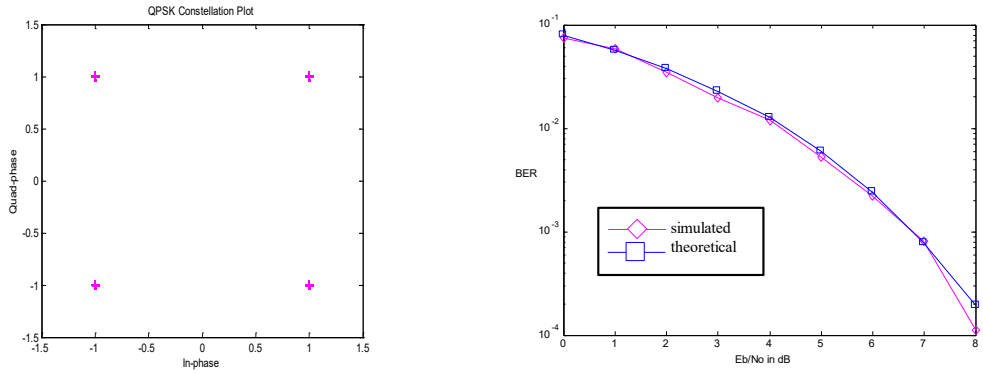


Figure 3.15 Output of W-CDMA modulator

The plot (below left) shows the received constellation in a noiseless channel and the plot (below right) shows the theoretical and simulated BER curves in an AWGN channel. The theoretical performance equation of QPSK is given in chapter 5.1.



W-CDMA / QPSK constellation W-CDMA / QPSK BER curves

Figure 3.16 End-to-end link simulation results

3.3 W-CDMA/16QAM (S-UMTS)

In order to compete with higher data rates offered by systems like wireless LANs, a high-speed data channel has been introduced to the 3G standard, which effectively doubles the achievable bit rates over QPSK, assuming favourable channel conditions.

Most of the W-CDMA details described in the previous chapter apply except in this case 16QAM is used instead of QPSK. As will be shown later, 16QAM requires typically an additional 5dB in Eb/No for the same BER. In addition, since the Euclidean distance between each constellation point is halved and the modulation scheme is amplitude modulated, 16QAM is much more susceptible to the effects of channel fading.

The following diagram shows the simulation test bench:

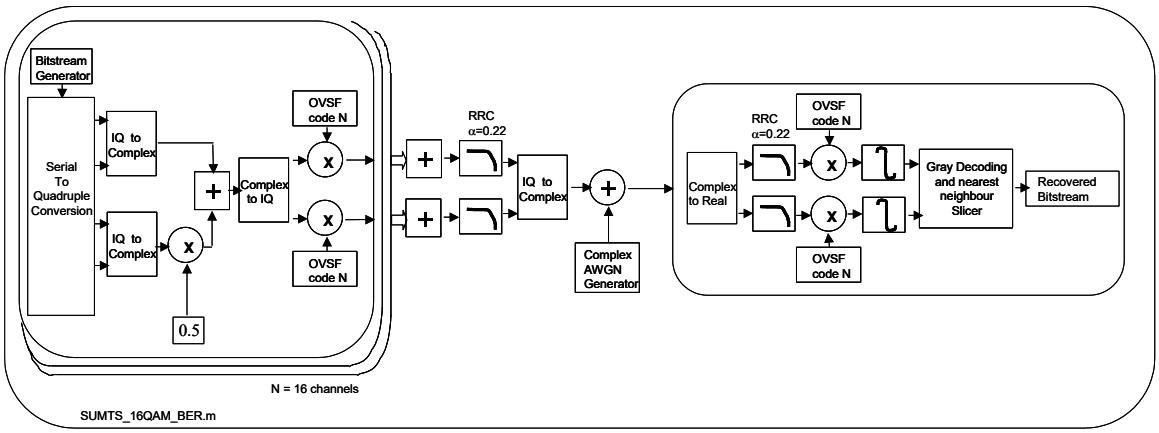


Figure 3.17 W-CDMA/16QAM simulation test bench

The following plots show the W-CDMA modulated signal in the complex IQ and frequency domains.

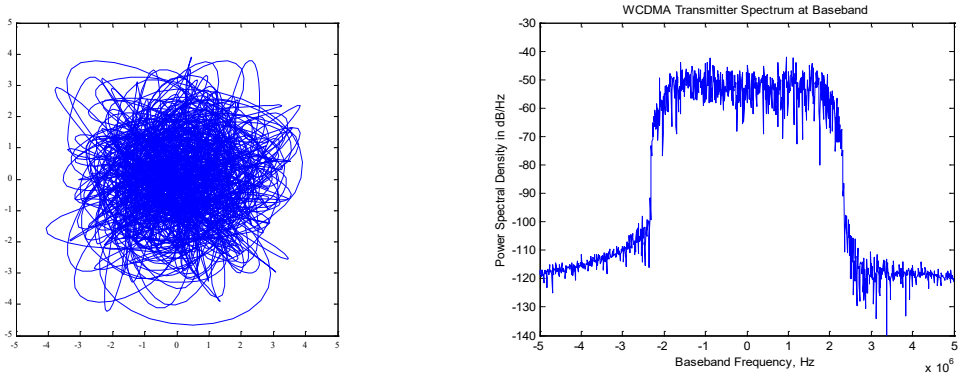
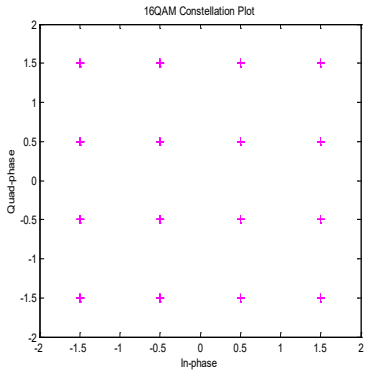
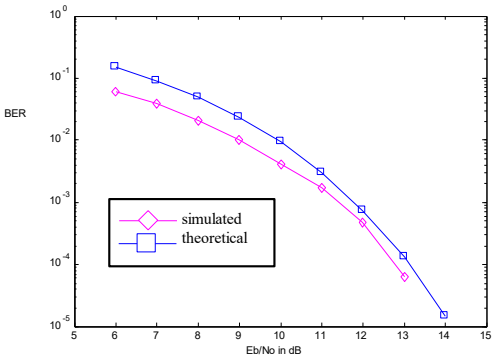


Figure 3.18 Output of W-CDMA/16QAM modulator

The plot (below left) shows the received constellation in a noiseless channel and the plot (below right) shows the theoretical and simulated BER curves in an AWGN channel. The simulations predict a slightly better performance than the theory used because the theory is stated as an upper bound. The theoretical performance equation of 16QAM is given in chapter 5.1.



W-CDMA / 16QAM constellation



W-CDMA / 16QAM BER curves

Figure 3.19 End-to-end link simulation results

3.4 OFDM/QPSK (DAB)

The Eureka 147 DAB system uses Coded Orthogonal Frequency Division Multiplex modulated by $\pi/4$ DQPSK. The main benefits of this technique are its spectral efficiency, its resilience toward frequency selective multipath fading, the ability to use a single frequency network and ability to cope with Doppler frequency shift. This comes at a cost: a higher Eb/No is required [21], the peak-to-average ratio is much higher than QPSK for example (although it can be reduced to approximately 8dB by digital signal processing techniques), and frequency offsets and phase noise have to be carefully controlled.

The following diagram shows the modulation and coding used in the Eureka DAB system. For a full mathematical description of these blocks, the reader is referred to the ETSI standard [62].

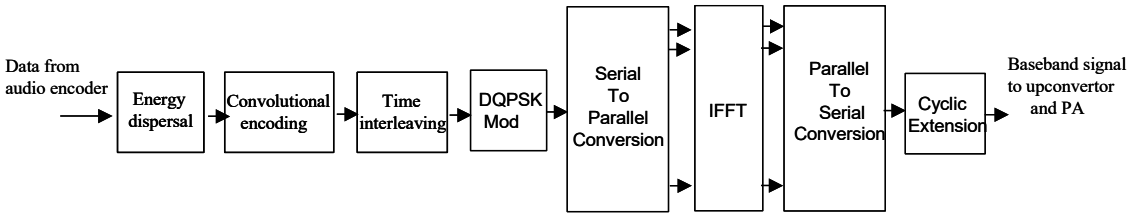


Figure 3.20 OFDM modulator

The core of how COFDM works is the use of FDM. Instead of modulating one carrier as in DVB-S, the spectrum is split into many low data rate carriers in a frequency division multiplex arrangement. Since the data rate at each carrier is now low, the symbol duration is increased (by the number of carriers). The channel rms delay spread is now much less in comparison to the DQPSK symbol duration. Another way to look at it is the coherence bandwidth (the bandwidth over which the channel can be assumed flat) is now greater than the bandwidth of each small carrier. This method significantly reduces the influence of ISI. It is also important that the spectrum of all the small carriers is greater than the coherence bandwidth of the channel. In this case multipath fading would not affect all the small carriers at the same time and FEC, which spreads the data over many carriers, can recover the data while losing some carriers. From channel sounding measurements, this requires the bandwidth to be greater than approximately 1MHz. A bandwidth of 1.536MHz is used in practice.

If all the small FDM carriers were separated completely in frequency with a guard band, then the spectrum for the multiplex would be quite large, (for example 192 * 8ksym/s * 1.5 + guard band which is more than 2.3MHz). However, if each carrier is separated by 1/(NT), where N is the number of carriers and 1/T is the sampling

frequency, the carriers can be overlapped considerably, reducing bandwidth to 1.536MHz for DAB. In this case, the carriers are orthogonal and can be resolved individually in the receiver, provided orthogonality is maintained. [52] gives a good mathematical description of the OFDM process and how this is obtained with the IFFT function.

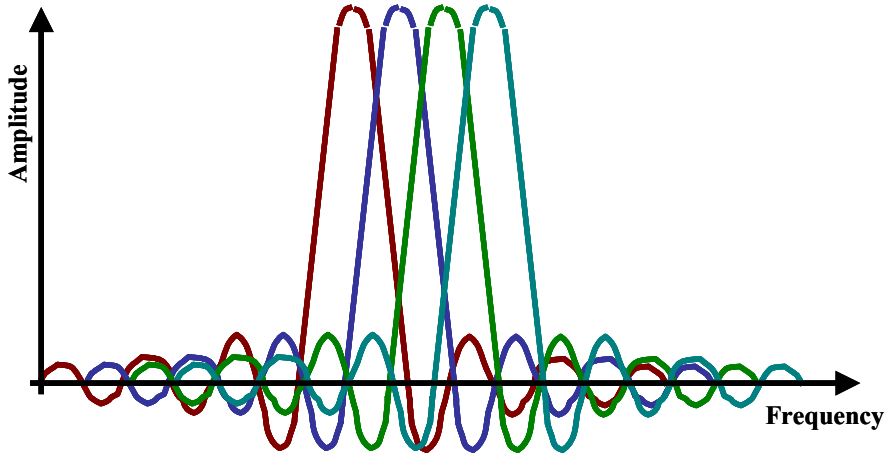


Figure 3.21 Orthogonal carriers

The incoming coded data is split into groups called symbols whose length is the number of carriers in the multiplex. Each carrier bit stream is DQPSK modulated. The symbols are applied to an IFFT function one by one (padded with zeros to ensure the IFFT deals with powers of two for speed). The resulting transformed signal is then arranged serially. This time signal represents the voltage sum of all the carriers superimposed. Each IFFT symbol contains one DQPSK symbol from each carrier.

Multipath echoes contained within one IFFT symbol produce a kind of linear distortion. However, if the echo traverses over two symbols then ISI can result. To counter this problem, a guard interval is applied at the start of each IFF transformed symbol (usually the last quarter of the symbol repeated). Any echo from the previous symbol only affects the guard period, which is dropped by the demodulator before applying the symbol to a FFT process. The guard period is also used for receiver synchronisation.

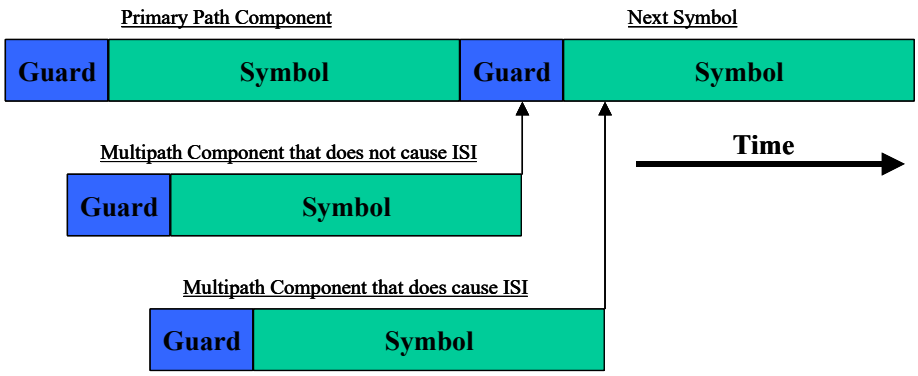


Figure 3.22 Effect of multipath on OFDM

DAB has been designed for mobile reception and is therefore slightly different from DVB-T in its makeup. If an echo is received in the same symbol plus guard band but offset slightly, then each received carrier will have a constant phase offset from the constellation points. If differential decoding is used then this offset can be removed. At high speeds, the phase offset between adjacent DQPSK constellation points increasingly differs and differential decoding is less effective. If the echo is delayed beyond the guard interval, which could happen in poorly designed single frequency networks, then the phase offset is not constant from one constellation point to the next and this kind of distortion degrades the signal. In fact, one of the key benefits of having a guard interval is that the receiver can cope with delayed signals from multiple transmitters. This provides the great benefit of a single frequency network. For satellite multicast/broadcast, each spotbeam could use the same frequency.

Coding is essential in an OFDM system especially in frequency selective channels. This subject is dealt with in depth in [56]. With coding and the addition of the guard interval, the useful bit rate is about 1.5Mbit/s.

ETSI have standardised four versions of OFDM for DAB as shown below:

Parameter	**Mode I**	**Mode II**	**Mode III**	**Mode IV**
Number of Carriers	1536	384	192	768
Sub-carrier spacing	1kHz	4kHz	8kHz	2kHz
Frame Duration	~96ms	~24ms	~24ms	~48ms
IFFT Symbol Duration	~1ms	~250us	~125us	~500us
Guard Interval	~246us	~62us	~31us	~123us
Total Symbol Duration	~1.246ms	~312us	~156us	~623us
No of Symbols per Frame	76	76	153	76
Carrier Frequency	< 375MHz	<1.5GHz	< 3GHz	<1.5GHz
Transmitter Separation	< 96km	< 24km	< 12km	< 96km

Table 3.1 Comparison of standardised DAB modes

Mode I has been selected for terrestrial audio broadcasting in the UK and mode III has been designed for satellite use. Mode III specifies 192 carriers, with each carrier modulated at 16kbit/s and an inter-carrier spacing of 8kHz. Each frame consists of 154 symbols comprising: (i) the null symbol used for coarse synchronisation, (ii) the phase reference symbol for fine synchronisation and tuning, (iii) 8 fast information channel symbols which carry various things including the multiplex configuration information and (iv) 144 symbols of payload data forming the main service channel. The main service channel is divided into sub-bands, each carrying 24ms of audio for a particular service. One symbol in one 24ms sub channel carries 384 bits, therefore each sub-band carries 16kbit/s of data. For example, if MPEG4 were broadcast at

64kbit/s with a code rate of 0.5, then eight symbols per frame would be required. This would allow 18 MPEG4 broadcasts per 1.536MHz of spectrum. It is possible for each broadcast sub-channel to originate from a geographically separated earth station provided each burst is synchronised in the TDM frame. This aspect is discussed in [22].

The Eureka 147 DAB system has been successfully demonstrated via tests on Optus B3, Solidaridad 2 and EMS geo-stationary satellites. In the US, WorldSpace, XM and Sirius have gone for QPSK while using COFDM for terrestrial gap fillers. QPSK has a 3dB advantage over DQPSK and has the advantage of a small peak-to-average ratio enabling the satellite HPA to be operated near saturation. However, COFDM has a higher peak-to-average of approximately 8dB. Both these factors mean QPSK has a 6dB link advantage over Eureka 147 DAB. Globally, the frequency band of 1452 to 1492MHz has been allocated to digital audio broadcasting by satellite but this only comes into effect in many countries by 2007.

In this project, uncoded OFDM will be modelled as follows:

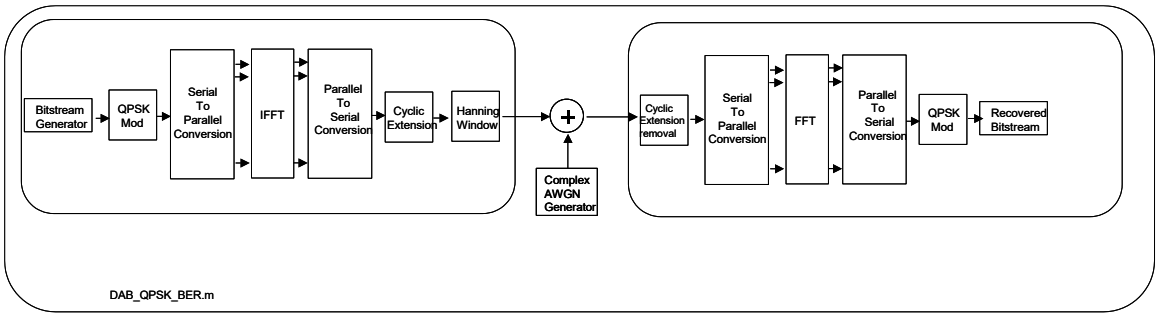


Figure 3.23 OFDM simulation test bench

A random number generator bit stream will be taken in pairs and used as IQ inputs to a QPSK modulator. Groups of 192 QPSK symbols will be taken at a time, which represent the OFDM symbol. To create N = 192 QPSK modulated carriers, 2*N information symbols are generated as follows.

$$X_k, \text{ where } k = 0,1,\ldots,191 \qquad \textbf{Equation 3.4}$$

$$X_{N-k} = X_k^*, \; k = 1,\ldots,191 \qquad \textbf{Equation 3.5}$$

$$X_0' = \mathrm{Re}(X_0) \qquad \textbf{Equation 3.6}$$

$$X_{192} = \mathrm{Im}(X_0) \qquad \textbf{Equation 3.7}$$

These values are padded with zeros to make 2048 and this symbol is fed to an IFFT operation that performs the following:

$$x_n = \frac{1}{\sqrt{N}} . \sum_{k=0}^{N-1} X_k . e^{j2\pi nk/N}$$ **Equation 3.8**

The resulting sequence $\{x_n, 0 \le n \le 2047\}$ corresponds to the time domain waveform of the sum of all the carriers. Full mathematical derivations are found in [48]. The following diagram shows just three of the 192 orthogonal carriers.

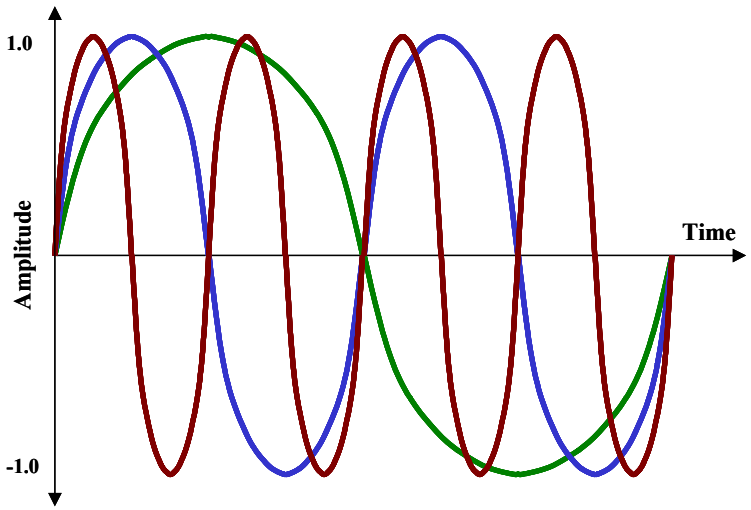


Figure 3.24 Orthogonal carriers in time domain

Each block of 2048 time domain samples are taken serially to form the baseband waveform. Each block of 2048 samples contains one IFFT symbol of 125us (or 256/ 2048000 seconds). The last 31us (or 63 / 2048000 seconds) or 504 samples are copied to the front of the time domain symbol to form the guard interval:

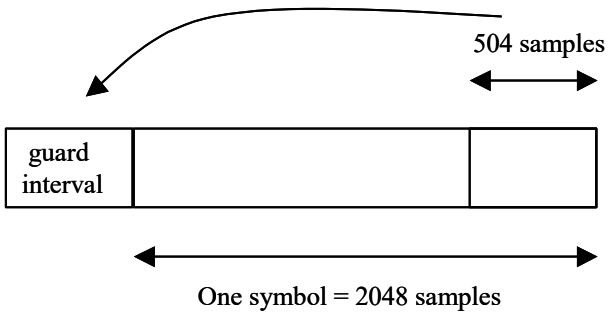


Figure 3.25 Addition of guard interval

The resulting baseband time and frequency domain waveforms are shown below:

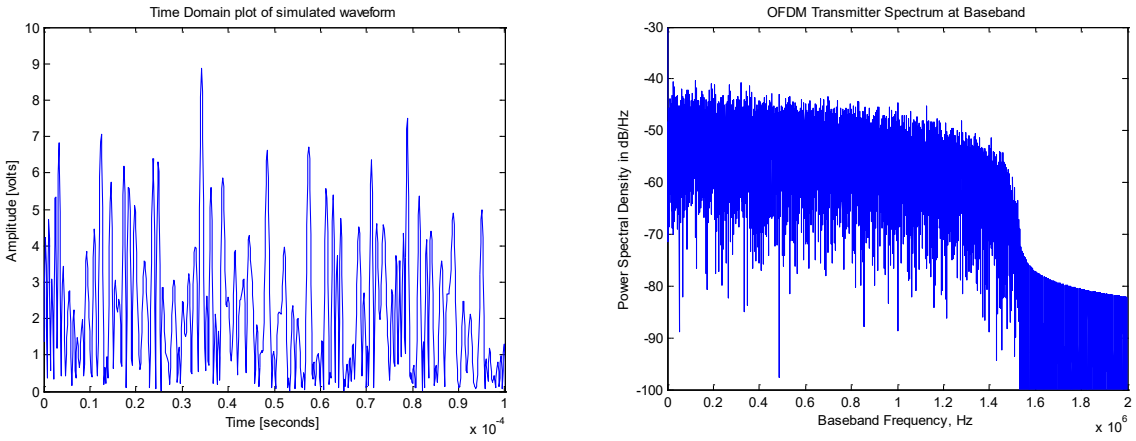
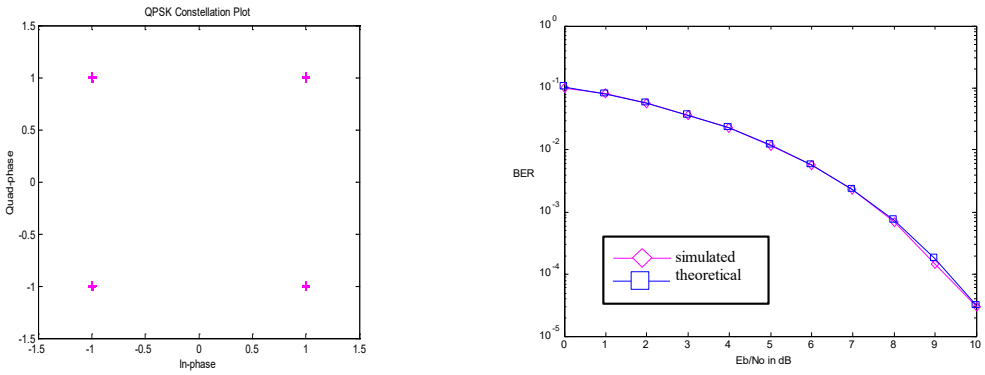


Figure 3.26 Output of OFDM modulator

The receiver performs the inverse process. The simulations shall assume the demodulator has synchronised with the modulator. The uncoded OFDM link model shall be tested under the conditions of Rayleigh, Ricean fading and multipath fading.

The plot (below left) shows the received constellation in a noiseless channel and the plot (below right) shows the theoretical and simulated BER curves in an AWGN channel. The theoretical performance equation of QPSK is given in chapter 5.1. For OFDM, it is scaled to consider the effect of the guard interval. In the DAB system, differential coding is used requiring 2.6dB more power than the curves below for the same BER.



OFDM / QPSK constellation

OFDM / QPSK BER curves

Figure 3.27 End-to-end link simulation results

4 Satellite Payload Non-linearity

Non-linearity in amplifiers is important because the signal is distorted causing an increase in bit error rate, enough output power may not be delivered to the next stage, unwanted spurious emissions are generated, the amplifier may overheat if overdriven and spectral regrowth occurs. In many cases, the amplifier non-linearity can be described as a pair of curves representing instantaneous amplitude and phase distortion – known as AM-AM and AM-PM.

The diagram below shows a simplified transparent satellite payload architecture. The graphs below show a typical amplitude transfer function of each of the amplifiers. The 1dB compression point of each amplifier is chosen so that the signal can pass through without too much distortion. To find the distortion curves of the cascaded system, each of the curves should be taken into account. However, because the signal power levels are lower at the output of the LNA and Preamp, it is not too expensive to provide more headroom at these stages. Unfortunately, the HPA, has to provide high transmit powers very efficiently and the signal power levels are maintained as near to saturated power as possible without causing too much distortion. Operating the HPA with a lot of backoff is wasteful of DC power and more heat is generated. In addition, it is more costly and less reliable.

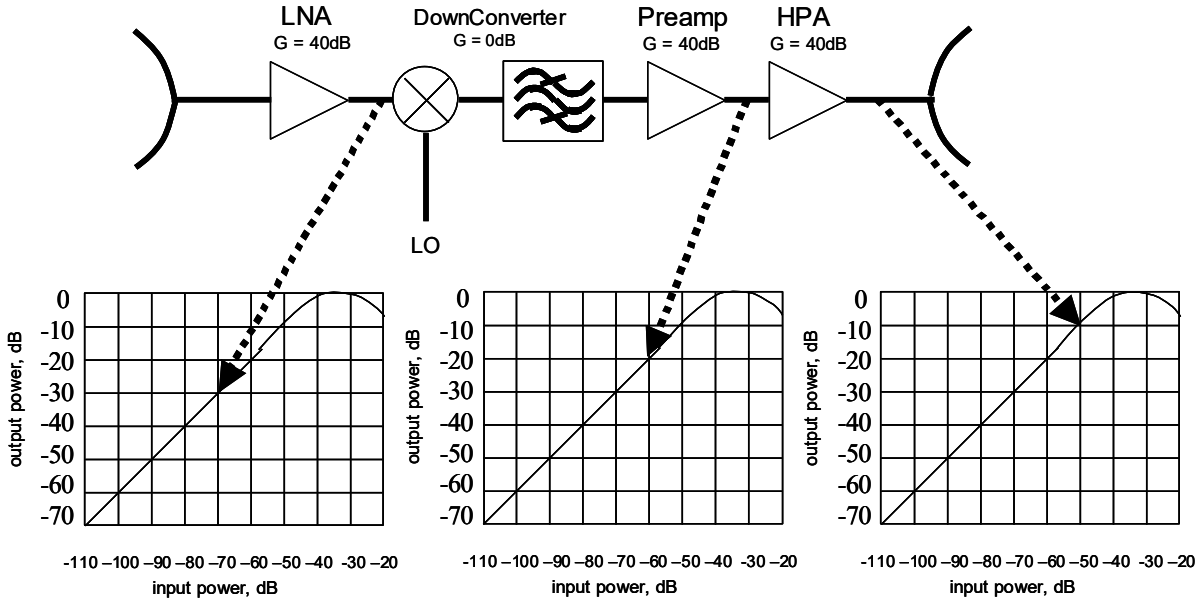


Figure 4.1 Backoff across satellite payload

As stated above, one of the problems with operating an amplifier too near saturation is that of spectral regrowth. This causes the spectrum either side of the wanted signal to increase in power causing interference to the adjacent and alternate channels. Since the power levels are high at this point, it is very costly in terms of wasted power to filter off some of this distortion. In practice, it is extremely difficult to produce such a filter with low loss and with such a high Q. However, filtering at this point is still used to remove harmonics and other spurious far removed from the wanted channel.

4.1 Modelling Non-linearity

The simplest way to model amplifier non-linearity is to assume that there are no memory effects. In this case the non-linearity can be modelled as a pair of AM-AM and AM-PM curves that describe the instantaneous amplitude and phase. When these curves have been measured, a polynomial can be fit to the data and used to simulate the effect of the non-linearity. Other methods include look up tables or a piece-wise polynomial near saturation with exact linear fit when backed off. The model proposed by [50] uses the polynomial approach and is used here due to its simplicity and accuracy. The input to the amplifier can be described as follows:

$$x(t) = r(t).\cos(\omega_0.t + \psi(t)) \qquad \textbf{Equation 4.1}$$

The output of the amplifier can be described as follows, showing the amplitude and phase distortion:

$$y(t) = A[r(t)].\cos(\omega_0.t + \psi(t) + \phi[r(t)]) \qquad \textbf{Equation 4.2}$$

The amplitude polynomial is given as:

$$A(r) = \frac{\alpha_a.r}{1 + \beta_a.r^2} \qquad \textbf{Equation 4.3}$$

The phase polynomial is given as:

$$\phi(r) = \frac{\alpha_\phi.r^2}{1 + \beta_\phi.r^2} \qquad \textbf{Equation 4.4}$$

The constants in each equation depend on the TWTA or SSPA characteristics. The Hughes 261-H tube model was used with the following constants [41]:

Parameter	α_a	β_a	α_ϕ	β_ϕ
Value	1.6623×10^3	5.52×10^4	1.533×10^5	3.456×10^5

Memory effects can occur when there is a heating effect in the amplifier with a slower time constant than the envelope, or the power supply cannot provide enough instantaneous power to follow the envelope and takes time to recover for example. In these cases, the instantaneous amplitude and phase response of the amplifier is not only dependent on the instantaneous input power, but also on the history of the envelope. Modelling memory effects can be achieved using the Volterra series [9].

4.2 The model used in Simulations

The following curves show the amplitude and phase distortion for the Hughes 261-H tube model [41].

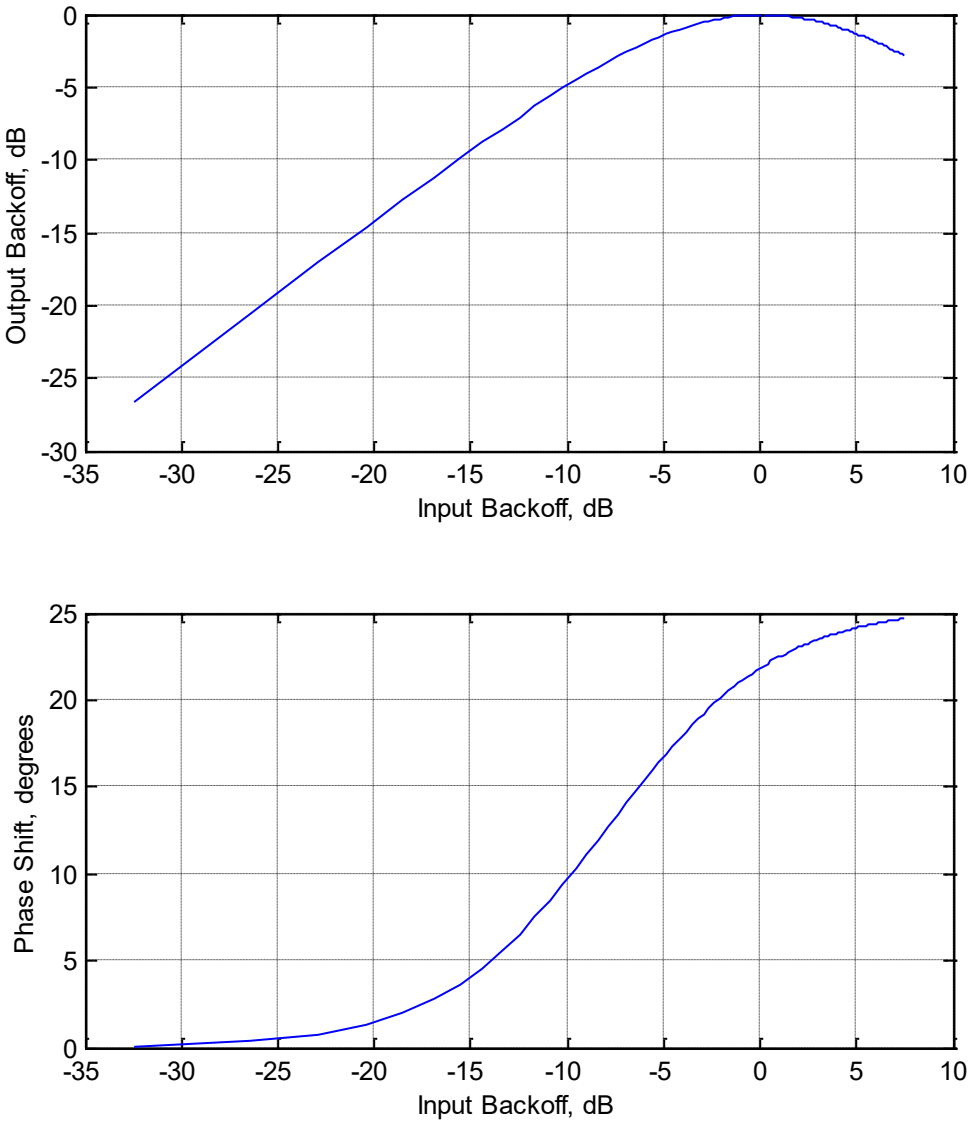


Figure 4.2 HPA non-linearity curves

4.3 Effect of Compression on ACPR

When the modulation spectrum is heavily backed off in the amplifier, the output spectrum would appear as shown below in black. However, when the output power is increased toward saturation, spectral regrowth occurs as shown below in blue. Specifications for the adjacent and alternate channels normally require a certain power relative to the total transmitted power in a stated bandwidth at a specified offset from the channel centre. For example, a T-UMTS basestation requires the adjacent channel to be 45dB down in a 3.84MHz bandwidth at 5MHz offset, measured using a receiver rrc filter.

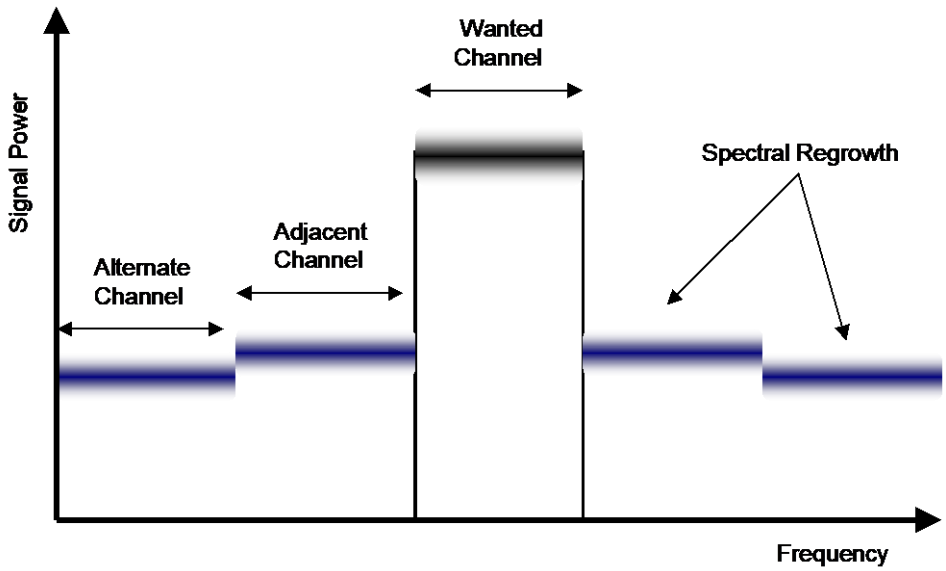


Figure 4.3 Adjacent power caused by spectral regrowth

Modulation schemes are carefully selected for their envelope variation properties. In particular, the peak-to-mean envelope gives a good figure of merit for how the modulation will respond to a non-linear amplifier. In practice, the envelope statistics give better understanding. The next section compares each modulation scheme in terms of the backoff required for a specified ACPR. The simulation results show the required OBO for an ACPR of 30dB and link BER in an AWGN channel for various backoffs.

4.3.1 QPSK (DVB-S)

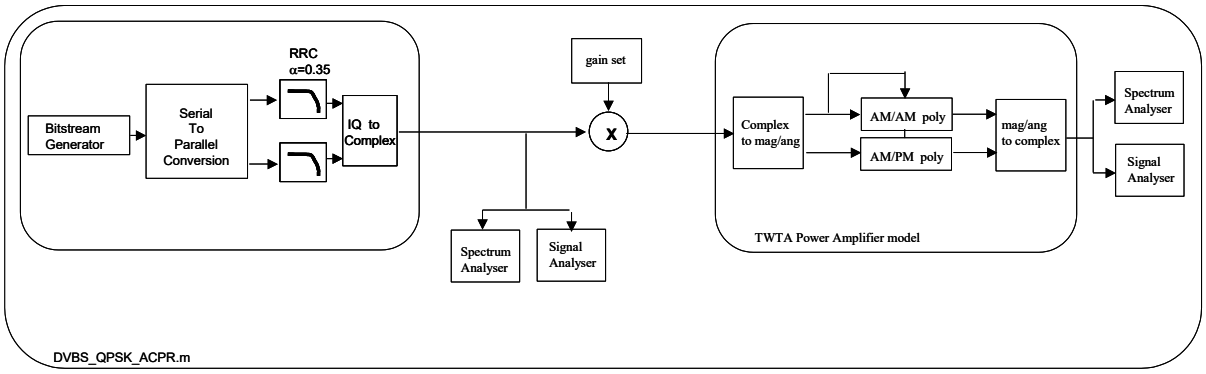
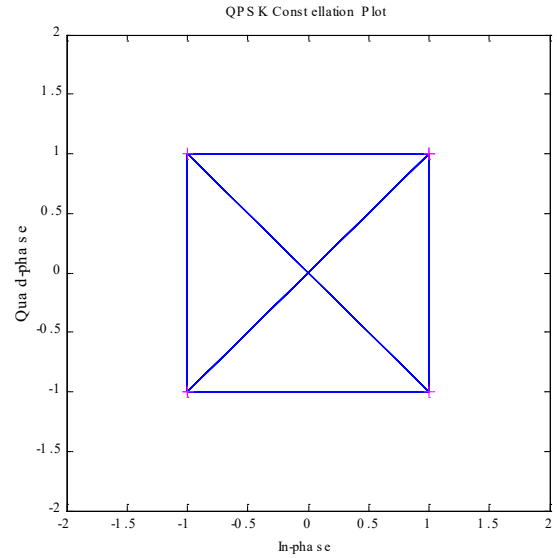
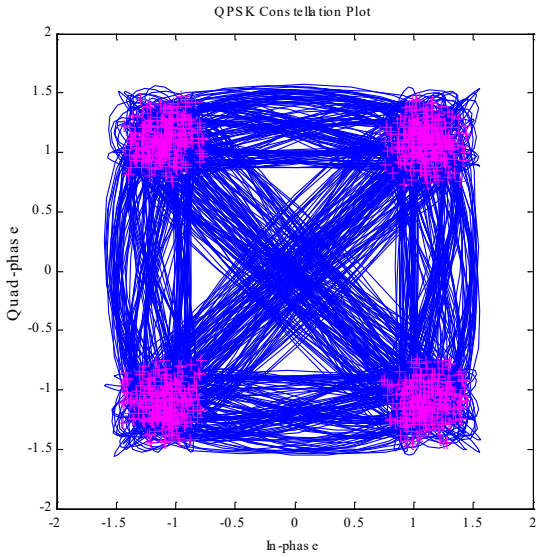


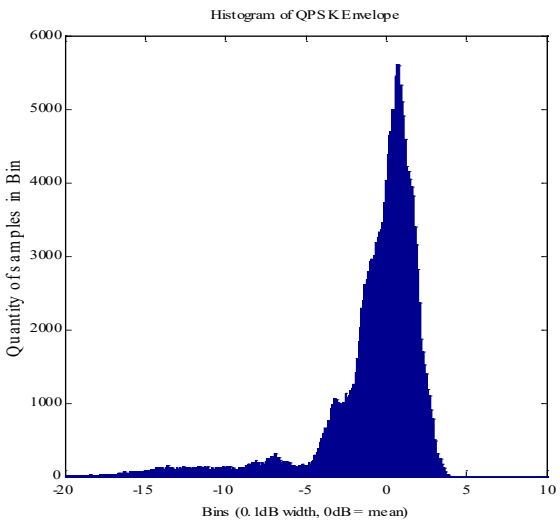
Figure 4.4 ACPR simulation test bench for QPSK



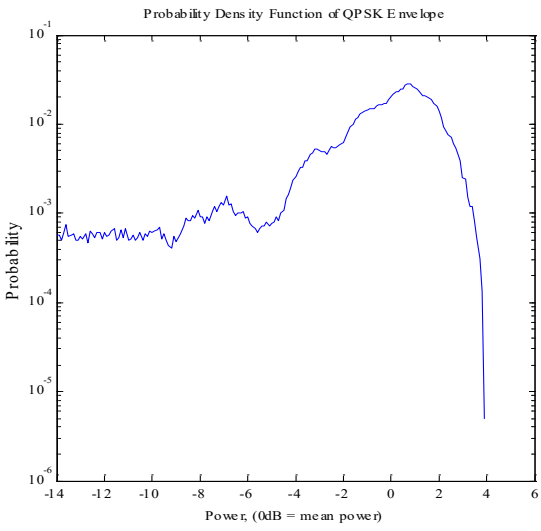
QPSK constellation before filtering



QPSK constellation after filtering



Statistics of envelope



Finer detail of envelope statistics

Figure 4.5 Results from QPSK simulations

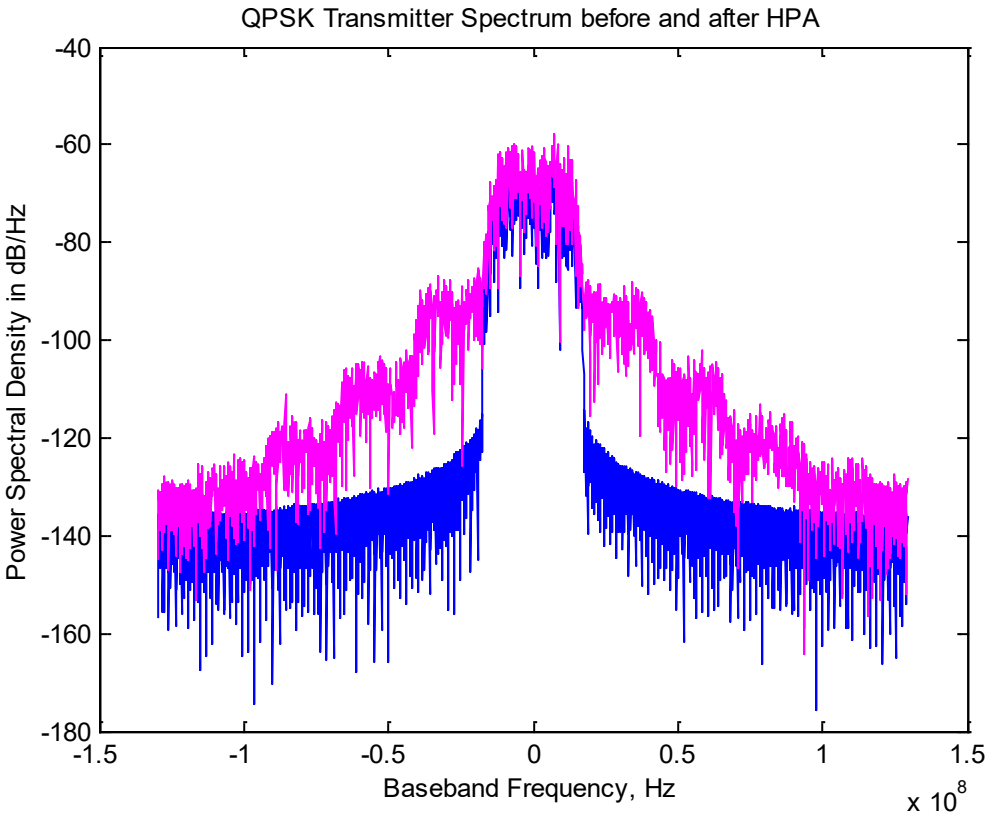


Figure 4.6 Spectral regrowth of QPSK

Parameter	Specification	Units
Wanted Power Bandwidth	42	MHz
Adjacent Channel Bandwidth	36	MHz
Adjacent Channel Offset	42	MHz
	Result	
OBO for 30dB ACPR	2.81	dB

Table 4.1 ACPR results for QPSK

4.3.2 W-CDMA/QPSK (S-UMTS)

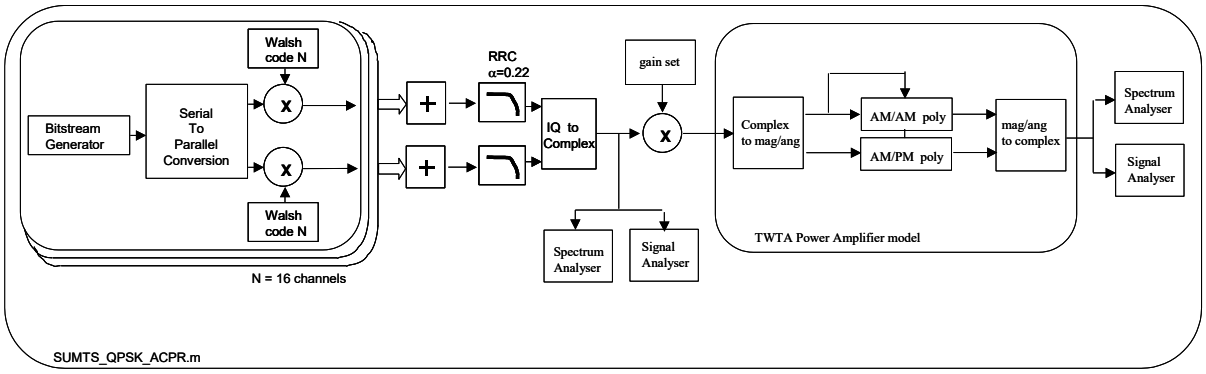
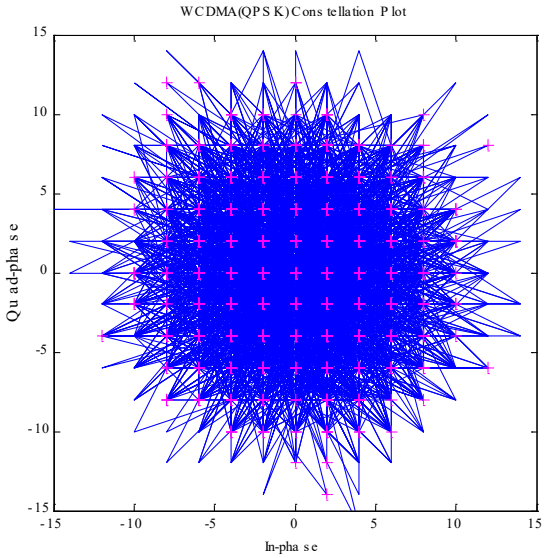
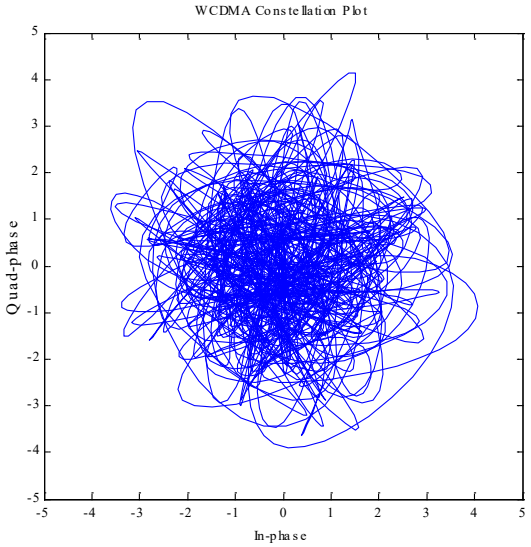


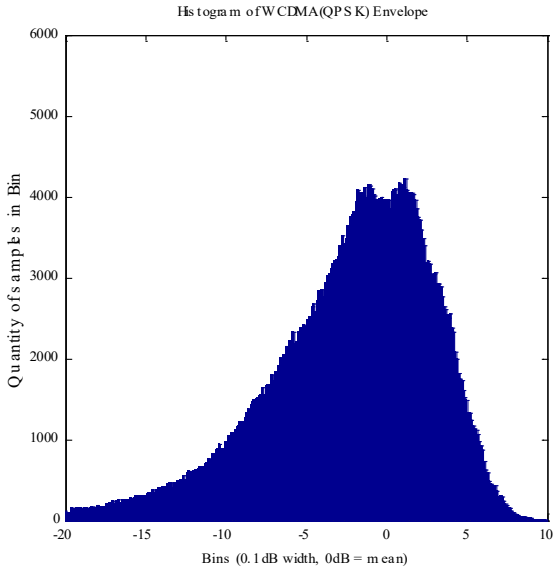
Figure 4.7 ACPR simulation test bench for W-CDMA/QPSK



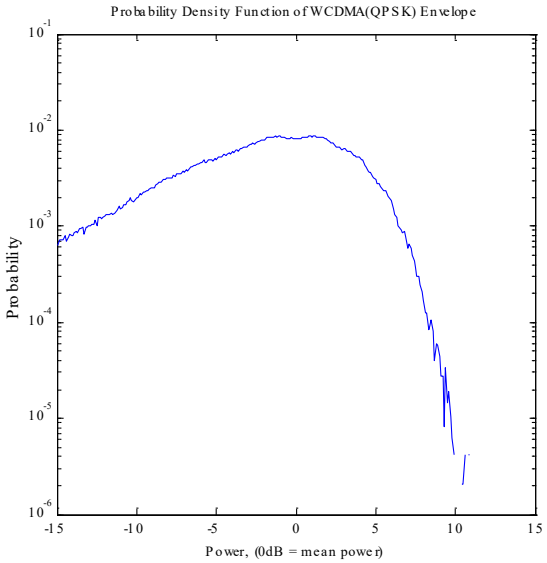
Constellation before filtering



Constellation after filtering



Statistics of envelope



Finer detail of envelope statistics

Figure 4.8 Results from W-CDMA/QPSK simulations

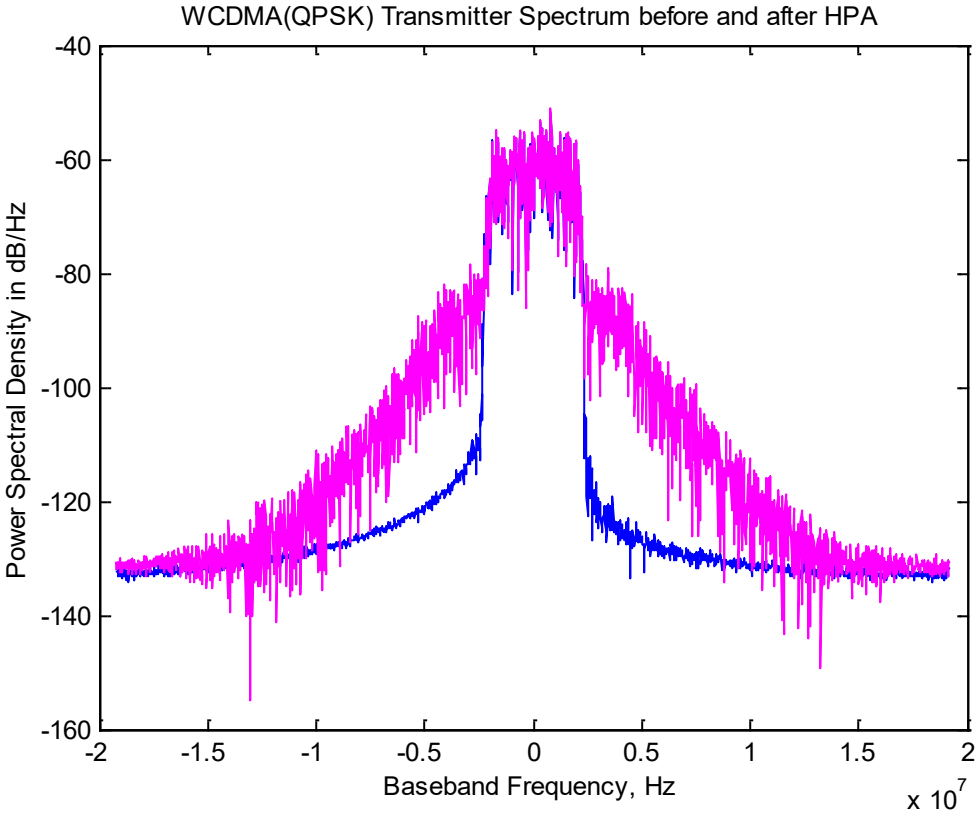


Figure 4.9 Spectral regrowth of W-CDMA/QPSK

Parameter	Specification	Units
Wanted Power Bandwidth	5	MHz
Adjacent Channel Bandwidth	3.84	MHz
Adjacent Channel Offset	5	MHz
	Result	
OBO for 30dB ACPR	5.35	dB

Table 4.2 ACPR results for W-CDMA/QPSK

4.3.3 W-CDMA/16QAM (S-UMTS)

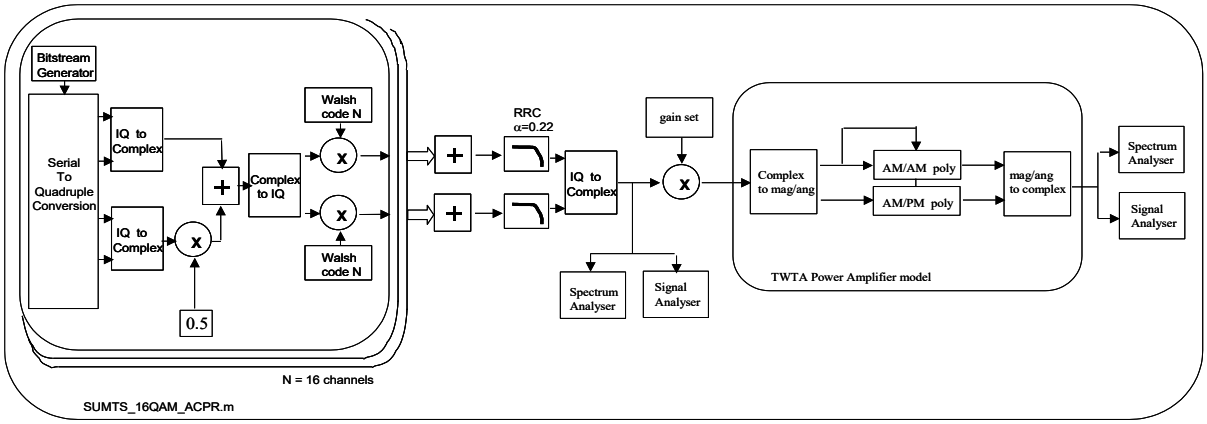
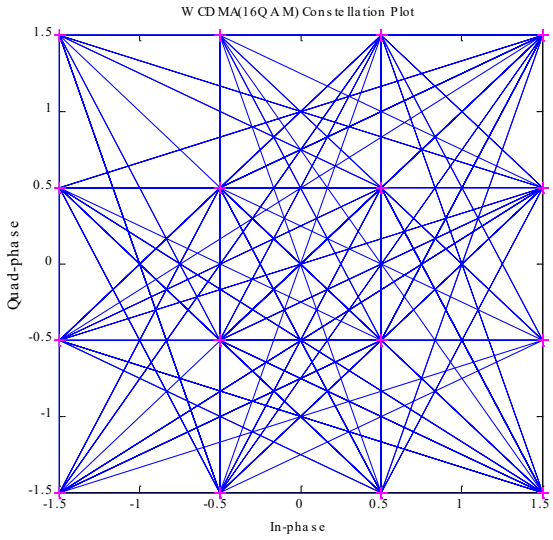
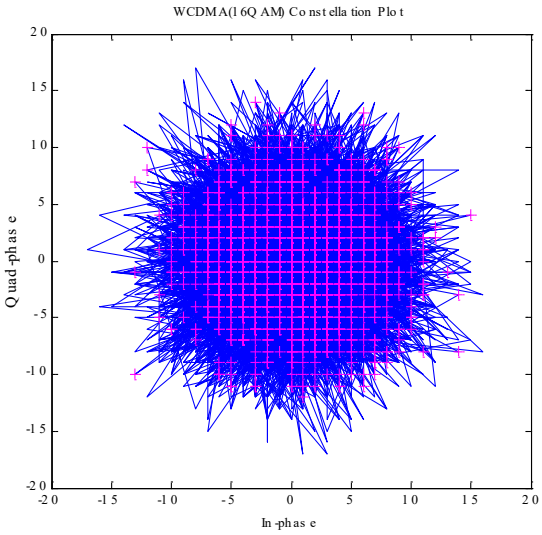


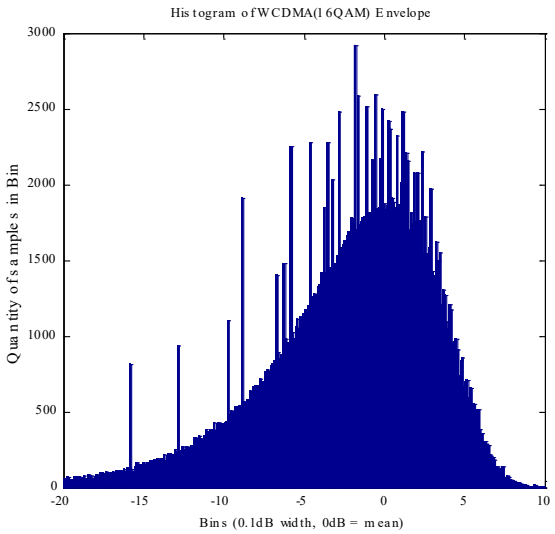
Figure 4.10 ACPR simulation test bench for W-CDMA/16QAM



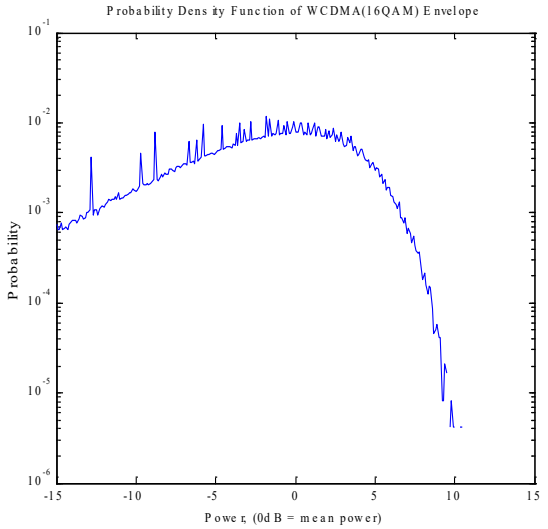
16QAM Constellation



W-CDMA constellation before filtering



Statistics of envelope



Finer details of envelope statistics

Figure 4.11 Results from W-CDMA/16QAM simulations

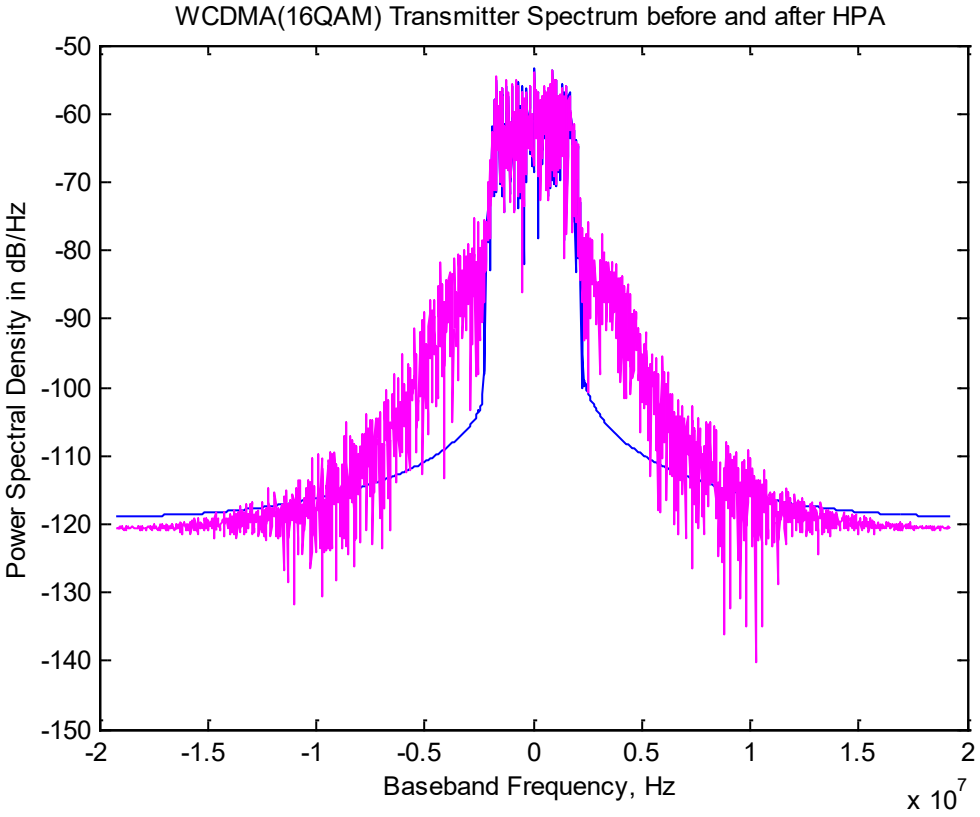


Figure 4.12 Spectral regrowth of W-CDMA/16QAM

Parameter	Specification	Units
Wanted Power Bandwidth	5	MHz
Adjacent Channel Bandwidth	3.84	MHz
Adjacent Channel Offset	5	MHz
	Result	
OBO for 30dB ACPR	5.25	dB

Table 4.3 ACPR results for W-CDMA/16QAM

4.3.4 OFDM/QPSK (DAB)

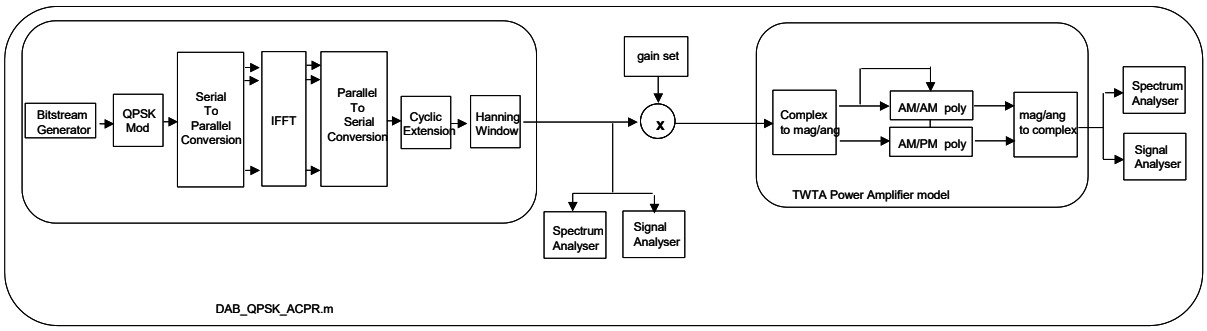
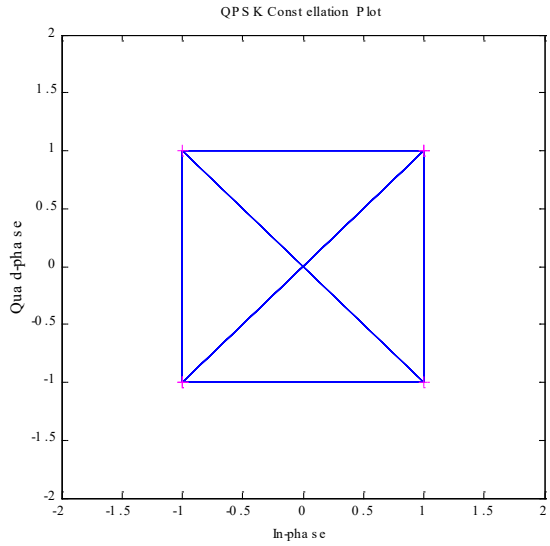
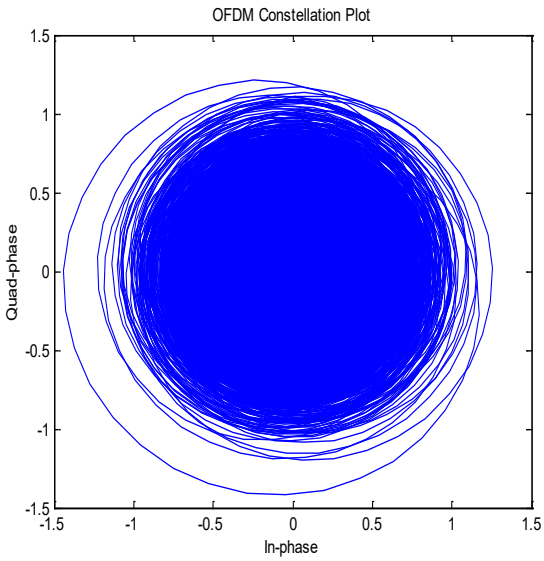


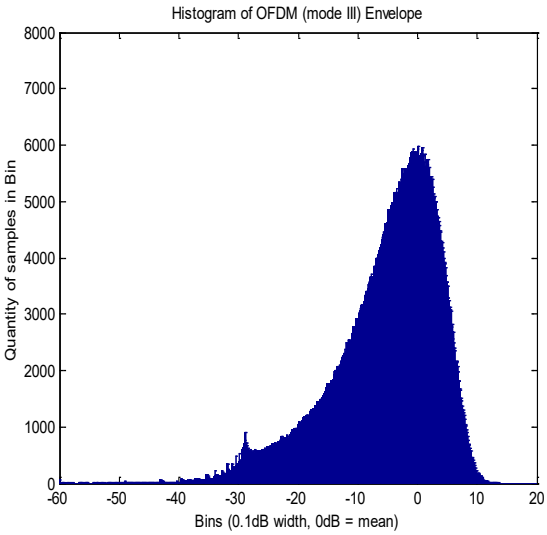
Figure 4.13 ACPR simulation test bench for OFDM/QPSK



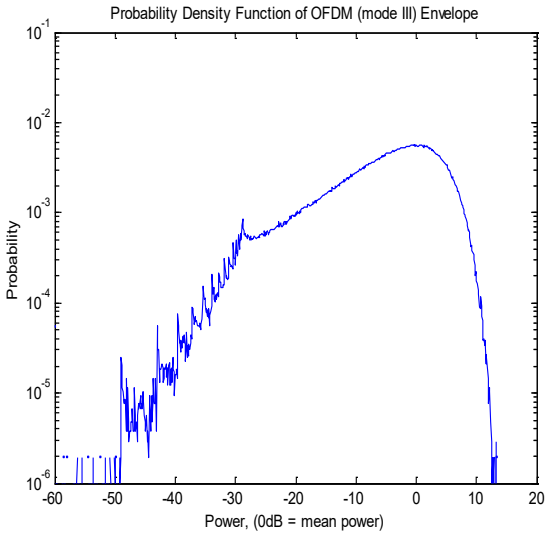
QPSK constellation



OFDM constellation



Statistics of envelope



Finer detail of envelope statistics

Figure 4.14 Results from OFDM/QPSK simulations

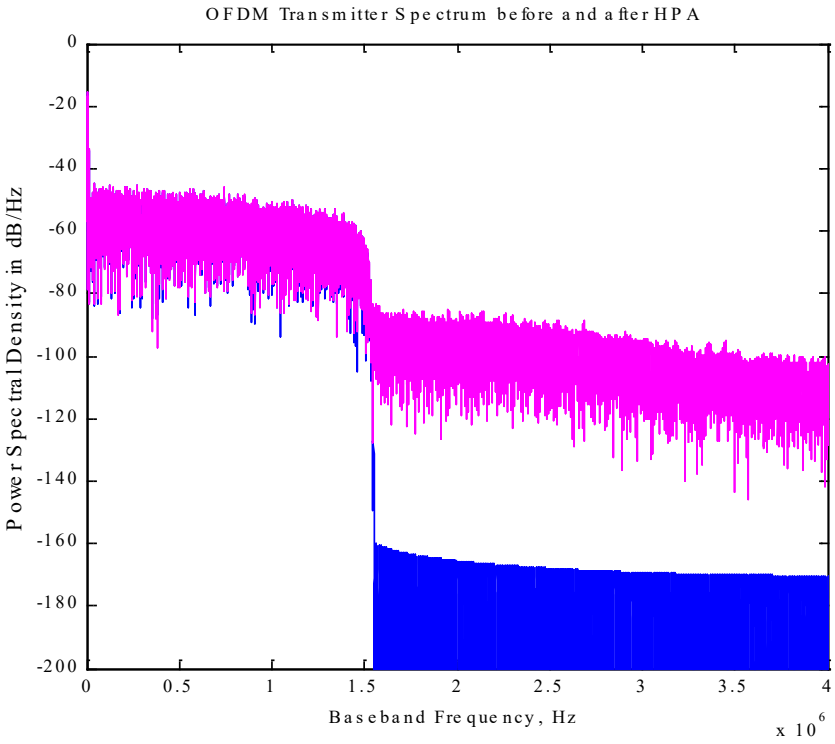
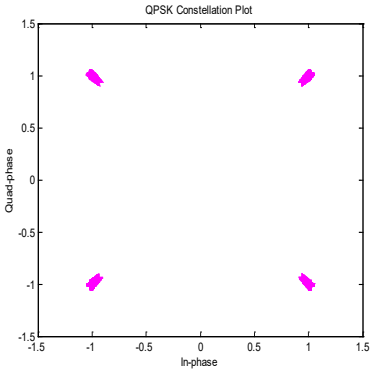


Figure 4.15 Spectral regrowth of OFDM/QPSK

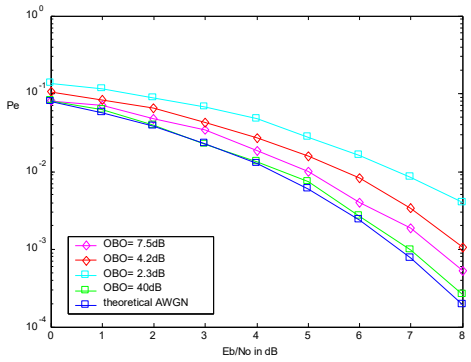
Parameter	Specification	Units
Wanted Power Bandwidth	1.6	MHz
Adjacent Channel Bandwidth	1.536	MHz
Adjacent Channel Offset	1.7	MHz
	Result	
OBO for 30dB ACPR	6.0	dB

Table 4.4 ACPR results for OFDM/QPSK

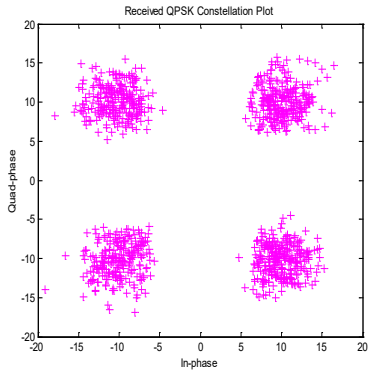
4.4 Effect of Compression on BER



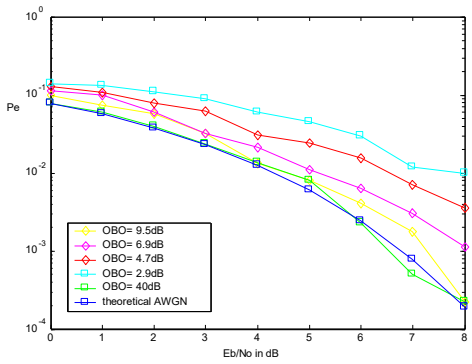
QPSK constellation



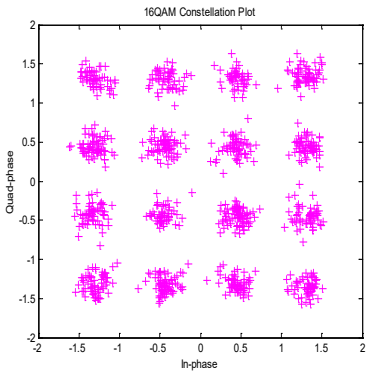
QPSK BER curves



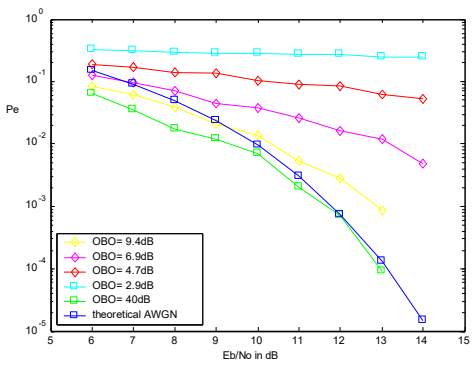
W-CDMA/QPSK constellation



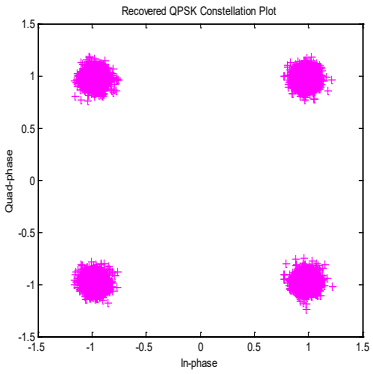
W-CDMA/QPSK BER curves



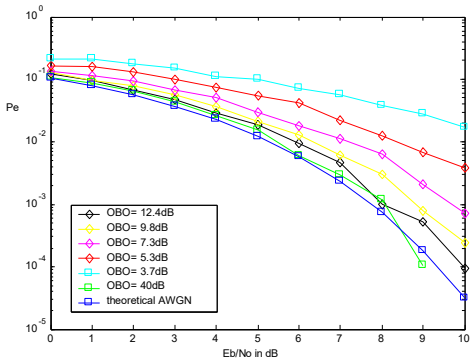
W-CDMA/16QAM constellation



W-CDMA/16QAM BER curves



OFDM/QPSK constellation



OFDM/QPSK BER curves

Figure 4.16 Simulation results in HPA and AWGN channel

4.5 Discussion on Simulation Results

The simulations show that for an ACPR of 30dB, the required OBO for QPSK is 2.8dB, for W-CDMA/QPSK and W-CDMA/16QAM it is 5.3dB and for OFDM it is 6dB. The bandwidths and offsets have been chosen to make a reasonably fair comparison and were estimated.

OBO also affects the required Eb/No for a specific BER. For example, QPSK needs an Eb/No of 4.1dB with no non-linearity but needs an Eb/No of 7dB through an HPA for a BER of 10^{-2} with an OBO of 2.3dB. This affects the link budget and is analysed in the final chapter.

The results are in line with expectations. QPSK requires small output backoff and can therefore be operated near saturation, which is one reason why it is so prevalent in satellite communications. W-CDMA and OFDM, on the other hand require additional backoff.

There are various techniques to control the peak-to-mean of OFDM including clipping and digital pre-processing methods. In practice, OFDM can be controlled to a peak-to-mean of approximately 8dB. It is also possible to reduce the peak-to-mean of W-CDMA.

In order to meet the ACPR specifications, the power amplifier can either be specified with enough headroom or it is possible to linearize the power amplifier. Methods of linearization include feedforward techniques, Cartesian loops, polar loops, pre-distortion or adaptive pre-distortion. Other techniques that could be used theoretically are to ensure the amplifier transfer function follows a purely second order curve or it may even be possible to pre-distort the earth station in a slow adaptive loop with the satellite HPA. Whilst many of these methods are common in terrestrial equipment, care must be taken over their use for satellites since they may be not as reliable as the brute force approach.

5 Channel Modelling

This chapter starts with a brief qualitative description of the channel and then provides details of the channel models used in the simulations.

Previously, four possible modulation/access schemes that could be used for multicast/broadcast to mobiles via satellite were highlighted. Also discussed was a possible scenario where the mobile would use the signal from the satellite when strong enough and use a terrestrial signal from a gapfiller when the path to the satellite was obstructed. The gapfiller is a repeater or transmodulator that picks up the signal from the satellite and retransmits locally. (Since a repeater does not use frequency translation, the gain of the amplifier chain and antennas has to be carefully controlled to avoid oscillation. Other techniques, including active equalisation and inserting a small frequency shift (that the mobile AFC would remove) can be applied to the repeater to ensure stability.)

As discussed earlier, there are many possible link scenarios, however for the purpose of the simulations in this project, it will be assumed that the satellite is geo-stationary and the repeater is fixed and terrestrial.

The channel from the satellite to repeater antenna is characterised by a dominant line of sight path with sky noise, ground noise, receiver noise and interference from other satellites/transponders and terrestrial systems the main interferers. The small signal level arriving at the repeater is mainly due to free space loss, but rain loss, atmospheric loss, scintillation, pointing loss, polarisation loss and implementation loss all add to the link budget. For a detailed description of link budget calculations, the reader is referred to [21] and [40]. Reference [51] provides a comprehensive description of the satellite fixed link channel.

The channel from the satellite directly to the mobile has all the effects detailed above, which can be used to calculate the mean power at the mobile, generally known as the mean path loss. However, this is not the only effect observed by a roaming mobile. The instantaneous power at the mobile fluctuates around the mean power. This deviation is accurately modelled by using the Lutz model. Although discussed in depth later in chapter 5.2.1, this model consists of two channel states. When in the good state, the channel is modelled as Ricean and when in the bad state, the channel is modelled as Rayleigh with shadowing. The good state refers to a situation where there is a strong line of sight path but with Rayleigh distributed interference usually from reflections surrounding the mobile (typically 100ns rms delay spread). The bad state refers to a situation where the line of sight path is obstructed and the signal arriving at the mobile is from scatterers and is therefore much weaker. Switching between these states is modelled by using a Markov model. For a single satellite system, the Markov model is two-state. However when using a two-satellite diversity

system, a four-state Markov model would be used. The switching probabilities used in the Markov model are dependent on satellite elevation, the environment and velocity. For a description and analysis of the Lutz model, the reader is referred to [38], [35] and [36]. Due to using a geo-stationary satellite with currently available eirp levels, the link is only just available with a low gain mobile antenna. Therefore, the link from the satellite is only feasible in the Lutz model good state. In the bad state, the satellite-mobile channel is assumed off and the mobile communicates via the terrestrial repeater. For this reason, the satellite-mobile channel is modelled as Ricean with a typical K of 5dB for urban and 15dB for highway environments. When the transmission is considered wideband, then there are numerous models available based on the delayed tap model with tap1 Ricean becoming smaller in amplitude and more Rayleigh for increasing delays. Reference [51] discusses satellite-mobile wideband models by Parks and Jahn.

The channel from the repeater to the mobile is modelled by splitting the total path loss into three parts. These are mean path loss, shadowing and fast fading, which can be independently modelled. As described earlier, there are various types of repeater with different EIRP levels. Link budgets for S-UMTS in reference [61] estimate a 400-metre cell radius for a lower power repeater and a 2km cell radius for a higher power repeater. The types of models to estimate the mean path loss are wide ranging and will vary upon the type of cell structure. Shadowing is normally modelled as log-normal with the standard deviation dependent on environment. The repeater would typically be used in a picocell or microcell environment but a macrocell environment is also possible. After estimating the mean path loss and shadowing, the fast fading is to be modelled. In many systems, the role of the receiver automatic gain control is to remove the variation from changes in mean path loss and shadowing. Fast transmit power control can also be used to track fading in a terrestrial system but not over satellite due to high delays. There are numerous strategies for coping with the fast fading including space, polarization and multipath diversity and forward error correction techniques. For terrestrial systems, a Rayleigh distribution is generally used. For wideband, frequency selective channels, a multipath model is used with each scaled delayed tap faded with a Rayleigh distribution.

The link budget can be visualised with the following graph. In the satellite-mobile channel, the Lutz channel good state refers to Ricean fading centred on the mean path loss. In practical systems the small scale fade margin is typically 5-10dB.

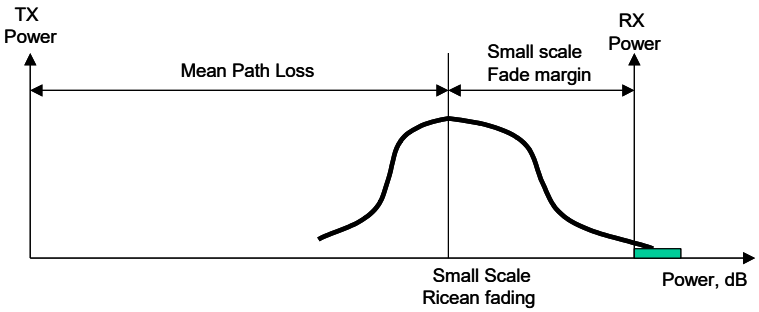


Figure 5.1 Satellite path loss power plan

In the terrestrial case from the repeater to the mobile, the link budget can be viewed as follows, which is also representative of the Lutz bad state.

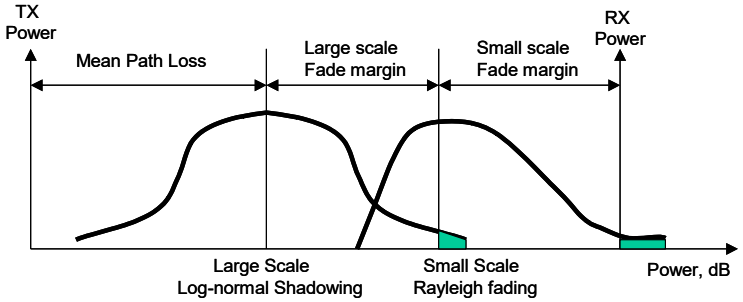


Figure 5.2 Terrestrial path loss power plan

In practical systems, the large-scale fade margin is typically 6-10dB and the small scale fade margin is typically 20-30dB. The higher the fade margin satisfactorily used in link budget calculations, the higher the link availability and the complexity of fading countermeasures can be reduced. However, designing for a large fade margin increases cost due to power increases for example.

It is important to apply the correct channel model to the signal, so it is necessary to explain fading and when to use the narrowband or wideband models. When the multipath delay spread is less than the symbol duration, flat fading occurs and is modelled using the single path Rayleigh or Ricean distributions, which causes a loss in signal to noise ratio. In the frequency domain, this can be described by stating the channel coherence bandwidth is greater than the symbol rate. However, when the multipath delay spread is greater than the symbol duration, then frequency selective fading occurs and a wideband channel model is used. Frequency selective fading results in an irreducible bit error rate due to inter symbol distortion and pulse mutilation. In the frequency domain, the channel is frequency selective if the channel coherence bandwidth is less than the symbol rate. The following table shows the type of channel model to be used for each modulation scheme:

Parameter	DVB-S	DARS	S-UMTS	S-UMTS	OFDM
Modulation	QPSK	QPSK	W-CDMA QPSK	W-CDMA 16QAM	pi/4 DQPSK
Approx. Symbol Duration	42ns	670ns	260ns	260ns	125us
Which Channel Model?					
Satellite-Mobile Channel rms delay spread 50-200ns	wide[1]	narrow	narrow[3]	narrow[3]	narrow
Repeater-Mobile Channel rms delay spread 0.4-20us	wide[1]	wide[1]	wide[2]	wide[2]	narrow[4]

Notes:
1. Requires equaliser to mitigate wideband fading.
2. Delayed paths spread into noise, which integrates to zero with perfect codes. If delayed paths are strong, longer than chip duration and less than bit duration, Rake receiver can be used to provide multipath diversity.
3. Some inter chip interference, which is integrated out and does not cause much intersymbol interference. Wideband model can be used to verify correlator.
4. Wideband model can be used to verify OFDM process.

Table 5.1 Type of channel for each system

The received signal at the mobile contains the wanted transmitted signal, which is varying in amplitude and phase as the mobile moves. Even if stationary, moving surroundings cause fading.

For coherent modulation schemes like QPSK, the demodulator requires phase coherent carrier recovery that needs to track the changing phase. Alternatively, a differential modulation can be used. Here provided the symbol rate is faster than the changing phase due to the channel, the symbol phasors are added with a constant phase error between symbols and the absolute phase at each symbol is removed. Differential modulation, which requires 2.6dB more power, is used in the DAB system. In the CDMA case, the Rake receiver employs an adaptive phase rotator for each finger.

Assuming the phase is removed using techniques described above, modelling can be performed using the multiplicative magnitude of the fading only. The Rayleigh and Ricean fading models describe the probability density of the fading magnitude. However, they do not describe the rate of change of the channel. For this, we look at the Doppler shift and second order statistics.

Doppler shift will be experienced by the mobile due to the satellite-earth movement and the speed of the mobile with respect to the Earth. Since the satellite-earth movement from a geo-stationary satellite is slow, it is assumed the Doppler

experienced will be negligible. The maximum Doppler shift experienced from the mobile speed relative to earth is 0Hz at 0km/hr to ±926Hz at 500km/hr at 2GHz. Since there are a multitude of received paths from different directions, the effect of Doppler is a frequency spreading from –Fd to +Fd, where

$$Fd = \frac{fc.v}{c}.\cos\theta \qquad \textbf{Equation 5.1}$$

Doppler spread viewed in the frequency domain produces a phenomenon known as random FM. The time-varying complex E and H fields arriving at the mobile antenna produce an apparent random frequency change with time, requiring a robust modulation and carrier recovery scheme. For a discussion on random FM, the reader is referred to [43].

Doppler spread, viewed in the time domain, has a direct impact on the fading second order statistics and can be observed by measuring the average fade duration and the level crossing rate. The faster the mobile travels the faster the channel changes in amplitude and phase. It is quite common to see the Doppler effect modelled by assuming the paths arrive horizontally and uniformly distributed over 2π radians - this leads to the classical Doppler spectrum. Later, Jakes sum of sinusoids model shall be explained, which provides a practical method to model channels with second order statistics.

Most modern systems have a channel-fading rate less than the symbol rate (i.e. the channel coherence time is greater than the symbol time). In this case, the fading amplitude can be assumed constant over each symbol. However, in high Doppler cases with low symbol rates, when the channel fading rate is greater than the symbol rate (i.e. the channel coherence time is less than the symbol time), an irreducible bit error rate floor occurs, getting worse with increasing speed, in addition to the carrier recovery loop losing lock.

5.1 Satellite – Repeater Channel

Since the repeater antenna gain is high and therefore highly directional toward the satellite, multipath reflections have been assumed negligible for this channel. It is also assumed in this case that the repeater is fixed and there is an unobstructed path to the satellite. Therefore the channel in this case is concerned with path loss only; shadowing due to obstructions and fast fading effects are assumed negligible. Of course if the repeater were located on a road vehicle, train or plane, then these effects would need to be taken into account.

When designing the link budget for this channel, if the repeater does not transmodulate, then we are aiming to provide enough link margin for the required percentage of time so that the noise temperature of the repeater low noise amplifier plays an insignificant part in the overall noise budget. In this case, most of the noise will be due to the low noise amplifier in the mobile receiver. If a transmodulator is used, perhaps converting coherent QPSK into COFDM, then the link budget is designed separately for the satellite-repeater path and for the repeater-mobile path. Details of link budget design are provided in [21] and [40].

The channel is described as an Additive white Gaussian noise channel. The AWGN channel is the best performance possible without channel coding and is used as a reference to compare faded channels against. In these simulations, two basic modulation schemes have been used: coherent QPSK and 16QAM. The theoretical performance is shown below:

QPSK

$$Pe = \frac{1}{2}.erfc\left(\sqrt{\frac{Eb}{No}}\right)$$

16QAM

$$Pe \le 2.erfc\left(\sqrt{\frac{2}{5}.\frac{Eb_{av}}{No}}\right)$$

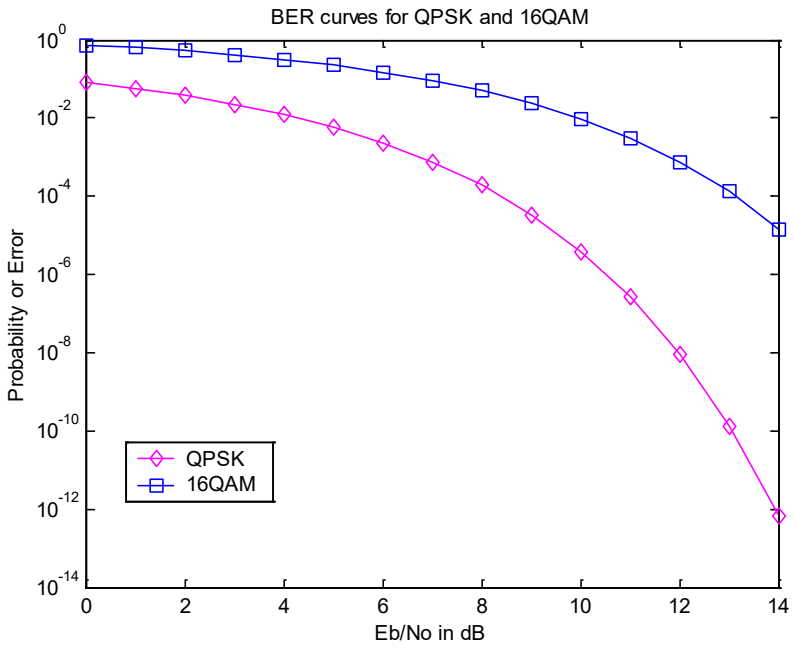


Figure 5.3 Theoretical performance of QPSK and 16QAM

5.2 Satellite – Mobile Channel Model

5.2.1 Lutz Model

To model the satellite-mobile channel, a two-state Lutz model is used. Since the loss from a GSO satellite is so great, the link is usually only achievable in the good state. For narrowband communications, the good state is modelled as a Ricean process. For wideband communications, the good state is modelled using the wideband model shown later. The Ricean K-factor is approximately 15dB for highway environments and 5dB for urban environments.

The following diagram shows the narrowband Lutz two-state model:

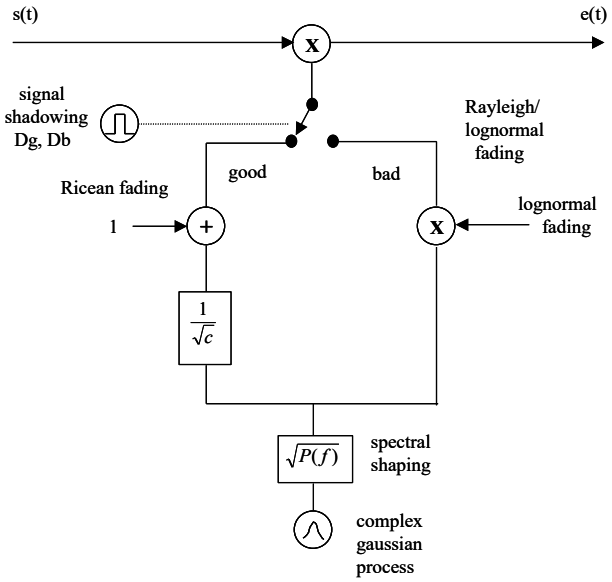


Figure 5.4 The Lutz model

Modelling the state statistics is performed using a Markov two-state model. The statistics differ predominantly depending on the satellite elevation, velocity and the environment. Further details of the model can be found in [38].

5.2.2 Jakes sum of sinusoids Model

Modelling a Rayleigh or Ricean process can be performed using a complex Gaussian noise source passed through a spectral shaping filter to model the Doppler spectrum. Alternatively, Jakes sum of sinusoids can be used and this model has been used here due to its simplicity. The following schematic shows the model. The top path comprises seven weighted sinusoids evenly spaced in frequency over the Doppler spread and with random phase. Due to the central limit theorem, the summing of these sinusoids approximates a Gaussian distribution. A similar process is shown for the bottom path. This group of sinusoids on each path is then added with a fixed sinewave that represents the line of sight component. The magnitude is then taken which represents the fading amplitude of the Ricean process.

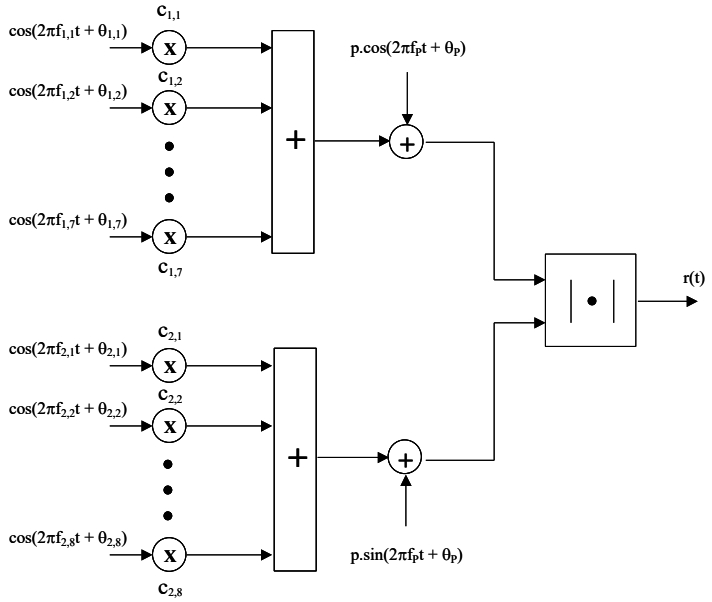


Figure 5.5 Sum of sinusoids model

The following equations were used in the simulation to determine the coefficients in the model above. Full details of the model are given in [44].

$$f\max = \frac{fc * speed}{3.6 * 299.8}$$ **Equation 5.2**

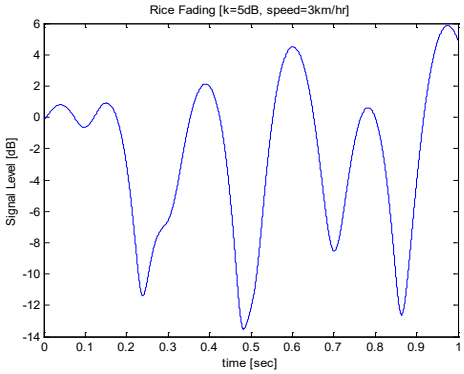
$$c_{i,n} = \sigma_0 \sqrt{\frac{2}{N_i}}, \quad for\ all\ n = 1,2,\cdots,N_i,\ i = 1,2\ and\ N_1 = 7, N_2 = 8$$ **Equation 5.3**

$$f_{i,n} = f\max.\sin\left[\frac{\pi}{2.N_i}.\left(n - \frac{1}{2}\right)\right], \quad for\ all\ n = 1,2,\cdots,N_i,\ i = 1,2\ and\ N_1 = 7, N_2 = 8$$ **Equation 5.4**

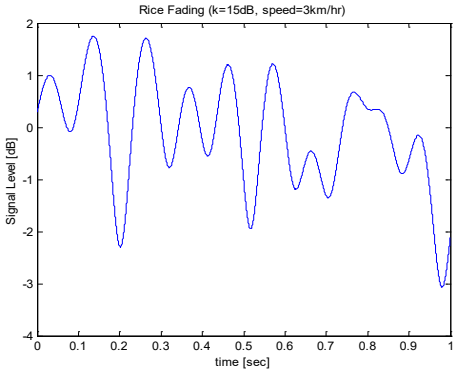
$$k = \frac{Power\ in\ LOS\ path}{Power\ in\ multipaths}$$ **Equation 5.5**

5.2.3 Narrowband Case

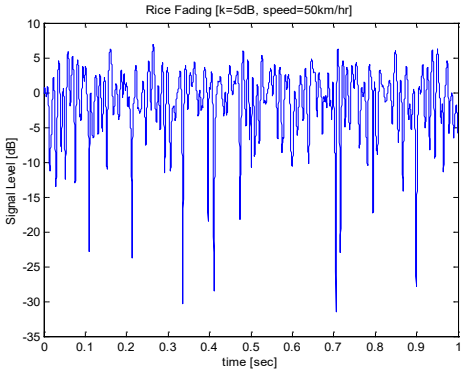
The following plots show the output from Jakes sum of sinusoids model for K values of 5dB and 15dB at a frequency of 2GHz. Speeds of 3km/hr, 50km/hr and 200km/hr are shown.



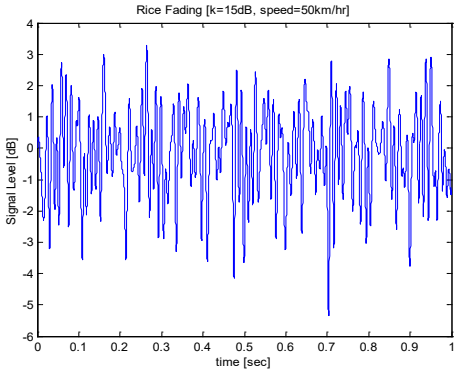
K=5dB, speed = 3km/hr



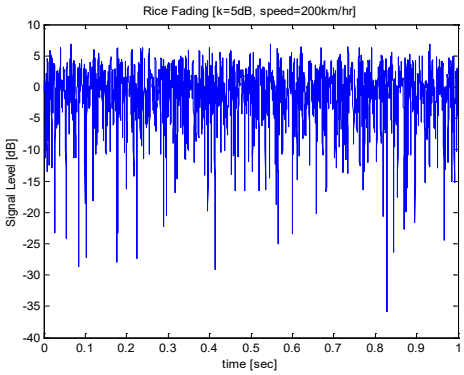
K=15dB, speed = 3km/hr



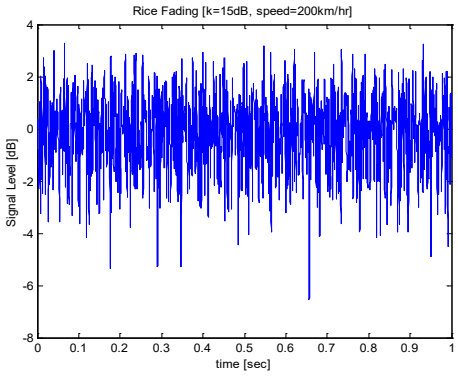
K=5dB, speed = 50km/hr



K=15dB, speed = 50km/hr



K=5dB, speed = 200km/hr



K=15dB, speed = 200km/hr

Figure 5.6 Example Ricean time domain waveforms

5.2.4 Wideband Case

The following model for a wideband satellite-mobile channel, given in [51] has been simulated and applied to each modulation scheme. Independent Ricean and Rayleigh processes using the sum of sinusoids model have been applied.

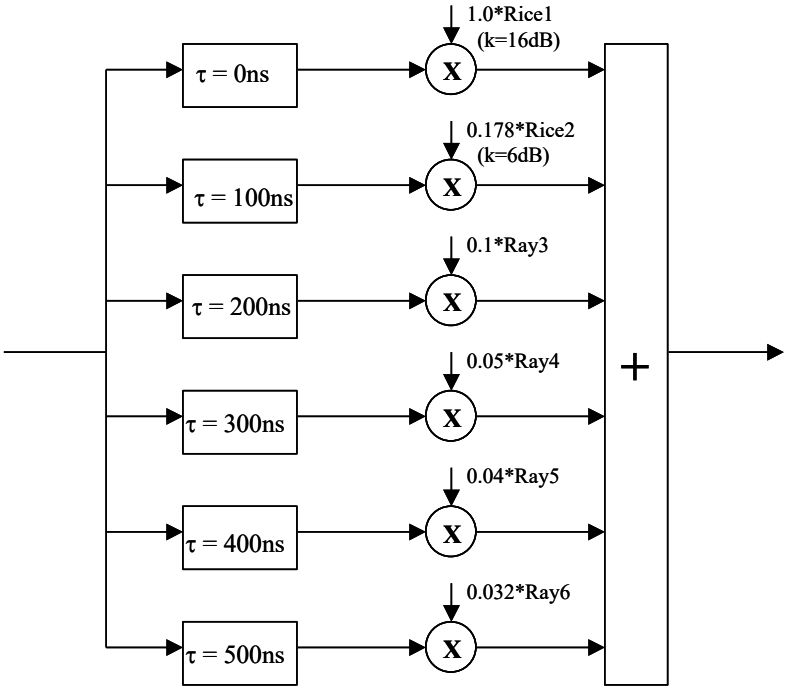


Figure 5.7 Satellite wideband channel model

The plot below on the left shows the output from each tap and the plot on the right shows their sum. Note that the sum is dominated by the first tap and little is to be gained from multipath diversity.

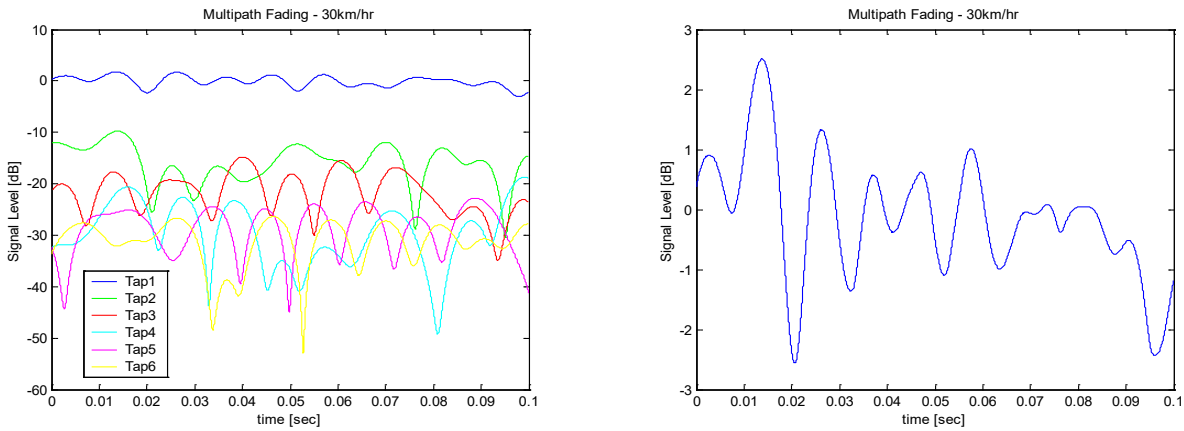


Figure 5.8 Satellite wideband channel model time domain waveforms

5.3 Terrestrial Repeater – Mobile Channel Model

5.3.1 Narrowband Case

Although for each of the four modulations schemes, the channel is considered wideband, it is important to understand the narrowband case as this gives the optimum performance after wideband mitigation methods have been applied. For example, OFDM performance in the wideband channel should be similar to that of a narrowband Rayleigh process. Rayleigh fading was again modelled using Jakes sum of sinusoids, where the line of sight component was set to zero.

In order to check the simulations, the theoretical performance of QPSK in a Rayleigh channel was plotted.

Coherent QPSK
in Rayleigh channel

$$Pe = \frac{1}{2}.\left[1 - \sqrt{\frac{\Gamma}{1+\Gamma}}\right]$$

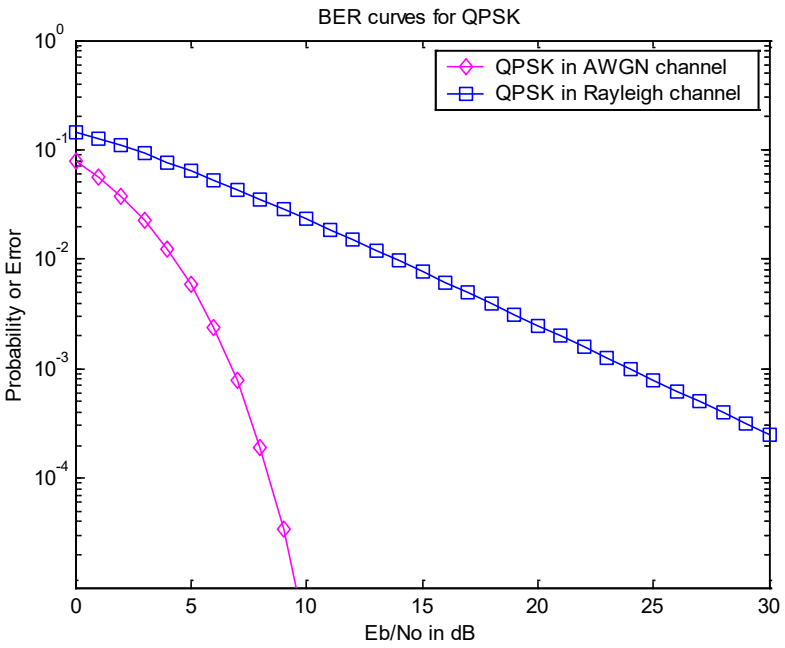


Figure 5.9 Theoretical performance of QPSK in Rayleigh channel

5.3.2 Wideband Case

The following model for a wideband repeater-mobile channel, given in [61] has been simulated and applied to each modulation scheme. Independent Rayleigh processes using the sum of sinusoids model have been applied.

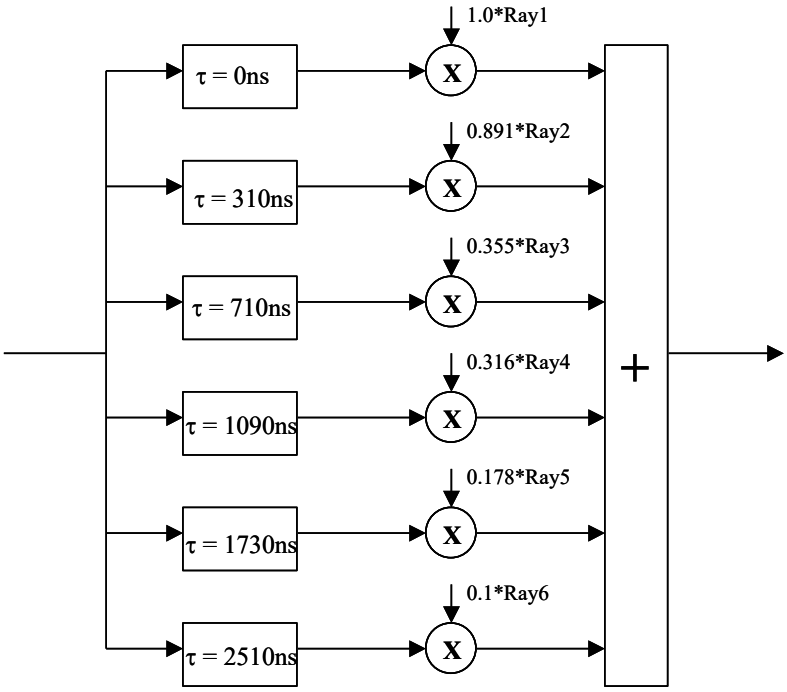


Figure 5.10 Terrestrial wideband channel model

The plot below on the left shows the output from each tap and the plot on the right shows their sum. Note that the sum has much reduced fluctuations and therefore, in the CDMA case, the Rake receiver can reduce single path fluctuations by combining all paths. This is known as multipath diversity.

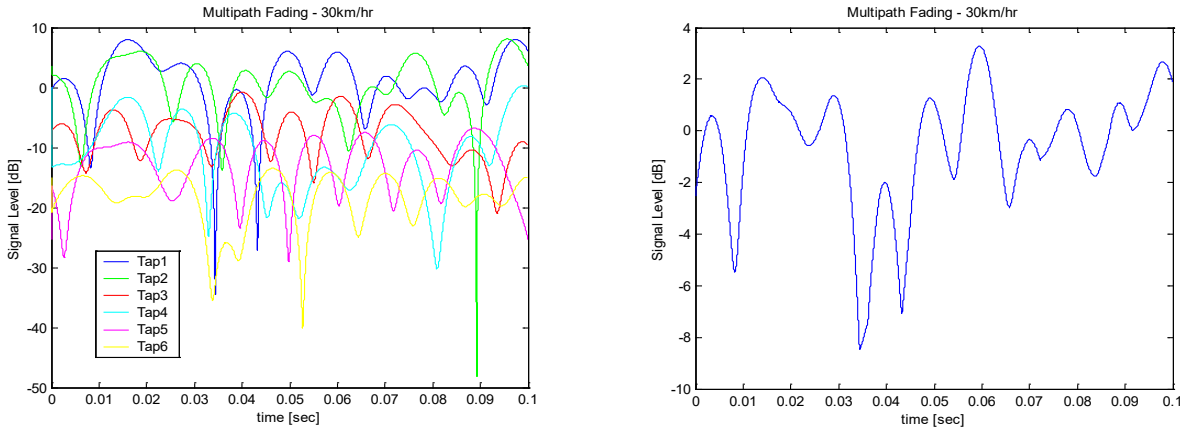


Figure 5.11 Terrestrial wideband channel model time domain waveforms

6 Narrowband Bit Error Rate Simulations

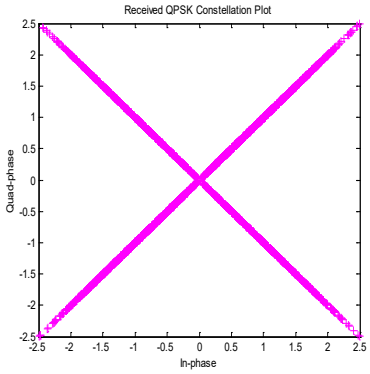
The following graphs show the results of the Monte Carlo simulations in narrowband channels. For each channel simulation, the theoretical additive white Gaussian noise case is presented to act as a reference.

Firstly, performance curves in a narrowband Rayleigh fading channel are given. These are given for terrestrial channels considered as narrowband and as a reference for how terrestrial channels can perform after mitigating wideband multipath fading.

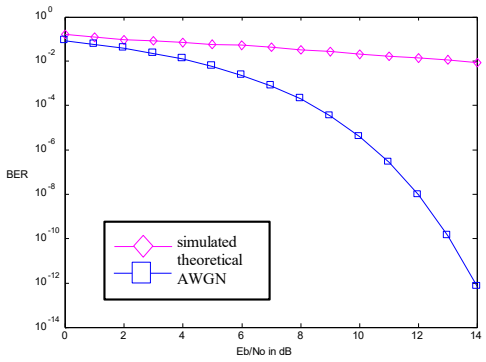
Two cases of narrowband Ricean channel performance curves are then provided. These are given for satellite channels considered as narrowband and as a reference for how satellite channels can perform after mitigating wideband multipath fading.

To the left of each performance curve, the noiseless constellation plot is given to aid understanding of the fading process.

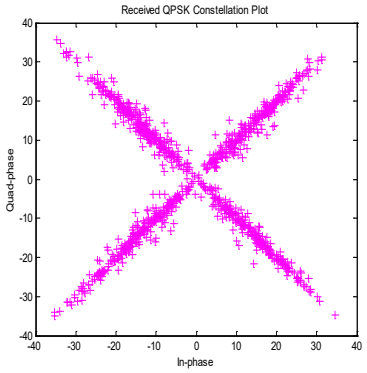
6.1 Bit Error Rate Performance in Rayleigh Channel



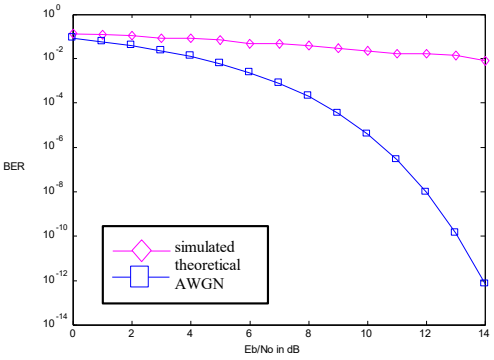
Received QPSK constellation



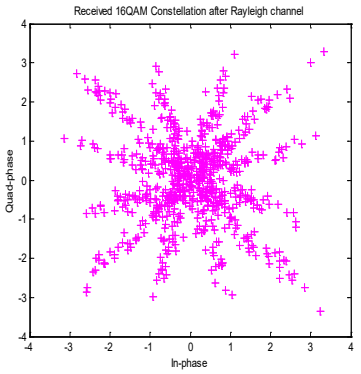
QPSK BER curves



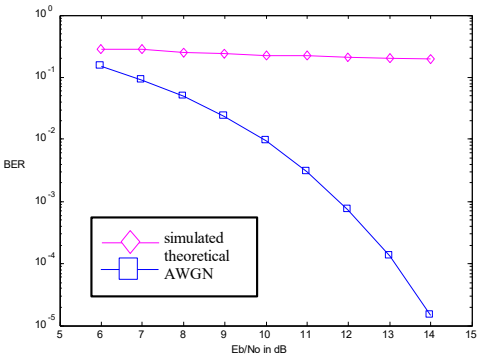
Received W-CDMA / QPSK constellation



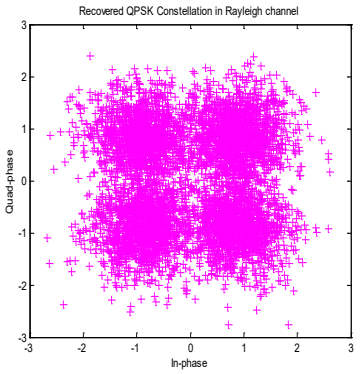
W-CDMA / QPSK BER curves



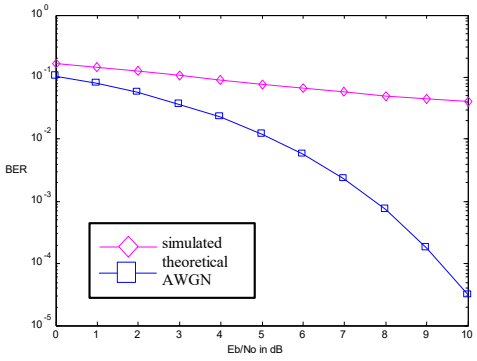
Received W-CDMA / 16QAM constellation



W-CDMA / 16QAM BER curves



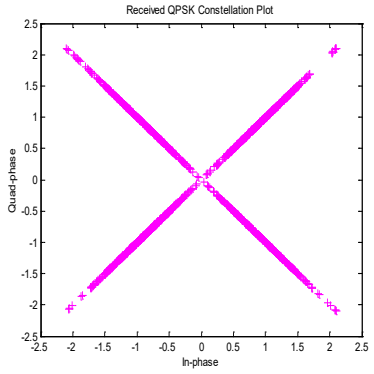
Received OFDM / QPSK constellation



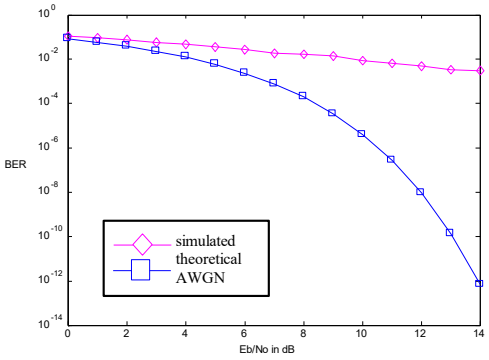
OFDM / QPSK BER curves

Figure 6.1 Simulation results in Rayleigh channel

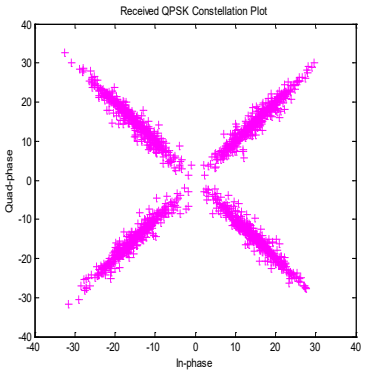
6.2 Bit Error Rate Performance in Ricean Channel (K=5dB)



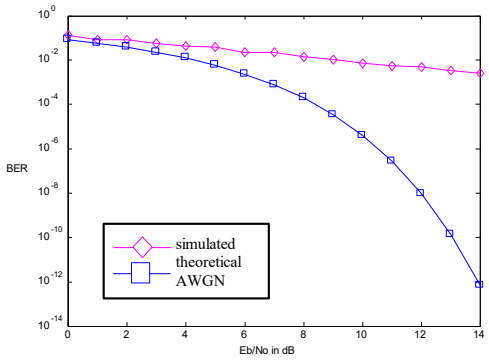
Received QPSK constellation



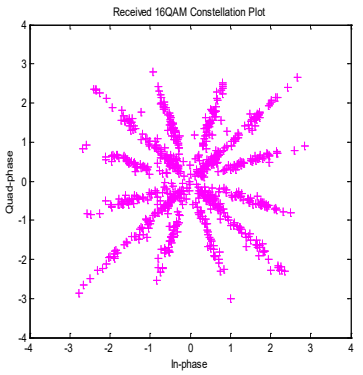
QPSK BER curves



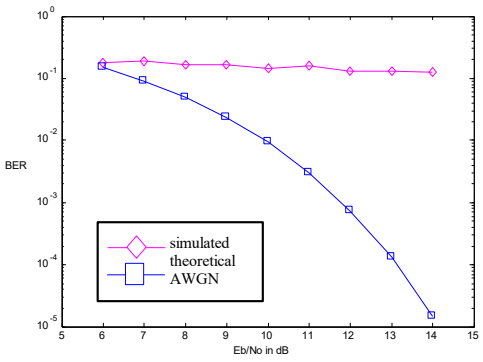
Received W-CDMA / QPSK constellation



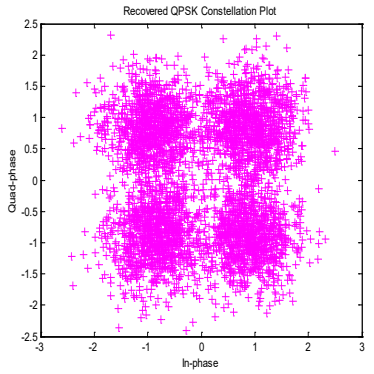
W-CDMA / QPSK BER curves



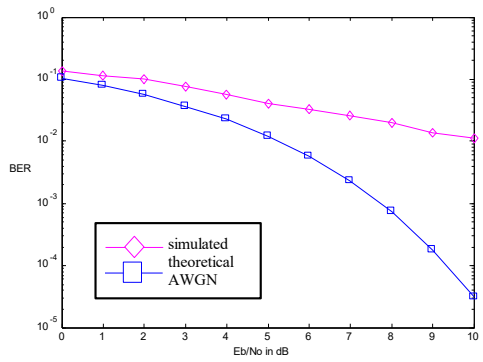
Received W-CDMA / 16QAM constellation



W-CDMA / 16QAM BER curves



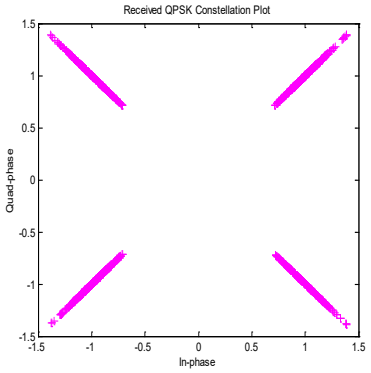
Received OFDM / QPSK constellation



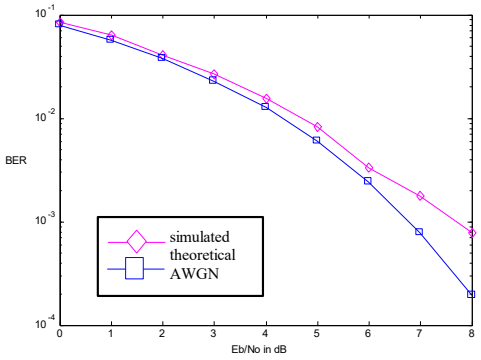
OFDM / QPSK BER curves

Figure 6.2 Simulation results in Ricean (k=5dB) channel

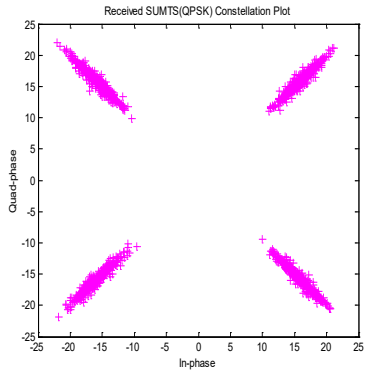
6.3 Bit Error Rate Performance in Ricean Channel (K=15dB)



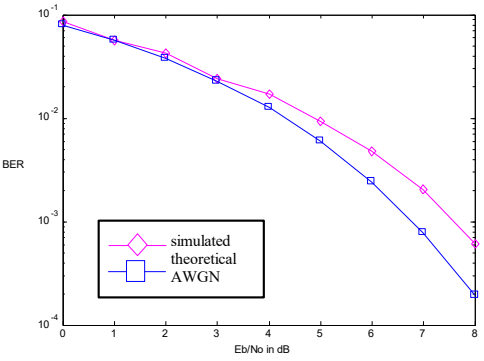
Received QPSK constellation



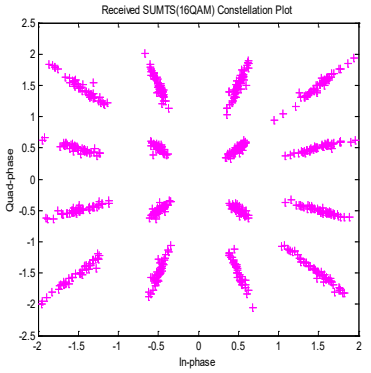
QPSK BER curves



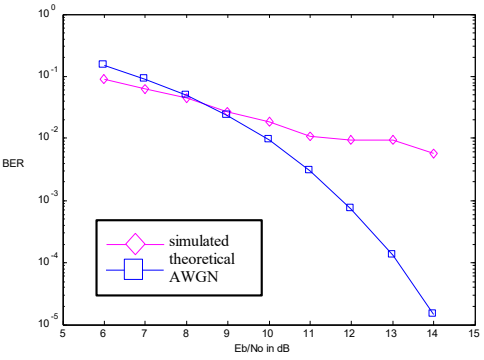
Received W-CDMA / QPSK constellation



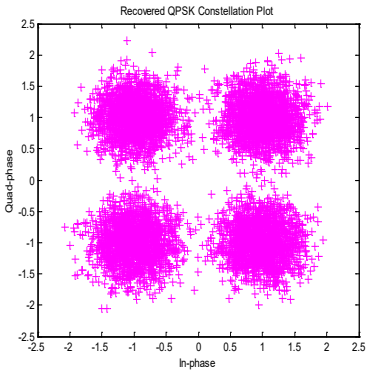
W-CDMA / QPSK BER curves



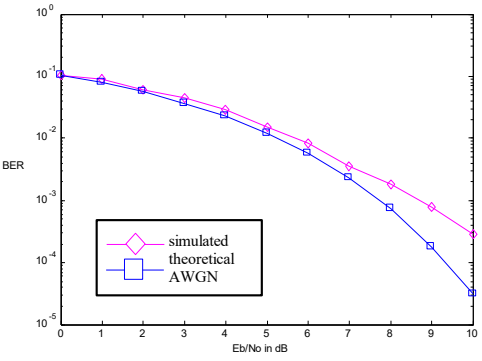
Received W-CDMA / 16QAM constellation



W-CDMA / 16QAM BER curves



Received OFDM / QPSK constellation



OFDM / QPSK BER curves

Figure 6.3 Simulation results in Ricean (k=15dB) channel

6.4 Discussion of Narrowband BER Simulations

The results above show each modulation scheme in a Rayleigh, Ricean (K=5dB) and Ricean (K=15dB) single-path fading channel. The theortetical AWGN case has been used as a reference.

In all cases, the left hand diagram shows the constellation plot with no noise present and the right hand diagram shows the bit error rate versus Eb/No curve. Although the fading varies the amplitude and phase, in these simulations it is assumed a perfect carrier recovery loop has removed the phase offset. The fading therefore simply varies the amplitude of the signal.

For the Rayleigh channel, the bit error rate curves for QPSK are in agreement with theory. Unfortunately it was not possible to locate the fading theory for 16QAM. In the 16QAM case with a Rayleigh channel, because the modulation is amplitude modulated, many of the points blend into each other without noise present. This means the bit error rate performance is poor regardless of the any noise present. As mentioned earlier, this problem can be removed in a terrestrial system using fast power control. However in a satellite link, fast power control is not possible due to the large delays. Fortunately, a satellite link with 16QAM is still possible since the channel is Ricean and not Rayleigh, although not very well particularly in the Ricean (K=5dB) case.

The OFDM results are very interesting since although the channel is fading in amplitude, the resulting constellation points form a circular shape. This means that a modulation scheme with high amplitude variations like 64QAM can be used with OFDM in a Rayleigh channel without complex fast power control provided there is enough Eb/No, making it an attractive solution, although complex fast power control would still be beneficial.

For the Ricean cases, the results are in line with theoretical expectations. The Ricean case with K=5dB experienced in urban environments performs little better than the Rayleigh case. However the Ricean case with K=15dB experienced in a highway environment is very much improved and approached the ideal AWGN case.

This section has dealt with a single path channel. However in many cases, as explained previously, the channel is wideband and therefore a multipath model is required. This is the subject of the next section.

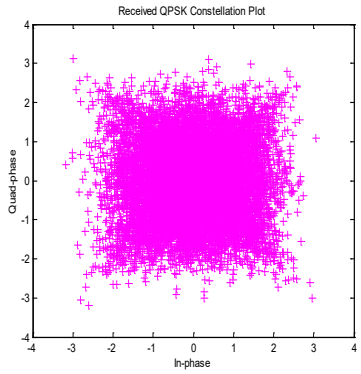
7 Wideband Bit Error Rate Simulations

The following graphs show the results of the Monte Carlo simulations in wideband channels. The performance curves in a terrestrial wideband Rayleigh fading channel are given. These highlight the severity of the problem. Comparing the wideband Rayleigh curves with the narrowband Rayleigh curves, gives an indication of the ability of each modulation to cope with wideband multipath.

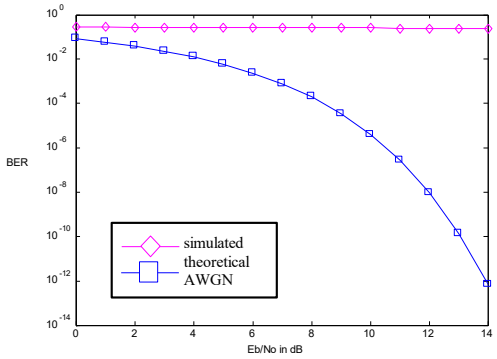
The performance curves in a satellite wideband Ricean/Rayleigh fading channel are then given. Again, comparing the wideband and narrowband performance curves gives good indication of the ability of the modulation to cope with wideband multipath. The satellite wideband channel is much less severe than the terrestrial wideband channel.

In the W-CDMA cases, a Rake receiver has not been implemented and is left for further work. To the left of each performance curve, the noiseless constellation plot is given to aid understanding of the fading process.

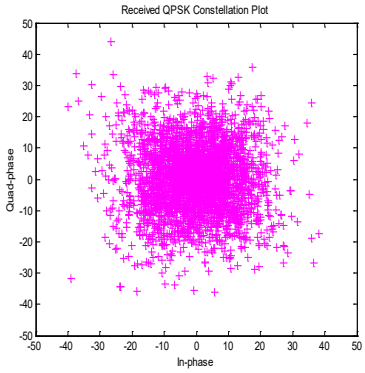
7.1 Bit Error Rate Performance in Wideband Terrestrial Channel



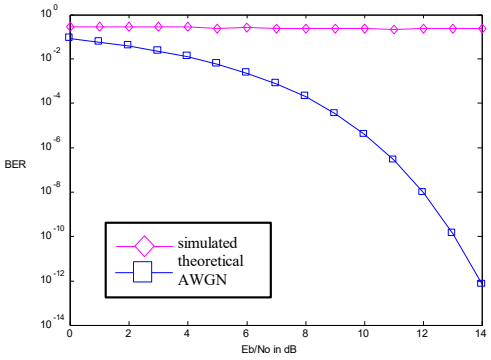
Received QPSK constellation



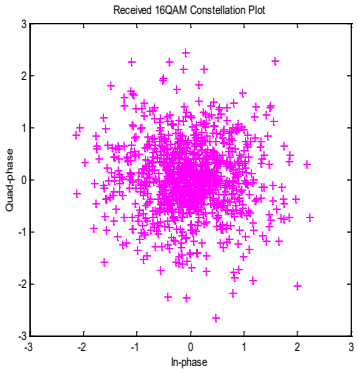
QPSK BER curves



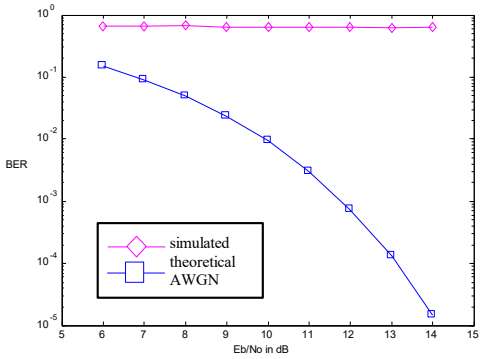
Received W-CDMA / QPSK constellation



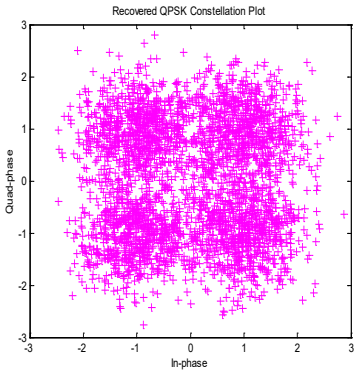
W-CDMA / QPSK BER curves



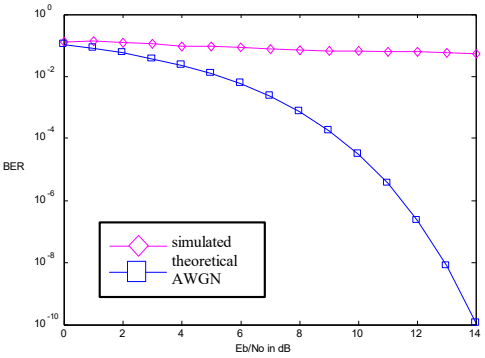
Received W-CDMA / 16QAM constellation



W-CDMA / 16QAM BER curves



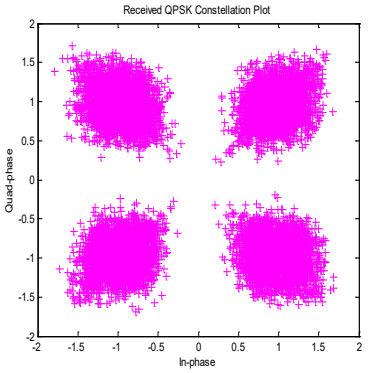
Received OFDM / QPSK constellation



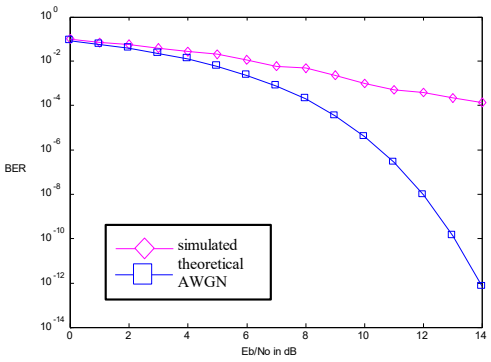
OFDM / QPSK BER curves

Figure 7.1 Simulation results in wideband terrestrial channel

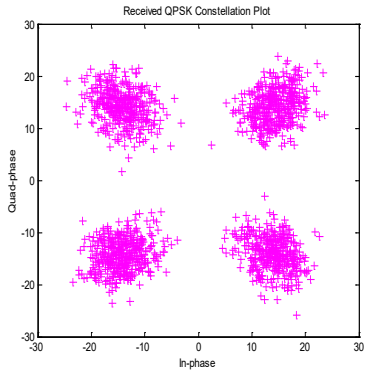
7.2 Bit Error Rate Performance in Wideband Satellite Channel



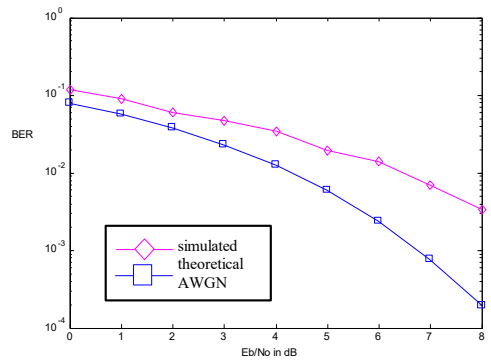
Received QPSK constellation



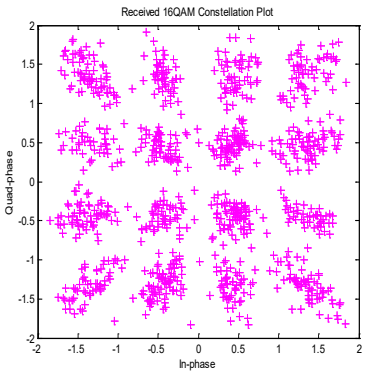
QPSK BER curves



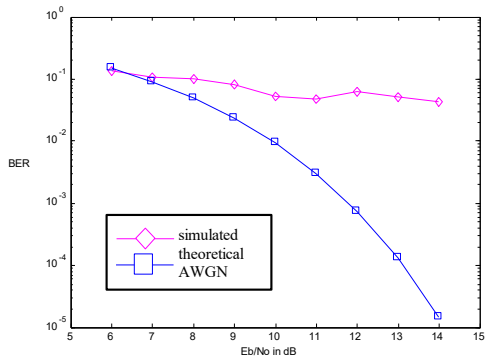
Received W-CDMA / QPSK constellation



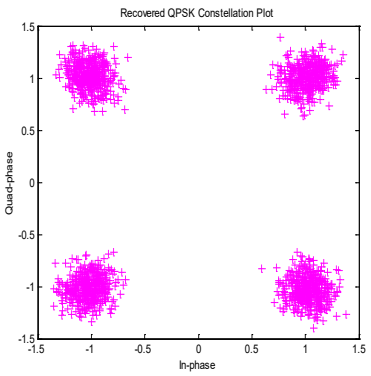
W-CDMA / QPSK BER curves



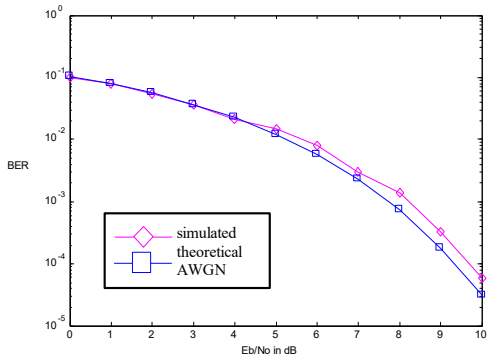
Received W-CDMA / 16QAM constellation



W-CDMA / 16QAM BER curves



Received OFDM / QPSK constellation



OFDM / QPSK BER curves

Figure 7.2 Simulation results of wideband satellite channel

7.3 Discussion of Wideband BER Simulations

The plots above show each modulation in both the terrestrial wideband channel and the satellite wideband channel. The plots on the left show the constellation without any noise added and the plots on the right show the bit error rate versus Eb/No curves.

In the terrestrial wideband case, the QPSK bit error rate approaches 0.5 and an equalizer is required to turn the channel back into the Rayleigh case. For the W-CDMA cases, again the bit error rate curves are approaching 0.5. In practice, a Rake receiver would improve the situation and even provide further improvements by multipath diversity. However, it is important to note that fast power control cannot be used via satellite due to the delays and signaling overhead. For the OFDM case, there is some resistance to multipath fading and the bit error rate curves are approaching the Rayleigh case.

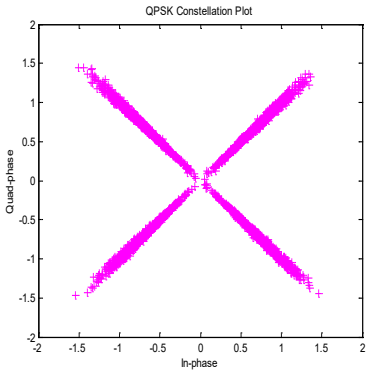
In the satellite wideband case, the performance is very much better because the first path is Ricean (K=16dB) and much stronger than the other delayed paths. However, for the QPSK case, the performance is not as good as a single path Ricean (K=16dB) channel and the multipaths have an effect. In the W-CDMA cases, the integrating action of the correlator does provide some resistance to multipath, since these secondary paths are spread and correlate to near zero. In the OFDM case, the performance in the wideband channel is almost as good as the first path alone as expected.

8 Combined effect of HPA and channel on BER

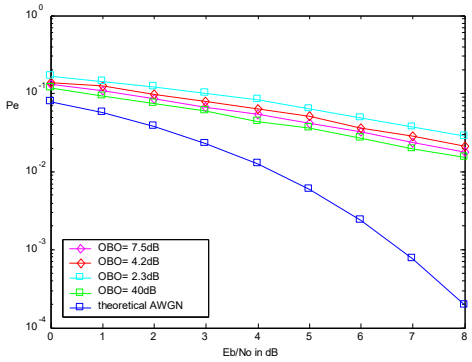
Once wideband channel effects have been dealt with, the satellite-mobile path can be accurately modelled as a single path Ricean (K = 5 to 15dB). However, there is an interaction between the HPA non-linearity and Ricean channel. Therefore, these two effects need to be modelled simultaneously.

The following plots show the effect of the HPA non-linearity on bit error rate in a narrowband Ricean channel. The plots to the left show the effect on the received constellation in a noiseless case with some combined HPA and channel effects. Note the HPA phase modulation has been removed for these simulations. In practice, the carrier recovery circuit would keep the average signal phase coherent but would not be fast enough to track all the phase modulation caused by the envelope variations. The effects of non-ideal carrier phase recovery are left for further work.

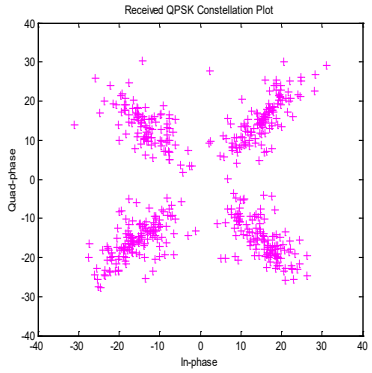
8.1 Bit Error Rate Performance in HPA and Ricean (K=5dB) Channel



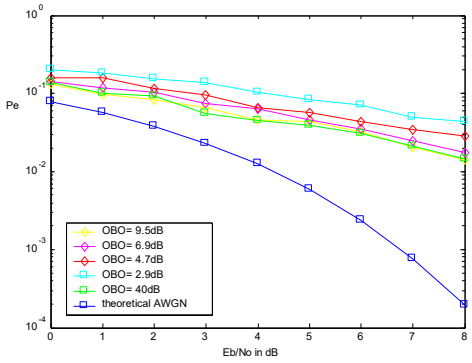
QPSK constellation



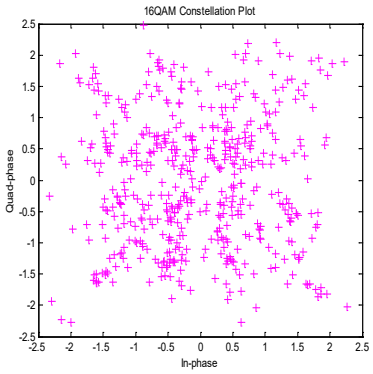
QPSK BER curves



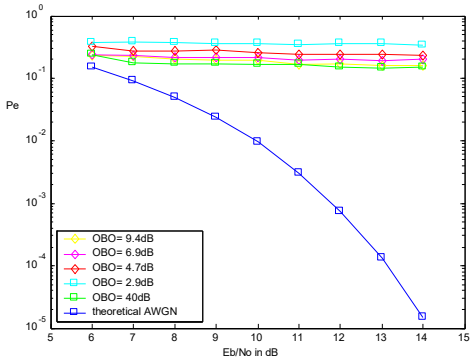
W-CDMA/QPSK constellation



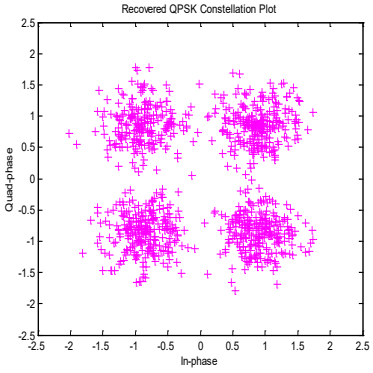
W-CDMA/QPSK BER curves



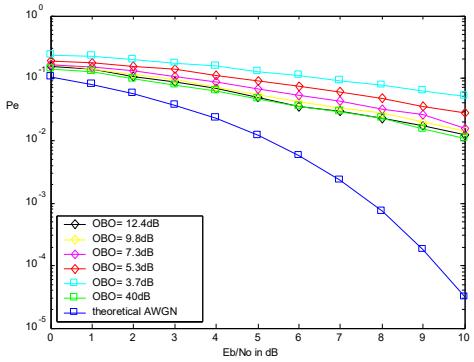
W-CDMA/16QAM constellation



W-CDMA/16QAM BER curves



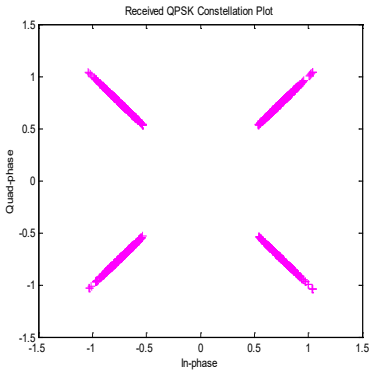
OFDM/QPSK constellation



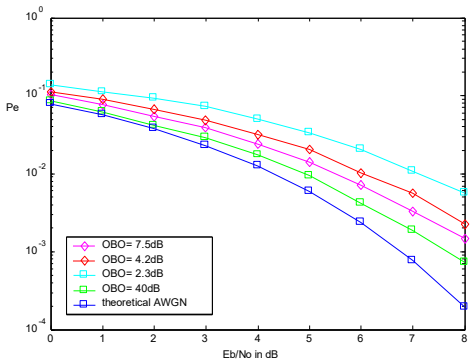
OFDM/QPSK BER curves

Figure 8.1 Simulation results in HPA and Ricean (K=5dB) channel

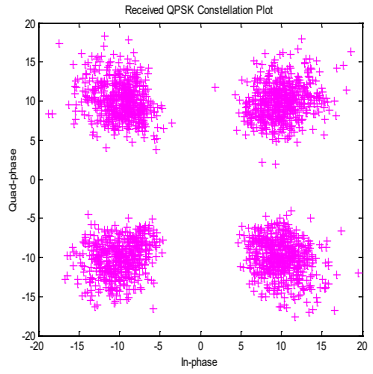
8.2 Bit Error Rate Performance in HPA and Ricean (K=15dB) Channel



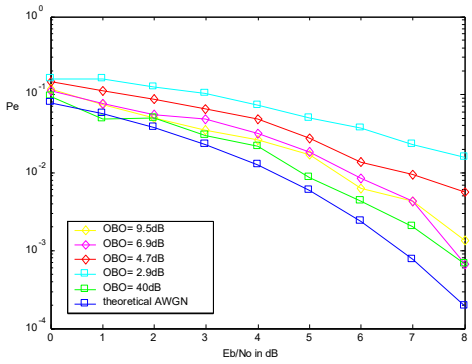
QPSK constellation



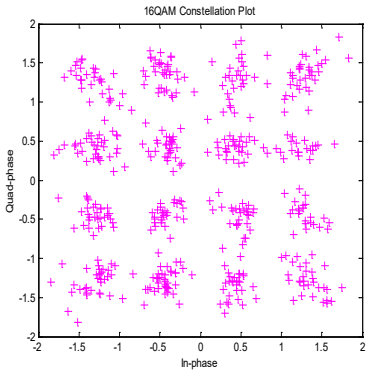
QPSK BER curves



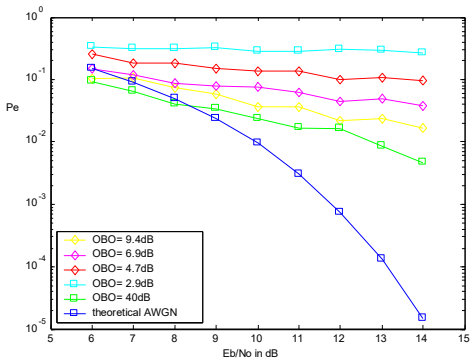
W-CDMA/QPSK constellation



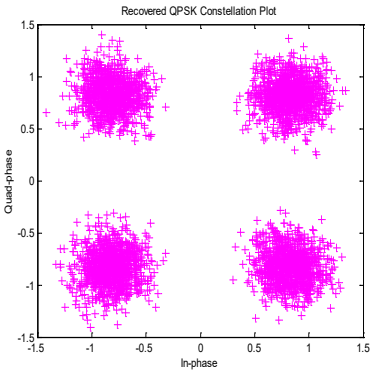
W-CDMA/QPSK BER curves



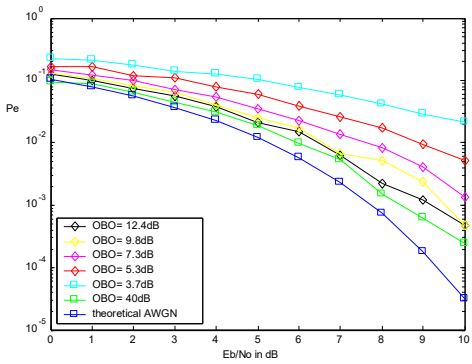
W-CDMA/16QAM constellation



W-CDMA/16QAM BER curves



OFDM/QPSK constellation



OFDM/QPSK BER curves

Figure 8.2 Simulation results in HPA and Ricean (K=15dB) channel

9 Summary of Findings and Recommendations for multicast/broadcast.

This project has compared five satellite systems for their suitability to deliver multicast/broadcast services to mobile phones. Simulations have concentrated on the effect of HPA non-linearity on BER and spectral regrowth, and the propagation channel on BER.

Simulations have assumed perfect carrier phase recover that tracks the phase changes in the propagation channel and HPA. In practice, this is not the case and is left for further work.

It has been shown that an equalizer can turn the effects of a wideband channel into a narrowband channel for QPSK. For the satellite-mobile path in the CDMA cases, it has been shown that a wideband channel can be modelled by taking the first tap only into account, since it is much stronger and the effect of the delayed taps are reduced by the correlation process. It was also shown that OFDM, due to the slowing down of the data, can also mitigate wideband effects and the channel can be accurately modelled as a single path.

In the case of a terrestrial repeater, the repeater-mobile path has much more severe multipath. Again, QPSK requires an equalizer and OFDM can mitigate the wideband effects. CDMA, on the other hand, now requires a Rake receiver to track the fading and coherently add energy from each path. The importance of power control in CDMA was shown, but due to the large delays from the satellite and large signalling overhead, it cannot be updated fast enough to track fast fading. Transmit power control is still used to overcome slow changes in received power at the mobile.

The satellite-mobile channel is only available when there is a LOS path. Without LOS, the mobile would receive its signal from a terrestrial repeater. The following analysis concentrates on the satellite-mobile path. System comparisons have therefore concentrated on a single path Ricean (K= 5dB to 15dB) channel combined with HPA non-linearity. The following table summarizes the results. They show the required Eb/No for a BER of 10^{-2} in each channel at various HPA backoffs.

Parameter	QPSK				CDMA/QPSK			CDMA/16QAM			OFDM/QPSK					Units
OBO for 30dB ACPR	2.81				5.35			5.25			6.0					dB
Eb/No for BER =10^{-2} in AWGN	4.1				4.1			9.8			5.0 (7.6 for DQPSK)					dB
Eb/No for BER =10^{-2} in HPA and AWGN channel	5.0	5.9	7.0		5.0	6.5	8.0	10.0	13.0	20.0	6.0	6.3	7.5	8.5	11.5	dB
OBO for above	7.5	4.2	2.3		6.9	4.7	2.9	9.4	6.9	4.7	12.4	9.8	7.3	5.3	3.7	dB
Eb/No for BER =10^{-2} in Ricean (5dB) channel	9.0				9.0			Cannot achieve			10.0					dB
Eb/No for BER =10^{-2} in HPA and Ricean (5dB) channel	9	10	12		9	10	12	Cannot achieve			10	10	11	13	16	dB
OBO for above	7.5	4.2	2.3		6.9	4.7	2.9	9.4	6.9	4.7	12.4	9.8	7.3	5.3	3.7	dB
Eb/No for BER =10^{-2} in Ricean (15dB) channel	4.5				4.8			11			5.5					dB
Eb/No for BER =10^{-2} in HPA and Ricean (15dB) channel	5.3	6	7		5.8	7	9	14	19	>25	6.2	6.3	7.4	9	12	dB
OBO for above	7.5	4.2	2.3		6.9	4.7	2.9	9.4	6.9	4.7	12.4	9.8	7.3	5.3	3.7	dB

Table 9.1 Summary of simulation results

From the table, the best HPA backoff can be found to maximize the link budget (shaded blue). Although operating near to saturation increases eirp, it requires a higher Eb/No and so is not the optimum level to operate. In practice, a certain backoff would be required to meet regulatory spectral emissions. The worst case in terms of link budget is the Ricean (K=5dB) and HPA channel. For example, for QPSK, operating at 2.3dB backoff requires an Eb/No of 12dB for a BER of 10^{-2} compared with an Eb/No of 7dB for the HPA alone. For each channel, the optimum backoff was chosen and entered into the following link budget, which compares the five systems.

Note that the link budget only considers the downlink and that many losses in a practical system have been removed for clarification. However, much comparative information can be gained from the table.

Also, note that for the DAB results, approximately 2.6dB must be added to the simulated results to reflect that the modulation is differential.

Parameter	DVB-S	DARS	S-UMTS	S-UMTS	DAB-S	Units
Modulation	QPSK	QPSK	WCDMA /QPSK	WCDMA /16QAM	COFDM /DQPSK	
Channel Bandwidth	36	4.2	5.0	5.0	1.536	MHz
Frequency	11.7	2.33	2.2	2.2	1.5	GHz
Free Space Loss	-205	-191	-190	-190	-187	dB
Saturated eirp/beam	55[2]	70	70	70	70	dBW
Mobile G/T[4]	-20(14[5])	-20	-20	-20	-20	dB/K
Boltzmann's constant	-228.6	-228.6	-228.6	-228.6	-228.6	dBW/K/Hz
HPA and AWGN channel						
Output backoff[3]	-2.3	-2.3	-2.9	-9.4	-5.3	dB
Downlink C/No[6]	56.3	85.3	85.7	79.2	86.3	dBHz
Required Eb/No[1]	7.0	7.0	8.0	10.0	11.1	dB
Required C/No	84.3	74.9	52.8	57.8	76	dBHz
Margin[7]	-28(6[5])	10.4	32.9	21.4	10.3	dB
HPA and Ricean (K=5dB) channel						
Output backoff[3]	-2.3	-2.3	-2.9	Not possible at 10^{-2}	-5.3	dB
Downlink C/No[6]	56.3	85.3	85.7		86.3	dBHz
Required Eb/No[1]	12.0	12.0	12.0		15.6	dB
Required C/No	89.3	79.9	56.8		80.5	dBHz
Margin[7]	-33	5.4	28.9		5.8	dB
HPA and Ricean (K=15dB) channel						
Output backoff[3]	-2.3	-2.3	-2.9	-9.4	-5.3	dB
Downlink C/No[6]	56.3	85.3	85.7	79.2	86.3	dBHz
Required Eb/No[1]	7.0	7.0	9.0	14.0	11.6	dB
Required C/No	84.3	74.9	53.8	61.8	76.5	dBHz
Margin[7]	-28	10.4	31.9	17.4	9.8	dB
Bit rate before channel coding	53.3	6.2	0.48	0.96	3.072	Mbit/s
Processing gain			12	12		dB

Notes:

1. Requirement for BER=10^{-2} with no channel coding and with hard decision slicing.
2. Based on footprint covering Great Britain.
3. Best efficiency/BER tradeoff in channel. Spectral emissions not taken into account.
4. Assumes 0dBi handheld mobile antenna.
5. Assumes fixed antenna with Bluetooth connection to mobile.
6. Atmospheric, pointing, rain and implementation losses not shown for clarity.
7. Calculations concentrate on downlink C/No only.

Table 9.2 Comparative link budget between systems

From the link budget, it is shown that a system based on DTH DVB-S is not possible with currently available satellite eirp levels due to the lower gain satellite antenna covering a wide geographical area. An extra 30dB of power is required in a Ricean (K=5dB) channel, which is only practical using higher gain satellite spotbeam antennas or higher gain fixed terrestrial antennas. Therefore introducing multicast/broadcast services concurrently through the same DTH DVB-S system would require a fixed high gain terrestrial antenna, which could be positioned at a repeater station.

Another system, also using coherent QPSK is the DARS system. In this case, satellite spotbeam antenna technology is used. For the worst-case channel, there is a 5.4dB link margin. This system would be suitable for multicast/broadcast. Each broadcast would be separated by TDM. A repeater would be required when a LOS is not available. Since the same material is being transmitted in each spotbeam, they could be on the same frequency. To offer different multicast services efficiently to different geographical locations could require separation of each cell in frequency.

WCDMA/QPSK, used for the S-UMTS system has a high link margin due to the low user data rate and the processing gain increase due to spreading. It performs well in a Ricean channel and only requires 2.9dB HPA backoff. Single cell frequency re-use is possible and there would be much commonality with T-UMTS in mobile transceiver design reducing cost, size and battery drain.

The WCDMA/16QAM system, proposed as a high-speed channel for T-UMTS, performs very badly in a channel without fast power control, only available in terrestrial systems. For example, in a Ricean (K=15dB) channel, 9.4dB of backoff and 14dB of Eb/No are required for a BER of 10^{-2}. For the Ricean (K=5dB) case, the channel is not available although a link may be possible with strong channel coding like Turbo coding and is left for further work. It would be essential to have some power control. It may be possible when the mobile speed is slow and the power control can track the power fluctuations. Power control and finding the maximum mobile speed are left as further work.

The DAB-S system using COFDM/ pi/4DQPSK is also suitable for multicast/broadcast. Although a backoff of 5.3dB and an Eb/No of 15.6dB are required for a BER of 10^{-2} in a Ricean (K=5dB) channel, the link is still achievable. A major advantage is the ability of OFDM to remove wideband effects in the repeater-mobile path. A single frequency network can be used. However, the receiver architecture is very different from that of T-UMTS increasing mobile cost, size and battery drain in a dual mode handset.

In all schemes especially DARS and DAB-S, when the uplink C/No and other losses are added, the link may become power limited and channel coding is required to reduce the Eb/No requirement although at the expense of a lower user bit rate.

To summarize, the link is possible in the DARS, S-UMTS (QPSK modulation) and DAB-S systems. S-UMTS offers the highest link margin. Other factors must be taken into account when deciding which system to use for multicast/broadcast. Since spectrum is so scarce, it is important to compare each system for its spectral efficiency. The following table shows the value of spectral efficiency in Bit/s/Hz for each system.

Parameter	**DVB-S**	**DARS**	**S-UMTS**	**S-UMTS**	**DAB-S**	**Units**
Modulation	QPSK	QPSK	WCDMA /QPSK	WCDMA /16QAM[8]	COFDM /DQPSK	
Channel Bandwidth	36	4.2	5.0	5.0	1.536	MHz
User Bit rate	53.3	6.2	0.48	0.96	3.072	Mbit/s
No. channels	1	1	15	15	1	
Spectral efficiency	1.48	1.48	1.44	2.88	2	Bit/s/Hz

Table 9.3 Spectral efficiency comparison

Out of the three systems identified so far based on link budget for multicast/broadcast, the DAB-S system offers the best spectral efficiency. This is very important as spectrum becomes scarcer and licences more expensive to the operators. However, using DAB-S requires more satellite HPA OBO and the satellite eirp could be reduced in the S-UMTS case making the HPA more expensive for DAB-S. In addition, incorporating a DAB-S receiver into a T-UMTS/GSM handset would increase cost of the handset whereas adding S-UMTS would not be as costly due to much commonality with T-UMTS. Another aspect is the amount of link margin. Recall that the link budget is based on a LOS path being available; having a high link margin would mean the link is still available with some path restriction from trees or building roofs for example. For these reasons, I would therefore suggest S-UMTS (modulated by QPSK) is optimum but further investigation into systems based on DARS, S-UMTS (modulated by QPSK) and DAB-S should be carried out.

The list of follow-on work is enormous - here is a list of potential research areas:

1. Channel coding for W-CDMA and OFDM
2. Peak-to-mean reduction techniques for W-CDMA and OFDM
3. Reliable power amplifier linearisation techniques for satellite
4. Deep interleaving for long bursts of fading
5. Further channel modelling based on measurements
6. Earth station satellite HPA pre-distortion
7. COFDM synchronization
8. Cheap mobile terminal integrated terrestrial/satellite transceiver architecture
9. The interaction channel
10. Using third party terminals as repeaters to remove gapfiller requirement
11. Model Rake receiver using MRC and actual Gold codes.
12. Effect and capability of carrier phase recovery loop to correct channel and HPA phase variations.

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11 Appendix A - ACPR Simulation Test Bench

11.1 QPSK (DVB-S)

```
%  MSc Project: "DVB versus S-UMTS for broadcast/multicast"
%  Student:  Pete King
%  Supervisor:  Professor Barry Evans
%
%  MATLAB file name:  DVB_QPSK_ACPR.m
%
%  This file simulates the ACPR generated in the HPA using coherent QPSK.
%
clear all
%%%%%%%%%%%%%%%%
%  Set up stream of data bits  %
%%%%%%%%%%%%%%%%
number_of_bits = 40000;
bit_stream = round(rand(1,number_of_bits));
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Convert from serial to parallel and make bipolar  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
i = 2 *bit_stream(1:2:number_of_bits) - 1;
q = 2 *bit_stream(2:2:number_of_bits) - 1;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Up-sample bit stream to enable filtering implementation  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
samples_per_bit = 10;
upsampled_i = zeros(1,length(i)*samples_per_bit);
upsampled_q = zeros(1,length(q)*samples_per_bit);
upsampled_i(1:samples_per_bit:end) = i;
upsampled_q(1:samples_per_bit:end) = q;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Calculate raised cosine impulse response and filter data  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
rrc_impulse = sqrt(samples_per_bit)*firrcos(501,1/samples_per_bit,0.35,2,'rolloff','sqrt');
% firrcos(n,F0,r,fs,'rolloff','sqrt')
scale = 3.16;
rrc_data_i = scale.*filter(rrc_impulse,1,upsampled_i);
rrc_data_q = scale.*filter(rrc_impulse,1,upsampled_q);
%%%%%%%%%%%%%%%%%%%%%%%%
%  Plot IQ constellation with filtered data  %
%%%%%%%%%%%%%%%%%%%%%%%%
figure(1);clf;
transient_delay = 251;
plot(rrc_data_i(1 + transient_delay:end),rrc_data_q(1 + transient_delay:end))
title('QPSK Constellation Plot')
xlabel('In-phase')
ylabel('Quad-phase')
hold on
plot(rrc_data_i(1 + transient_delay:samples_per_bit:end),rrc_data_q(1 +
transient_delay:samples_per_bit:end),'m+')
hold off
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Plot in-phase filtered data showing sampling points  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%figure(2);clf;
%delay = 51;
%plot(rrc_data_i(1+delay:600+delay))
%title('In-phase Data After RRC')
%xlabel('Samples')
%ylabel('Amplitude')
%hold on
%stem(upsampled_i(1:600))
%hold off
%%%%%%%%%%%%%%%%%%%%%%%%
```

```
%  Plot raised cosine impulse response  %
%%%%%%%%%%%%%%%%%%%%%
%figure(3);clf;
%stem(rrc_impulse)
%title('FIR Raised Cosine Impulse Response')
%xlabel('Samples (10 times oversampling)')
%ylabel('Amplitude')
%axis([1 500 -0.1 0.4])
%%%%%%%%%%%%
%  Set up time vector  %
%%%%%%%%%%%%
quad_mod_output = rrc_data_i + sqrt(-1)*rrc_data_q;
bit_rate = 51.8e6;
symbol_rate = bit_rate / 2;
time_step = 1 / symbol_rate / samples_per_bit;
time = (0:time_step:length(quad_mod_output) * time_step - time_step);
%%%%%%%%%%%%%%%%%%%%
%  Plot filtered in-phase data stream  %
%%%%%%%%%%%%%%%%%%%%
%figure(4);clf;
%plot(time,rrc_data_i)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Plot power spectral density centred around baseband  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure(50);clf;
freq_points = 4096/2;
[Pxx, w] = periodogram(quad_mod_output(501:end),[],'twosided',freq_points,(1 / time_step));
Dxx = zeros(1,freq_points);
Dxx(1:freq_points/2) = Pxx(freq_points/2+1:end);
Dxx(freq_points/2+1:end) = Pxx(1:freq_points/2);
ww = w - (1 / time_step)/2;
plot(ww,10*log10(Dxx))
title('QPSK Transmitter Spectrum at Baseband')
xlabel('Baseband Frequency, Hz')
ylabel('Power Spectral Density in dB/Hz')
%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Calculate channel power in 5MHz before HPA  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%
channel_bandwidth = 40e6;
frequency_resolution = freq_points / (1/time_step);
bandwidth_correction = -10*log10(frequency_resolution);
channel_power = sum(Dxx(round(freq_points/2-
frequency_resolution*channel_bandwidth/2):round(freq_points/2+frequency_resolution*channel_bandwidth/2)));
channel_power_dB = 10*log10(channel_power) + bandwidth_correction;
%fprintf('channel power before HPA = %.4g\n',channel_power_dB)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Calculate adjacent channel power before HPA  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%
channel_bandwidth = 36e6;
adjacent_channel_offset = 42e6;
frequency_resolution = freq_points / (1/time_step);
bandwidth_correction = -10*log10(frequency_resolution);
adjacent_channel_power = sum(Dxx(round(freq_points/2-adjacent_channel_offset*frequency_resolution-
frequency_resolution*channel_bandwidth/2):round(freq_points/2-
adjacent_channel_offset*frequency_resolution+frequency_resolution*channel_bandwidth/2)));
adjacent_channel_power_dB = 10*log10(adjacent_channel_power) + bandwidth_correction;
%fprintf('adjacent_channel power before HPA = %.4g\n',adjacent_channel_power_dB)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Plot envelope in dB and display mean and peak  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%figure(6);clf;
%plot(20*log10(abs(quad_mod_output)))
backoff = 0;
mean_power_dB = 10.*log10(( mean(    (abs(quad_mod_output(100:end))).^2    )) ./2);
peak_power_dB = 10.*log10(( max (    (abs(quad_mod_output(100:end))).^2    )) ./2);
envelope_rms = std(abs(quad_mod_output(100:end)));
peak_envelope = ( max (    (abs(quad_mod_output(100:end)))));
```

```
%fprintf('mean power before HPA = %.4g\n',mean_power_dB - backoff)
%fprintf('envelope rms before HPA = %.4g\n',envelope_rms)
%fprintf('envelope peak before HPA = %.4g\n',peak_envelope)
%fprintf('peak power before HPA = %.4g\n',peak_power_dB - backoff)
%fprintf('peak to mean before HPA = %.4g\n',peak_power_dB - mean_power_dB)
%fprintf('ACPR before HPA = %.4g\n',channel_power_dB - adjacent_channel_power_dB)
%%%%%%%%%%%%%%%%%%%%%%%%
%  Calculate and plot histogram of envelope  %
%%%%%%%%%%%%%%%%%%%%%%%%

instantaneous_power_dB = 10.*log10(  (  (abs(quad_mod_output)).^2)./2);

figure(6);clf;
bins = -40:0.1:20;
hist(instantaneous_power_dB(100:end) - mean_power_dB, bins);
axis([-20 10 0 6000])
title('Histogram of QPSK Envelope')
xlabel('Bins (0.1dB width, 0dB = mean)')
ylabel('Quantity of samples in Bin')
%%%%%%%%%%%%%%%%%%%%%%%%
%  Calculate and plot pdf of envelope  %
%%%%%%%%%%%%%%%%%%%%%%%%
figure(11);clf;
bins = -40:0.1:20;
[sample_bins,power_bins]=hist(instantaneous_power_dB(100:end) - mean_power_dB, bins);
semilogy(power_bins,sample_bins/length(instantaneous_power_dB(100:end)))
axis([-14 6 1e-6 1e-1])
title('Probability Density Function of QPSK Envelope')
xlabel('Power, (0dB = mean power)')
ylabel('Probability')
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Create AM-AM and AM-PM interpolated curves from measured data  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
b_off = 39;
backoff = 96.39 - b_off;
Pin_dBW = instantaneous_power_dB - backoff;
r = sqrt((10.^(Pin_dBW./10)).*2);
%r = sqrt(r_W);
a = 1.6623e3;
b = 5.52e4;

A = (a.*r)./(1+b.*r.^2);
Pout_dBW = 20.*log10(A);

c = 1.533e5;
d = 3.456e5;
B = (c.*r.^2)./(1+d.*r.^2);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Apply WCDMA to non-linear amplifier curves and plot power spectral density  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
quad_mod_output_phase_rads = angle(quad_mod_output);
HPA_output_phase_rads = quad_mod_output_phase_rads + B;
HPA_output = A .* exp(sqrt(-1) .* HPA_output_phase_rads);

mean_power_before_dBW = 10.*log10(( mean(    (abs(quad_mod_output(100:end))).^2    )) ./2);
peak_power_before_dBW = 10.*log10(( max (    (abs(quad_mod_output(100:end))).^2    )) ./2);
mean_power_after_dBW = 10.*log10(( mean(    (abs(HPA_output(100:end))).^2    )) ./2);
peak_power_after_dBW = 10.*log10(( max (    (abs(HPA_output(100:end))).^2    )) ./2);

fprintf('mean power before HPA = %.4g\n',mean_power_before_dBW)
fprintf('peak power before HPA = %.4g\n',peak_power_before_dBW)
fprintf('mean power after HPA = %.4g\n',mean_power_after_dBW)
fprintf('peak power after HPA = %.4g\n',peak_power_after_dBW)

figure(51);clf;
freq_points = 4096/2;
[Pxx, w] = periodogram(quad_mod_output(501:end),[],'twosided',freq_points,(1 / time_step));
```

```
Dxx = zeros(1,freq_points);
Dxx(1:freq_points/2) = Pxx(freq_points/2+1:end);
Dxx(freq_points/2+1:end) = Pxx(1:freq_points/2);
ww = w - (1 / time_step)/2;
plot(ww,10*log10(Dxx))
title('QPSK Transmitter Spectrum at Baseband')
xlabel('Baseband Frequency, Hz')
ylabel('Power Spectral Density in dB/Hz')

figure(80);clf;
[Power_spectrum_quad_mod_output, frequency_quad_mod_output] =
periodogram(quad_mod_output(501:end),[],'twosided',freq_points,(1 / time_step));
Power_spectrum_quad_mod_output_complex_baseband = zeros(1,freq_points);
Power_spectrum_quad_mod_output_complex_baseband(1:freq_points/2) =
Power_spectrum_quad_mod_output(freq_points/2+1:end);
Power_spectrum_quad_mod_output_complex_baseband(freq_points/2+1:end) =
Power_spectrum_quad_mod_output(1:freq_points/2);
frequency_quad_mod_output_shifted = frequency_quad_mod_output - (1 / time_step)/2;
plot(frequency_quad_mod_output_shifted,10*log10(Power_spectrum_quad_mod_output_complex_baseband))
title('QPSK Transmitter Spectrum before and after HPA')
xlabel('Baseband Frequency, Hz')
ylabel('Power Spectral Density in dB/Hz')
[Power_spectrum_HPA_output, frequency_HPA_output] =
periodogram(HPA_output(501:end),[],'twosided',freq_points,(1 / time_step));
Power_spectrum_HPA_output_complex_baseband = zeros(1,freq_points);
Power_spectrum_HPA_output_complex_baseband(1:freq_points/2) =
Power_spectrum_HPA_output(freq_points/2+1:end);
Power_spectrum_HPA_output_complex_baseband(freq_points/2+1:end) =
Power_spectrum_HPA_output(1:freq_points/2);
frequency_HPA_output_shifted = frequency_HPA_output - (1 / time_step)/2;
hold on
plot(frequency_HPA_output_shifted,10*log10(Power_spectrum_HPA_output_complex_baseband),'m')
hold off
%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Calculate channel power in 40MHz after HPA  %
%%%%%%%%%%%%%%%%%%%%%%%%%%
channel_bandwidth = 36e6;
frequency_resolution = freq_points / (1/time_step);
bandwidth_correction = -10*log10(frequency_resolution);
channel_power = sum(Power_spectrum_HPA_output_complex_baseband(round(freq_points/2-
frequency_resolution*channel_bandwidth/2):round(freq_points/2+frequency_resolution*channel_bandwidth/2)));
channel_power_HPA_dB = 10*log10(channel_power) + bandwidth_correction;
fprintf('channel power in 40MHz after HPA = %.4g\n',channel_power_HPA_dB)
%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Calculate adjacent channel power after HPA  %
%%%%%%%%%%%%%%%%%%%%%%%%%%
channel_bandwidth = 36e6;
adjacent_channel_offset = 42e6;
frequency_resolution = freq_points / (1/time_step);
bandwidth_correction = -10*log10(frequency_resolution);
adjacent_channel_power = sum(Power_spectrum_HPA_output_complex_baseband(round(freq_points/2-
adjacent_channel_offset*frequency_resolution-frequency_resolution*channel_bandwidth/2):round(freq_points/2-
adjacent_channel_offset*frequency_resolution+frequency_resolution*channel_bandwidth/2)));
adjacent_channel_power_HPA_dB = 10*log10(adjacent_channel_power) + bandwidth_correction;
fprintf('adjacent_channel power = %.4g\n',adjacent_channel_power_HPA_dB)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Plot envelope in dB and display mean and peak after HPA %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure(9);clf;
plot(20*log10(abs(HPA_output(100:end))))
mean_power_HPA_dB = 20*log10(mean(abs(HPA_output(100:end))));
peak_power_HPA_dB = 20*log10(max(abs(HPA_output(100:end))));
%fprintf('mean power after HPA = %.4g\n',mean_power_HPA_dB)
%fprintf('peak power after HPA= %.4g\n',peak_power_HPA_dB)
%fprintf('peak to mean after HPA= %.4g\n',peak_power_HPA_dB - mean_power_HPA_dB)
fprintf('ACPR after HPA= %.4g\n',channel_power_HPA_dB - adjacent_channel_power_HPA_dB)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
%  Calculate and plot histogram of envelope after HPA %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
HPA_output_envelope_dB = 20*log10(abs(HPA_output));
figure(10);clf;
bins = -40:0.1:20;
hist(HPA_output_envelope_dB(100:end) - mean_power_HPA_dB, bins)
title('Histogram of QPSK Envelope after HPA')
xlabel('Bins (0.1dB width, centred around mean)')
ylabel('Quantity of samples in Bin')
```

11.2 W-CDMA/QPSK (S-UMTS)

```
%  MSc Project: "DVB versus S-UMTS for broadcast/multicast"
%  Student:  Pete King
%  Supervisor:  Professor Barry Evans
%
%  MATLAB file name:  SUMTS_QPSK_ACPR.m
%
%  This file simulates the ACPR generated in the HPA using W-CDMA / QPSK.
%
clear all;
%%%%%%%%%%%%%%%
%  Set up stream of data bits  %
%%%%%%%%%%%%%%%
number_of_bits = 1000;
bit_streamCh1 = round(rand(1,number_of_bits));
bit_streamCh2 = round(rand(1,number_of_bits));
bit_streamCh3 = round(rand(1,number_of_bits));
bit_streamCh4 = round(rand(1,number_of_bits));
bit_streamCh5 = round(rand(1,number_of_bits));
bit_streamCh6 = round(rand(1,number_of_bits));
bit_streamCh7 = round(rand(1,number_of_bits));
bit_streamCh8 = round(rand(1,number_of_bits));
bit_streamCh9 = round(rand(1,number_of_bits));
bit_streamCh10 = round(rand(1,number_of_bits));
bit_streamCh11 = round(rand(1,number_of_bits));
bit_streamCh12 = round(rand(1,number_of_bits));
bit_streamCh13 = round(rand(1,number_of_bits));
bit_streamCh14 = round(rand(1,number_of_bits));
bit_streamCh15 = round(rand(1,number_of_bits));
bit_streamCh16 = round(rand(1,number_of_bits));
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Convert from serial to parallel and make bipolar  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
iCh1 = 2 *bit_streamCh1(1:2:number_of_bits) - 1;
qCh1 = 2 *bit_streamCh1(2:2:number_of_bits) - 1;
iCh2 = 2 *bit_streamCh2(1:2:number_of_bits) - 1;
qCh2 = 2 *bit_streamCh2(2:2:number_of_bits) - 1;
iCh3 = 2 *bit_streamCh3(1:2:number_of_bits) - 1;
qCh3 = 2 *bit_streamCh3(2:2:number_of_bits) - 1;
iCh4 = 2 *bit_streamCh4(1:2:number_of_bits) - 1;
qCh4 = 2 *bit_streamCh4(2:2:number_of_bits) - 1;
iCh5 = 2 *bit_streamCh5(1:2:number_of_bits) - 1;
qCh5 = 2 *bit_streamCh5(2:2:number_of_bits) - 1;
iCh6 = 2 *bit_streamCh6(1:2:number_of_bits) - 1;
qCh6 = 2 *bit_streamCh6(2:2:number_of_bits) - 1;
iCh7 = 2 *bit_streamCh7(1:2:number_of_bits) - 1;
qCh7 = 2 *bit_streamCh7(2:2:number_of_bits) - 1;
iCh8 = 2 *bit_streamCh8(1:2:number_of_bits) - 1;
qCh8 = 2 *bit_streamCh8(2:2:number_of_bits) - 1;
iCh9 = 2 *bit_streamCh9(1:2:number_of_bits) - 1;
qCh9 = 2 *bit_streamCh9(2:2:number_of_bits) - 1;
iCh10 = 2 *bit_streamCh10(1:2:number_of_bits) - 1;
qCh10 = 2 *bit_streamCh10(2:2:number_of_bits) - 1;
iCh11 = 2 *bit_streamCh11(1:2:number_of_bits) - 1;
qCh11 = 2 *bit_streamCh11(2:2:number_of_bits) - 1;
```

```
iCh12 = 2 *bit_streamCh12(1:2:number_of_bits) - 1;
qCh12 = 2 *bit_streamCh12(2:2:number_of_bits) - 1;
iCh13 = 2 *bit_streamCh13(1:2:number_of_bits) - 1;
qCh13 = 2 *bit_streamCh13(2:2:number_of_bits) - 1;
iCh14 = 2 *bit_streamCh14(1:2:number_of_bits) - 1;
qCh14 = 2 *bit_streamCh14(2:2:number_of_bits) - 1;
iCh15 = 2 *bit_streamCh15(1:2:number_of_bits) - 1;
qCh15 = 2 *bit_streamCh15(2:2:number_of_bits) - 1;
iCh16 = 2 *bit_streamCh16(1:2:number_of_bits) - 1;
qCh16 = 2 *bit_streamCh16(2:2:number_of_bits) - 1;
%%%%%%%%%%%%
walsh_row_length = 16;
%%%%%%%%%%%%
H2 = [0 0;0 1];
H4 = [H2 H2;H2 xor(1,H2)];
H8 = [H4 H4;H4 xor(1,H4)];
H16 = [H8 H8;H8 xor(1,H8)];
H16bipolar = 2.*H16-1;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%    %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Ch1=[];Ch2=[];Ch3=[];Ch4=[];Ch5=[];Ch6=[];Ch7=[];Ch8=[];H16_2=[];
Ch9=[];Ch10=[];Ch11=[];Ch12=[];Ch13=[];Ch14=[];Ch15=[];Ch16=[];
for n = 1:length(iCh1)
Ch1 = [Ch1 iCh1(n) .* H16bipolar(1,:) + sqrt(-1) .* qCh1(n) .* H16bipolar(1,:)];
Ch2 = [Ch2 iCh2(n) .* H16bipolar(2,:) + sqrt(-1) .* qCh2(n) .* H16bipolar(2,:)];
Ch3 = [Ch3 iCh3(n) .* H16bipolar(3,:) + sqrt(-1) .* qCh3(n) .* H16bipolar(3,:)];
Ch4 = [Ch4 iCh4(n) .* H16bipolar(4,:) + sqrt(-1) .* qCh4(n) .* H16bipolar(4,:)];
Ch5 = [Ch5 iCh5(n) .* H16bipolar(5,:) + sqrt(-1) .* qCh5(n) .* H16bipolar(5,:)];
Ch6 = [Ch6 iCh6(n) .* H16bipolar(6,:) + sqrt(-1) .* qCh6(n) .* H16bipolar(6,:)];
Ch7 = [Ch7 iCh7(n) .* H16bipolar(7,:) + sqrt(-1) .* qCh7(n) .* H16bipolar(7,:)];
Ch8 = [Ch8 iCh8(n) .* H16bipolar(8,:) + sqrt(-1) .* qCh8(n) .* H16bipolar(8,:)];
Ch9 = [Ch9 iCh9(n) .* H16bipolar(9,:) + sqrt(-1) .* qCh9(n) .* H16bipolar(9,:)];
Ch10 = [Ch10 iCh10(n) .* H16bipolar(10,:) + sqrt(-1) .* qCh10(n) .* H16bipolar(10,:)];
Ch11 = [Ch11 iCh11(n) .* H16bipolar(11,:) + sqrt(-1) .* qCh11(n) .* H16bipolar(11,:)];
Ch12 = [Ch12 iCh12(n) .* H16bipolar(12,:) + sqrt(-1) .* qCh12(n) .* H16bipolar(12,:)];
Ch13 = [Ch13 iCh13(n) .* H16bipolar(13,:) + sqrt(-1) .* qCh13(n) .* H16bipolar(13,:)];
Ch14 = [Ch14 iCh14(n) .* H16bipolar(14,:) + sqrt(-1) .* qCh14(n) .* H16bipolar(14,:)];
Ch15 = [Ch15 iCh15(n) .* H16bipolar(15,:) + sqrt(-1) .* qCh15(n) .* H16bipolar(15,:)];
Ch16 = [Ch16 iCh16(n) .* H16bipolar(16,:) + sqrt(-1) .* qCh16(n) .* H16bipolar(16,:)];
H16_2 = [H16_2 H16bipolar(2,:)];
end


CDMAcomp =
Ch1+Ch2+Ch3+Ch4+Ch5+Ch6+Ch7+Ch8+Ch9+Ch10+Ch11+Ch12+Ch13+Ch14+Ch15+Ch16;%+Ch3+Ch4+Ch
5+Ch6+Ch7+Ch8+Ch9+Ch10+Ch11+Ch12+Ch13+Ch14+Ch15+Ch16;
CDMAcomp_i = real(CDMAcomp);
CDMAcomp_q = imag(CDMAcomp);

%figure(11);clf;
%plot(1:1000,CDMAcomp(1:1000))


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Up-sample bit stream to enable filtering implementation  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
samples_per_bit = 10;
upsampled_i = zeros(1,length(CDMAcomp)*samples_per_bit);
upsampled_q = zeros(1,length(CDMAcomp)*samples_per_bit);
upsampled_i(1:samples_per_bit:end) = CDMAcomp_i;
upsampled_q(1:samples_per_bit:end) = CDMAcomp_q;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Calculate raised cosine impulse response and filter data  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
rrc_impulse = sqrt(samples_per_bit)*firrcos(501,1/samples_per_bit,0.22,2,'rolloff','sqrt');
% firrcos(n,F0,r,fs,'rolloff','sqrt')
```

```
scale = 1;
rrc_data_i = scale.*filter(rrc_impulse,1,upsampled_i);
rrc_data_q = scale.*filter(rrc_impulse,1,upsampled_q);
%%%%%%%%%%%%%%%%%%%%%%%%
%  Plot IQ constellation with filtered data  %
%%%%%%%%%%%%%%%%%%%%%%%%
figure(1);clf;
transient_delay = 0;
plot(CDMAcomp_i(1 + transient_delay:end),CDMAcomp_q(1 + transient_delay:end))
title('QPSK Constellation Plot')
xlabel('In-phase')
ylabel('Quad-phase')
hold on
plot(CDMAcomp_i(1 + transient_delay:samples_per_bit:end),CDMAcomp_q(1 +
transient_delay:samples_per_bit:end),'m+')
hold off
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Plot in-phase filtered data showing sampling points  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure(2);clf;
delay = 51;
plot(rrc_data_i(1+delay:600+delay))
title('In-phase Data After RRC')
xlabel('Samples')
ylabel('Amplitude')
hold on
stem(upsampled_i(1:600))
hold off
%%%%%%%%%%%%%%%%%%%%
%  Plot raised cosine impulse response  %
%%%%%%%%%%%%%%%%%%%%
figure(3);clf;
stem(rrc_impulse)
title('FIR Raised Cosine Impulse Response')
xlabel('Samples (10 times oversampling)')
ylabel('Amplitude')
axis([1 300 -0.1 0.4])
%%%%%%%%%%%
%  Set up time vector  %
%%%%%%%%%%%
quad_mod_output = rrc_data_i + sqrt(-1)*rrc_data_q;
chip_rate = 3.84e6;
time_step = 1 / chip_rate / samples_per_bit;
time = (0:time_step:length(quad_mod_output) * time_step - time_step);
%%%%%%%%%%%%%%%%%%%%
%  Plot filtered in-phase data stream  %
%%%%%%%%%%%%%%%%%%%%
%figure(4);clf;
%plot(time,rrc_data_i)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Plot power spectral density centred around baseband  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure(5);clf;
freq_points = 4096/2;
[Pxx, w] = periodogram( ((quad_mod_output(100:end)).^2)/2,[],'twosided',freq_points,(1 / time_step));
Dxx = zeros(1,freq_points);
Dxx(1:freq_points/2) = Pxx(freq_points/2+1:end);
Dxx(freq_points/2+1:end) = Pxx(1:freq_points/2);
ww = w - (1 / time_step)/2;
plot(ww,10*log10(Dxx))
title('WCDMA Transmitter Spectrum at Baseband')
xlabel('Baseband Frequency, Hz')
ylabel('Power Spectral Density in dB/Hz in 1 ohm load')
%%%%%%%%%%%%%%%%%%%%%%%%
%  Calculate channel power in 5MHz before HPA  %
%%%%%%%%%%%%%%%%%%%%%%%%
channel_bandwidth = 5e6;
```

```
frequency_resolution = freq_points / (1/time_step);
bandwidth_correction = -10*log10(frequency_resolution);
channel_power = sum(Dxx(round(freq_points/2-
frequency_resolution*channel_bandwidth/2):round(freq_points/2+frequency_resolution*channel_bandwidth/2)));
channel_power_dB = 10*log10(channel_power) + bandwidth_correction;
fprintf('channel power before HPA = %.4g\n',channel_power_dB)
%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Calculate adjacent channel power before HPA  %
%%%%%%%%%%%%%%%%%%%%%%%%%%
channel_bandwidth = 3.84e6;
adjacent_channel_offset = 5e6;
frequency_resolution = freq_points / (1/time_step);
bandwidth_correction = -10*log10(frequency_resolution);
adjacent_channel_power = sum(Dxx(round(freq_points/2-adjacent_channel_offset*frequency_resolution-
frequency_resolution*channel_bandwidth/2):round(freq_points/2-
adjacent_channel_offset*frequency_resolution+frequency_resolution*channel_bandwidth/2)));
adjacent_channel_power_dB = 10*log10(adjacent_channel_power) + bandwidth_correction;
fprintf('adjacent_channel power before HPA = %.4g\n',adjacent_channel_power_dB)
%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Plot envelope in dB and display mean and peak  %
%%%%%%%%%%%%%%%%%%%%%%%%%%
%figure(6);clf;
%plot(20*log10(abs(quad_mod_output)))
backoff = 10;
mean_power_dB = 10.*log10(( mean(    (abs(quad_mod_output(100:end))).^2    )) ./2);
peak_power_dB = 10.*log10(( max (    (abs(quad_mod_output(100:end))).^2    )) ./2);
envelope_rms = std(abs(quad_mod_output(100:end)));
peak_envelope = ( max (    (abs(quad_mod_output(100:end)))));
fprintf('mean power before HPA = %.4g\n',mean_power_dB - backoff)
%fprintf('envelope rms before HPA = %.4g\n',envelope_rms)
%fprintf('envelope peak before HPA = %.4g\n',peak_envelope)
fprintf('peak power before HPA = %.4g\n',peak_power_dB - backoff)
fprintf('peak to mean before HPA = %.4g\n',peak_power_dB - mean_power_dB)
%fprintf('ACPR before HPA = %.4g\n',channel_power_dB - adjacent_channel_power_dB)
%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Calculate and plot histogram of envelope  %
%%%%%%%%%%%%%%%%%%%%%%%%%%

instantaneous_power_dB = 10.*log10(  (  (abs(quad_mod_output)).^2)./2);
figure(6);clf;
bins = -40:0.1:20;
hist(instantaneous_power_dB(100:end) - mean_power_dB, bins);
axis([-20 10 0 6000])
title('Histogram of WCDMA(QPSK) Envelope')
xlabel('Bins (0.1dB width, 0dB = mean)')
ylabel('Quantity of samples in Bin')
%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Calculate and plot pdf of envelope  %
%%%%%%%%%%%%%%%%%%%%%%%%%%
figure(11);clf;
bins = -40:0.1:20;
[sample_bins,power_bins]=hist(instantaneous_power_dB(100:end) - mean_power_dB, bins);
semilogy(power_bins,sample_bins/length(instantaneous_power_dB(100:end)))
axis([-15 15 1e-6 1e-1])
title('Probability Density Function of WCDMA(QPSK) Envelope')
xlabel('Power, (0dB = mean power)')
ylabel('Probability')
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Create AM-AM and AM-PM interpolated curves from measured data  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
b_off = 36;
backoff = 98.39 - b_off;
Pin_dBW = instantaneous_power_dB - backoff;
r = sqrt((10.^(Pin_dBW./10)).*2);
%r = sqrt(r_W);
a = 1.6623e3;
b = 5.52e4;
```

```
A = (a.*r)./(1+b.*r.^2);
Pout_dBW = 20.*log10(A);

c = 1.533e5;
d = 3.456e5;
B = (c.*r.^2)./(1+d.*r.^2);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Apply WCDMA to non-linear amplifier curves and plot power spectral density  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
quad_mod_output_phase_rads = angle(quad_mod_output);
HPA_output_phase_rads = quad_mod_output_phase_rads + B;
HPA_output = A .* exp(sqrt(-1) .* HPA_output_phase_rads);

mean_power_before_dBW = 10.*log10(( mean(    (abs(quad_mod_output(100:end))).^2    )) ./2);
peak_power_before_dBW = 10.*log10(( max (    (abs(quad_mod_output(100:end))).^2    )) ./2);
mean_power_after_dBW = 10.*log10(( mean(    (abs(HPA_output(100:end))).^2    )) ./2);
peak_power_after_dBW = 10.*log10(( max (    (abs(HPA_output(100:end))).^2    )) ./2);

fprintf('mean power before HPA = %.4g\n',mean_power_before_dBW)
fprintf('peak power before HPA = %.4g\n',peak_power_before_dBW)
fprintf('mean power after HPA = %.4g\n',mean_power_after_dBW)
fprintf('peak power after HPA = %.4g\n',peak_power_after_dBW)

figure(8);clf;
[Power_spectrum_quad_mod_output, frequency_quad_mod_output] =
periodogram(quad_mod_output(100:end),[],'twosided',freq_points,(1 / time_step));
Power_spectrum_quad_mod_output_complex_baseband = zeros(1,freq_points);
Power_spectrum_quad_mod_output_complex_baseband(1:freq_points/2) =
Power_spectrum_quad_mod_output(freq_points/2+1:end);
Power_spectrum_quad_mod_output_complex_baseband(freq_points/2+1:end) =
Power_spectrum_quad_mod_output(1:freq_points/2);
frequency_quad_mod_output_shifted = frequency_quad_mod_output - (1 / time_step)/2;
plot(frequency_quad_mod_output_shifted,10*log10(Power_spectrum_quad_mod_output_complex_baseband))
title('WCDMA(QPSK) Transmitter Spectrum before and after HPA')
xlabel('Baseband Frequency, Hz')
ylabel('Power Spectral Density in dB/Hz')
hold on
[Power_spectrum_HPA_output, frequency_HPA_output] =
periodogram(HPA_output(100:end),[],'twosided',freq_points,(1 / time_step));
Power_spectrum_HPA_output_complex_baseband = zeros(1,freq_points);
Power_spectrum_HPA_output_complex_baseband(1:freq_points/2) =
Power_spectrum_HPA_output(freq_points/2+1:end);
Power_spectrum_HPA_output_complex_baseband(freq_points/2+1:end) =
Power_spectrum_HPA_output(1:freq_points/2);
frequency_HPA_output_shifted = frequency_HPA_output - (1 / time_step)/2;
plot(frequency_quad_mod_output_shifted,10*log10(Power_spectrum_HPA_output_complex_baseband),'m')
% NOTE:  Both plots have same frequency vector - problem with doppler
hold off
%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Calculate channel power in 40MHz after HPA  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%
channel_bandwidth = 5e6;
frequency_resolution = freq_points / (1/time_step);
bandwidth_correction = -10*log10(frequency_resolution);
channel_power = sum(Power_spectrum_HPA_output_complex_baseband(round(freq_points/2-
frequency_resolution*channel_bandwidth/2):round(freq_points/2+frequency_resolution*channel_bandwidth/2)));
channel_power_HPA_dB = 10*log10(channel_power) + bandwidth_correction;
fprintf('channel power in 40MHz after HPA = %.4g\n',channel_power_HPA_dB)
%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Calculate adjacent channel power after HPA  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%
channel_bandwidth = 3.84e6;
adjacent_channel_offset = 5e6;
frequency_resolution = freq_points / (1/time_step);
bandwidth_correction = -10*log10(frequency_resolution);
```

```
adjacent_channel_power = sum(Power_spectrum_HPA_output_complex_baseband(round(freq_points/2-
adjacent_channel_offset*frequency_resolution-frequency_resolution*channel_bandwidth/2):round(freq_points/2-
adjacent_channel_offset*frequency_resolution+frequency_resolution*channel_bandwidth/2)));
adjacent_channel_power_HPA_dB = 10*log10(adjacent_channel_power) + bandwidth_correction;
fprintf('adjacent_channel power = %.4g\n',adjacent_channel_power_HPA_dB)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Plot envelope in dB and display mean and peak after HPA %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure(9);clf;
plot(20*log10(abs(HPA_output(100:end))))
mean_power_HPA_dB = 20*log10(mean(abs(HPA_output(100:end))));
peak_power_HPA_dB = 20*log10(max(abs(HPA_output(100:end))));
%fprintf('mean power after HPA = %.4g\n',mean_power_HPA_dB)
%fprintf('peak power after HPA= %.4g\n',peak_power_HPA_dB)
%fprintf('peak to mean after HPA= %.4g\n',peak_power_HPA_dB - mean_power_HPA_dB)
fprintf('ACPR after HPA= %.4g\n',channel_power_HPA_dB - adjacent_channel_power_HPA_dB)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Calculate and plot histogram of envelope after HPA %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
HPA_output_envelope_dB = 20*log10(abs(HPA_output));
figure(10);clf;
bins = -40:0.1:20;
hist(HPA_output_envelope_dB(100:end) - mean_power_HPA_dB, bins)
title('Histogram of QPSK Envelope after HPA')
xlabel('Bins (0.1dB width, centred around mean)')
ylabel('Quantity of samples in Bin')
```

11.3 W-CDMA/16QAM (S-UMTS)

```
%  MSc Project: "DVB versus S-UMTS for broadcast/multicast"
%  Student:  Pete King
%  Supervisor:  Professor Barry Evans
%
%  MATLAB file name:  SUMTS_16QAM_ACPR.m
%
%  This file simulates the ACPR generated in the HPA using W-CDMA / 16QAM.
%
clear all;
%%%%%%%%%%%%%%%
%  Set up stream of data bits  %
%%%%%%%%%%%%%%%
number_of_bits = 2000;
bit_streamCh1 = round(rand(1,number_of_bits));
bit_streamCh2 = round(rand(1,number_of_bits));
bit_streamCh3 = round(rand(1,number_of_bits));
bit_streamCh4 = round(rand(1,number_of_bits));
bit_streamCh5 = round(rand(1,number_of_bits));
bit_streamCh6 = round(rand(1,number_of_bits));
bit_streamCh7 = round(rand(1,number_of_bits));
bit_streamCh8 = round(rand(1,number_of_bits));
bit_streamCh9 = round(rand(1,number_of_bits));
bit_streamCh10 = round(rand(1,number_of_bits));
bit_streamCh11 = round(rand(1,number_of_bits));
bit_streamCh12 = round(rand(1,number_of_bits));
bit_streamCh13 = round(rand(1,number_of_bits));
bit_streamCh14 = round(rand(1,number_of_bits));
bit_streamCh15 = round(rand(1,number_of_bits));
bit_streamCh16 = round(rand(1,number_of_bits));
%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Convert from serial to parallel and make bipolar  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%
iCh1M = 2 *bit_streamCh1(1:4:number_of_bits) - 1;
qCh1M = 2 *bit_streamCh1(2:4:number_of_bits) - 1;
iCh1S = 2 *bit_streamCh1(3:4:number_of_bits) - 1;
qCh1S = 2 *bit_streamCh1(4:4:number_of_bits) - 1;
iCh2M = 2 *bit_streamCh2(1:4:number_of_bits) - 1;
```

```
qCh2M = 2 *bit_streamCh2(2:4:number_of_bits) - 1;
iCh2S = 2 *bit_streamCh2(3:4:number_of_bits) - 1;
qCh2S = 2 *bit_streamCh2(4:4:number_of_bits) - 1;
iCh3M = 2 *bit_streamCh3(1:4:number_of_bits) - 1;
qCh3M = 2 *bit_streamCh3(2:4:number_of_bits) - 1;
iCh3S = 2 *bit_streamCh3(3:4:number_of_bits) - 1;
qCh3S = 2 *bit_streamCh3(4:4:number_of_bits) - 1;
iCh4M = 2 *bit_streamCh4(1:4:number_of_bits) - 1;
qCh4M = 2 *bit_streamCh4(2:4:number_of_bits) - 1;
iCh4S = 2 *bit_streamCh4(3:4:number_of_bits) - 1;
qCh4S = 2 *bit_streamCh4(4:4:number_of_bits) - 1;
iCh5M = 2 *bit_streamCh5(1:4:number_of_bits) - 1;
qCh5M = 2 *bit_streamCh5(2:4:number_of_bits) - 1;
iCh5S = 2 *bit_streamCh5(3:4:number_of_bits) - 1;
qCh5S = 2 *bit_streamCh5(4:4:number_of_bits) - 1;
iCh6M = 2 *bit_streamCh6(1:4:number_of_bits) - 1;
qCh6M = 2 *bit_streamCh6(2:4:number_of_bits) - 1;
iCh6S = 2 *bit_streamCh6(3:4:number_of_bits) - 1;
qCh6S = 2 *bit_streamCh6(4:4:number_of_bits) - 1;
iCh7M = 2 *bit_streamCh7(1:4:number_of_bits) - 1;
qCh7M = 2 *bit_streamCh7(2:4:number_of_bits) - 1;
iCh7S = 2 *bit_streamCh7(3:4:number_of_bits) - 1;
qCh7S = 2 *bit_streamCh7(4:4:number_of_bits) - 1;
iCh8M = 2 *bit_streamCh8(1:4:number_of_bits) - 1;
qCh8M = 2 *bit_streamCh8(2:4:number_of_bits) - 1;
iCh8S = 2 *bit_streamCh8(3:4:number_of_bits) - 1;
qCh8S = 2 *bit_streamCh8(4:4:number_of_bits) - 1;
iCh9M = 2 *bit_streamCh9(1:4:number_of_bits) - 1;
qCh9M = 2 *bit_streamCh9(2:4:number_of_bits) - 1;
iCh9S = 2 *bit_streamCh9(3:4:number_of_bits) - 1;
qCh9S = 2 *bit_streamCh9(4:4:number_of_bits) - 1;
iCh10M = 2 *bit_streamCh10(1:4:number_of_bits) - 1;
qCh10M = 2 *bit_streamCh10(2:4:number_of_bits) - 1;
iCh10S = 2 *bit_streamCh10(3:4:number_of_bits) - 1;
qCh10S = 2 *bit_streamCh10(4:4:number_of_bits) - 1;
iCh11M = 2 *bit_streamCh11(1:4:number_of_bits) - 1;
qCh11M = 2 *bit_streamCh11(2:4:number_of_bits) - 1;
iCh11S = 2 *bit_streamCh11(3:4:number_of_bits) - 1;
qCh11S = 2 *bit_streamCh11(4:4:number_of_bits) - 1;
iCh12M = 2 *bit_streamCh12(1:4:number_of_bits) - 1;
qCh12M = 2 *bit_streamCh12(2:4:number_of_bits) - 1;
iCh12S = 2 *bit_streamCh12(3:4:number_of_bits) - 1;
qCh12S = 2 *bit_streamCh12(4:4:number_of_bits) - 1;
iCh13M = 2 *bit_streamCh13(1:4:number_of_bits) - 1;
qCh13M = 2 *bit_streamCh13(2:4:number_of_bits) - 1;
iCh13S = 2 *bit_streamCh13(3:4:number_of_bits) - 1;
qCh13S = 2 *bit_streamCh13(4:4:number_of_bits) - 1;
iCh14M = 2 *bit_streamCh14(1:4:number_of_bits) - 1;
qCh14M = 2 *bit_streamCh14(2:4:number_of_bits) - 1;
iCh14S = 2 *bit_streamCh14(3:4:number_of_bits) - 1;
qCh14S = 2 *bit_streamCh14(4:4:number_of_bits) - 1;
iCh15M = 2 *bit_streamCh15(1:4:number_of_bits) - 1;
qCh15M = 2 *bit_streamCh15(2:4:number_of_bits) - 1;
iCh15S = 2 *bit_streamCh15(3:4:number_of_bits) - 1;
qCh15S = 2 *bit_streamCh15(4:4:number_of_bits) - 1;
iCh16M = 2 *bit_streamCh16(1:4:number_of_bits) - 1;
qCh16M = 2 *bit_streamCh16(2:4:number_of_bits) - 1;
iCh16S = 2 *bit_streamCh16(3:4:number_of_bits) - 1;
qCh16S = 2 *bit_streamCh16(4:4:number_of_bits) - 1;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%    %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
walsh_row_length = 16;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%    %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
H2 = [0 0;0 1];
H4 = [H2 H2;H2 xor(1,H2)];
H8 = [H4 H4;H4 xor(1,H4)];
H16 = [H8 H8;H8 xor(1,H8)];
H16bipolar = 2.*H16-1;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%    %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Ch1=[];Ch2=[];Ch3=[];Ch4=[];Ch5=[];Ch6=[];Ch7=[];Ch8=[];H16_2=[];
Ch9=[];Ch10=[];Ch11=[];Ch12=[];Ch13=[];Ch14=[];Ch15=[];Ch16=[];
for n = 1:length(iCh1M)
Ch1qam16(n) = (iCh1M(n) + sqrt(-1) .* qCh1M(n)) + 0.5.*(iCh1S(n) + sqrt(-1) .* qCh1S(n));
Ch1 = [Ch1 Ch1qam16(n) .* H16bipolar(1,:)];
Ch2qam16(n) = (iCh2M(n) + sqrt(-1) .* qCh2M(n)) + 0.5.*(iCh2S(n) + sqrt(-1) .* qCh2S(n));
Ch2 = [Ch2 Ch2qam16(n) .* H16bipolar(2,:)];
Ch3qam16(n) = (iCh3M(n) + sqrt(-1) .* qCh3M(n)) + 0.5.*(iCh3S(n) + sqrt(-1) .* qCh3S(n));
Ch3 = [Ch3 Ch3qam16(n) .* H16bipolar(3,:)];
Ch4qam16(n) = (iCh4M(n) + sqrt(-1) .* qCh4M(n)) + 0.5.*(iCh4S(n) + sqrt(-1) .* qCh4S(n));
Ch4 = [Ch4 Ch4qam16(n) .* H16bipolar(4,:)];
Ch5qam16(n) = (iCh5M(n) + sqrt(-1) .* qCh5M(n)) + 0.5.*(iCh5S(n) + sqrt(-1) .* qCh5S(n));
Ch5 = [Ch5 Ch5qam16(n) .* H16bipolar(5,:)];
Ch6qam16(n) = (iCh6M(n) + sqrt(-1) .* qCh6M(n)) + 0.5.*(iCh6S(n) + sqrt(-1) .* qCh6S(n));
Ch6 = [Ch6 Ch6qam16(n) .* H16bipolar(6,:)];
Ch7qam16(n) = (iCh7M(n) + sqrt(-1) .* qCh7M(n)) + 0.5.*(iCh7S(n) + sqrt(-1) .* qCh7S(n));
Ch7 = [Ch7 Ch7qam16(n) .* H16bipolar(7,:)];
Ch8qam16(n) = (iCh8M(n) + sqrt(-1) .* qCh8M(n)) + 0.5.*(iCh8S(n) + sqrt(-1) .* qCh8S(n));
Ch8 = [Ch8 Ch8qam16(n) .* H16bipolar(8,:)];
Ch9qam16(n) = (iCh9M(n) + sqrt(-1) .* qCh9M(n)) + 0.5.*(iCh9S(n) + sqrt(-1) .* qCh9S(n));
Ch9 = [Ch9 Ch9qam16(n) .* H16bipolar(9,:)];
Ch10qam16(n) = (iCh10M(n) + sqrt(-1) .* qCh10M(n)) + 0.5.*(iCh10S(n) + sqrt(-1) .* qCh10S(n));
Ch10 = [Ch10 Ch10qam16(n) .* H16bipolar(10,:)];
Ch11qam16(n) = (iCh11M(n) + sqrt(-1) .* qCh11M(n)) + 0.5.*(iCh11S(n) + sqrt(-1) .* qCh11S(n));
Ch11 = [Ch11 Ch11qam16(n) .* H16bipolar(11,:)];
Ch12qam16(n) = (iCh12M(n) + sqrt(-1) .* qCh12M(n)) + 0.5.*(iCh12S(n) + sqrt(-1) .* qCh12S(n));
Ch12 = [Ch12 Ch12qam16(n) .* H16bipolar(12,:)];
Ch13qam16(n) = (iCh13M(n) + sqrt(-1) .* qCh13M(n)) + 0.5.*(iCh13S(n) + sqrt(-1) .* qCh13S(n));
Ch13 = [Ch13 Ch13qam16(n) .* H16bipolar(13,:)];
Ch14qam16(n) = (iCh14M(n) + sqrt(-1) .* qCh14M(n)) + 0.5.*(iCh14S(n) + sqrt(-1) .* qCh14S(n));
Ch14 = [Ch14 Ch14qam16(n) .* H16bipolar(14,:)];
Ch15qam16(n) = (iCh15M(n) + sqrt(-1) .* qCh15M(n)) + 0.5.*(iCh15S(n) + sqrt(-1) .* qCh15S(n));
Ch15 = [Ch15 Ch15qam16(n) .* H16bipolar(15,:)];
Ch16qam16(n) = (iCh16M(n) + sqrt(-1) .* qCh16M(n)) + 0.5.*(iCh16S(n) + sqrt(-1) .* qCh16S(n));
Ch16 = [Ch16 Ch16qam16(n) .* H16bipolar(16,:)];
H16_2 = [H16_2 H16bipolar(2,:)];
end


CDMAcomp =
Ch1+Ch2+Ch3+Ch4+Ch5+Ch6+Ch7+Ch8+Ch9+Ch10+Ch11+Ch12+Ch13+Ch14+Ch15+Ch16;%+Ch3+Ch4+Ch
5+Ch6+Ch7+Ch8+Ch9+Ch10+Ch11+Ch12+Ch13+Ch14+Ch15+Ch16;
CDMAcomp_i = real(CDMAcomp);
CDMAcomp_q = imag(CDMAcomp);

%figure(11);clf;
%plot(1:1000,CDMAcomp(1:1000))


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Up-sample bit stream to enable filtering implementation  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
samples_per_bit = 10;
upsampled_i = zeros(1,length(CDMAcomp)*samples_per_bit);
upsampled_q = zeros(1,length(CDMAcomp)*samples_per_bit);
upsampled_i(1:samples_per_bit:end) = CDMAcomp_i;
upsampled_q(1:samples_per_bit:end) = CDMAcomp_q;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Calculate raised cosine impulse response and filter data  %
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%
rrc_impulse = sqrt(samples_per_bit)*firrcos(501,1/samples_per_bit,0.22,2,'rolloff','normal');
% firrcos(n,F0,r,fs,'rolloff','sqrt')
scale = 1;
rrc_data_i = scale.*filter(rrc_impulse,1,upsampled_i);
rrc_data_q = scale.*filter(rrc_impulse,1,upsampled_q);
%%%%%%%%%%%%%%%%%%%%%%%%
%  Plot IQ constellation with filtered data  %
%%%%%%%%%%%%%%%%%%%%%%%%
figure(1);clf;
transient_delay = 251;
plot(rrc_data_i(1 + transient_delay:end),rrc_data_q(1 + transient_delay:end))
title('WCDMA(16QAM) Constellation Plot')
xlabel('In-phase')
ylabel('Quad-phase')
%hold on
%plot(CDMAcomp_i(1 + transient_delay:samples_per_bit:end),CDMAcomp_q(1 +
transient_delay:samples_per_bit:end),'m+')
%hold off
%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Plot in-phase filtered data showing sampling points  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure(2);clf;
delay = 51;
plot(rrc_data_i(1+delay:600+delay))
title('In-phase Data After RRC')
xlabel('Samples')
ylabel('Amplitude')
hold on
stem(upsampled_i(1:600))
hold off
%%%%%%%%%%%%%%%%%%%%
%  Plot raised cosine impulse response  %
%%%%%%%%%%%%%%%%%%%%
figure(3);clf;
stem(rrc_impulse)
title('FIR Raised Cosine Impulse Response')
xlabel('Samples (10 times oversampling)')
ylabel('Amplitude')
axis([1 300 -0.1 0.4])
%%%%%%%%%%%
%  Set up time vector  %
%%%%%%%%%%%
quad_mod_output = rrc_data_i + sqrt(-1)*rrc_data_q;
chip_rate = 3.84e6;
time_step = 1 / chip_rate / samples_per_bit;
time = (0:time_step:length(quad_mod_output) * time_step - time_step);
%%%%%%%%%%%%%%%%%%%%
%  Plot filtered in-phase data stream  %
%%%%%%%%%%%%%%%%%%%%
%figure(4);clf;
%plot(time,rrc_data_i)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Plot power spectral density centred around baseband  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure(5);clf;
freq_points = 4096/2;
[Pxx, w] = periodogram( ((quad_mod_output(100:end)).^2)/2,[],'twosided',freq_points,(1 / time_step));
Dxx = zeros(1,freq_points);
Dxx(1:freq_points/2) = Pxx(freq_points/2+1:end);
Dxx(freq_points/2+1:end) = Pxx(1:freq_points/2);
ww = w - (1 / time_step)/2;
plot(ww,10*log10(Dxx))
title('WCDMA Transmitter Spectrum at Baseband')
xlabel('Baseband Frequency, Hz')
ylabel('Power Spectral Density in dB/Hz in 1 ohm load')
%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
% Calculate channel power in 5MHz before HPA %
%%%%%%%%%%%%%%%%%%%%%%%%%%
channel_bandwidth = 5e6;
frequency_resolution = freq_points / (1/time_step);
bandwidth_correction = -10*log10(frequency_resolution);
channel_power = sum(Dxx(round(freq_points/2-
frequency_resolution*channel_bandwidth/2):round(freq_points/2+frequency_resolution*channel_bandwidth/2)));
channel_power_dB = 10*log10(channel_power) + bandwidth_correction;
fprintf('channel power before HPA = %.4g\n',channel_power_dB)
%%%%%%%%%%%%%%%%%%%%%%%%%%
% Calculate adjacent channel power before HPA %
%%%%%%%%%%%%%%%%%%%%%%%%%%
channel_bandwidth = 3.84e6;
adjacent_channel_offset = 5e6;
frequency_resolution = freq_points / (1/time_step);
bandwidth_correction = -10*log10(frequency_resolution);
adjacent_channel_power = sum(Dxx(round(freq_points/2-adjacent_channel_offset*frequency_resolution-
frequency_resolution*channel_bandwidth/2):round(freq_points/2-
adjacent_channel_offset*frequency_resolution+frequency_resolution*channel_bandwidth/2)));
adjacent_channel_power_dB = 10*log10(adjacent_channel_power) + bandwidth_correction;
fprintf('adjacent_channel power before HPA = %.4g\n',adjacent_channel_power_dB)
%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Plot envelope in dB and display mean and peak %
%%%%%%%%%%%%%%%%%%%%%%%%%%
%figure(6);clf;
%plot(20*log10(abs(quad_mod_output)))
backoff = 11;
mean_power_dB = 10.*log10(( mean(    (abs(quad_mod_output(100:end))).^2    )) ./2);
peak_power_dB = 10.*log10(( max (    (abs(quad_mod_output(100:end))).^2    )) ./2);
envelope_rms = std(abs(quad_mod_output(100:end)));
peak_envelope = ( max (    (abs(quad_mod_output(100:end)))));
fprintf('mean power before HPA = %.4g\n',mean_power_dB - backoff)
%fprintf('envelope rms before HPA = %.4g\n',envelope_rms)
%fprintf('envelope peak before HPA = %.4g\n',peak_envelope)
fprintf('peak power before HPA = %.4g\n',peak_power_dB - backoff)
fprintf('peak to mean before HPA = %.4g\n',peak_power_dB - mean_power_dB)
%fprintf('ACPR before HPA = %.4g\n',channel_power_dB - adjacent_channel_power_dB)
%%%%%%%%%%%%%%%%%%%%%%%%
% Calculate and plot histogram of envelope %
%%%%%%%%%%%%%%%%%%%%%%%%

instantaneous_power_dB = 10.*log10( (  (abs(quad_mod_output)).^2)./2);
figure(6);clf;
bins = -40:0.1:20;
hist(instantaneous_power_dB(100:end) - mean_power_dB, bins);
axis([-20 10 0 6000])
title('Histogram of WCDMA(16QAM) Envelope')
xlabel('Bins (0.1dB width, 0dB = mean)')
ylabel('Quantity of samples in Bin')
%%%%%%%%%%%%%%%%%%%%%
% Calculate and plot pdf of envelope %
%%%%%%%%%%%%%%%%%%%%%
figure(11);clf;
bins = -40:0.1:20;
[sample_bins,power_bins]=hist(instantaneous_power_dB(100:end) - mean_power_dB, bins);
semilogy(power_bins,sample_bins/length(instantaneous_power_dB(100:end)))
axis([-15 15 1e-6 1e-1])
title('Probability Density Function of WCDMA(16QAM) Envelope')
xlabel('Power, (0dB = mean power)')
ylabel('Probability')
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Create AM-AM and AM-PM interpolated curves from measured data %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
b_off = 36.3;
backoff = 99.2 - b_off;
Pin_dBW = instantaneous_power_dB - backoff;
r = sqrt((10.^(Pin_dBW./10)).*2);
```

```
%r = sqrt(r_W);
a = 1.6623e3;
b = 5.52e4;

A = (a.*r)./(1+b.*r.^2);
Pout_dBW = 20.*log10(A);

c = 1.533e5;
d = 3.456e5;
B = (c.*r.^2)./(1+d.*r.^2);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Apply WCDMA to non-linear amplifier curves and plot power spectral density  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
quad_mod_output_phase_rads = angle(quad_mod_output);
HPA_output_phase_rads = quad_mod_output_phase_rads + B;
HPA_output = A .* exp(sqrt(-1) .* HPA_output_phase_rads);

mean_power_before_dBW = 10.*log10(( mean(    (abs(quad_mod_output(100:end))).^2    )) ./2);
peak_power_before_dBW = 10.*log10(( max (    (abs(quad_mod_output(100:end))).^2    )) ./2);
mean_power_after_dBW = 10.*log10(( mean(    (abs(HPA_output(100:end))).^2    )) ./2);
peak_power_after_dBW = 10.*log10(( max (    (abs(HPA_output(100:end))).^2    )) ./2);

fprintf('mean power before HPA = %.4g\n',mean_power_before_dBW)
fprintf('peak power before HPA = %.4g\n',peak_power_before_dBW)
fprintf('mean power after HPA = %.4g\n',mean_power_after_dBW)
fprintf('peak power after HPA = %.4g\n',peak_power_after_dBW)
figure(8);clf;
[Power_spectrum_quad_mod_output, frequency_quad_mod_output] =
periodogram(quad_mod_output(100:end),[],'twosided',freq_points,(1 / time_step));
Power_spectrum_quad_mod_output_complex_baseband = zeros(1,freq_points);
Power_spectrum_quad_mod_output_complex_baseband(1:freq_points/2) =
Power_spectrum_quad_mod_output(freq_points/2+1:end);
Power_spectrum_quad_mod_output_complex_baseband(freq_points/2+1:end) =
Power_spectrum_quad_mod_output(1:freq_points/2);
frequency_quad_mod_output_shifted = frequency_quad_mod_output - (1 / time_step)/2;
plot(frequency_quad_mod_output_shifted,10*log10(Power_spectrum_quad_mod_output_complex_baseband))
title('WCDMA(16QAM) Transmitter Spectrum before and after HPA')
xlabel('Baseband Frequency, Hz')
ylabel('Power Spectral Density in dB/Hz')
hold on
[Power_spectrum_HPA_output, frequency_HPA_output] =
periodogram(HPA_output(100:end),[],'twosided',freq_points,(1 / time_step));
Power_spectrum_HPA_output_complex_baseband = zeros(1,freq_points);
Power_spectrum_HPA_output_complex_baseband(1:freq_points/2) =
Power_spectrum_HPA_output(freq_points/2+1:end);
Power_spectrum_HPA_output_complex_baseband(freq_points/2+1:end) =
Power_spectrum_HPA_output(1:freq_points/2);
frequency_HPA_output_shifted = frequency_HPA_output - (1 / time_step)/2;
plot(frequency_quad_mod_output_shifted,10*log10(Power_spectrum_HPA_output_complex_baseband),'m')
% NOTE:  Both plots have same frequency vector - problem with doppler
hold off
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Calculate channel power in 40MHz after HPA  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
channel_bandwidth = 5e6;
frequency_resolution = freq_points / (1/time_step);
bandwidth_correction = -10*log10(frequency_resolution);
channel_power = sum(Power_spectrum_HPA_output_complex_baseband(round(freq_points/2-
frequency_resolution*channel_bandwidth/2):round(freq_points/2+frequency_resolution*channel_bandwidth/2)));
channel_power_HPA_dB = 10*log10(channel_power) + bandwidth_correction;
fprintf('channel power in 40MHz after HPA = %.4g\n',channel_power_HPA_dB)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Calculate adjacent channel power after HPA  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
channel_bandwidth = 3.84e6;
adjacent_channel_offset = 5e6;
frequency_resolution = freq_points / (1/time_step);
```

```
bandwidth_correction = -10*log10(frequency_resolution);
adjacent_channel_power = sum(Power_spectrum_HPA_output_complex_baseband(round(freq_points/2-
adjacent_channel_offset*frequency_resolution-frequency_resolution*channel_bandwidth/2):round(freq_points/2-
adjacent_channel_offset*frequency_resolution+frequency_resolution*channel_bandwidth/2)));
adjacent_channel_power_HPA_dB = 10*log10(adjacent_channel_power) + bandwidth_correction;
fprintf('adjacent_channel power = %.4g\n',adjacent_channel_power_HPA_dB)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Plot envelope in dB and display mean and peak after HPA %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure(9);clf;
plot(20*log10(abs(HPA_output(100:end))))
mean_power_HPA_dB = 20*log10(mean(abs(HPA_output(100:end))));
peak_power_HPA_dB = 20*log10(max(abs(HPA_output(100:end))));
%fprintf('mean power after HPA = %.4g\n',mean_power_HPA_dB)
%fprintf('peak power after HPA= %.4g\n',peak_power_HPA_dB)
%fprintf('peak to mean after HPA= %.4g\n',peak_power_HPA_dB - mean_power_HPA_dB)
fprintf('ACPR after HPA= %.4g\n',channel_power_HPA_dB - adjacent_channel_power_HPA_dB)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Calculate and plot histogram of envelope after HPA %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
HPA_output_envelope_dB = 20*log10(abs(HPA_output));
figure(10);clf;
bins = -40:0.1:20;
hist(HPA_output_envelope_dB(100:end) - mean_power_HPA_dB, bins)
title('Histogram of QPSK Envelope after HPA')
xlabel('Bins (0.1dB width, centred around mean)')
ylabel('Quantity of samples in Bin')
```

11.4 OFDM/QPSK (DAB)

```
%  MSc Project: "DVB versus S-UMTS for broadcast/multicast"
%  Student:  Pete King
%  Supervisor:  Professor Barry Evans
%
%  MATLAB file name:  DAB_QPSK_ACPR.m
%
%  This file simulates the ACPR generated in the HPA using OFDM / QPSK.
%
clear all;
%%%%%%%%%%%%%%%
%  Set up stream of data bits  %
%%%%%%%%%%%%%%%
no_of_carriers = 192;
number_of_bits = 256*2*no_of_carriers;

bit_streamCh1 = round(rand(1,number_of_bits));

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Convert from serial to parallel and make bipolar  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
iCh1 = 2 *bit_streamCh1(1:2:number_of_bits) - 1;
qCh1 = 2 *bit_streamCh1(2:2:number_of_bits) - 1;
d1 = iCh1 + sqrt(-1)*qCh1;
d1 = 2.*d1;
%%%%%%%%%%%%%%%
%  Put bits into blocks of 10  %
%%%%%%%%%%%%%%%

no_of_symbols = length(d1)/no_of_carriers;
for i = 1:no_of_symbols % 1:number of blocks
   block(i,1:no_of_carriers) = d1((i-1)*no_of_carriers+1:(i-1)*no_of_carriers+no_of_carriers);
   %block(k+1,154:192) = zeros(1,(192-153));

end

ifftsize = 1024*2;
```

```
spacing=1;
offset=256;
start_carrier = 1;%ifftsize/2-no_of_carriers+1;
final_carrier = no_of_carriers;%ifftsize/4-1+1;
carriers = [2+offset:192+offset];
neg_carriers = [384+offset:-1:194+offset];
spectrum = zeros(no_of_carriers,ifftsize);

for k = 1:no_of_symbols
spectrum(k,carriers) = (block(k,2:192));
spectrum(k,neg_carriers) = conj(block(k,2:192));
spectrum(k,1+offset) = real(block(k,1));
spectrum(k,193+offset) = imag(block(k,1));
end


%%%%%%%%%%%%%%%%%
%  Take Inverse DFT of each block  %
%%%%%%%%%%%%%%%%%

Sm = (ifft(spectrum'));

%
%
%
window = hamming(ifftsize);
window2 = zeros(ifftsize,no_of_symbols);
for k = 1:no_of_carriers
   window2(:,k) = window;
end

%Sm = window2.*Sm;
%Sm = window2.*Sm;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Return blocks of time domain data back into series data  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
OFDM_tx = reshape(Sm,1,size(Sm,1)*size(Sm,2));
OFDM = 1e2.*(real(OFDM_tx) + sqrt(-1).*imag(OFDM_tx));
OFDM_i = real(OFDM);
OFDM_q = imag(OFDM);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Up-sample bit stream to enable filtering implementation  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Calculate raised cosine impulse response and filter data  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%
%  Plot IQ constellation with filtered data  %
%%%%%%%%%%%%%%%%%%%%%
figure(1);clf;
transient_delay = 0;
plot(OFDM_i(1 + transient_delay:end),OFDM_q(1 + transient_delay:end))
title('OFDM Constellation Plot')
xlabel('In-phase')
ylabel('Quad-phase')
%hold on
%plot(rrc_data_i(1 + transient_delay:samples_per_bit:end),rrc_data_q(1 +
transient_delay:samples_per_bit:end),'m+')
%hold off
%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Plot in-phase filtered data showing sampling points  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%
```

```
%  Plot raised cosine impulse response  %
%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%
%  Set up time vector  %
%%%%%%%%%%

T = 1/2048000;
Ts = 256*T;
symbol_rate = 1/Ts;
time_step = Ts/ifftsize*2;
time = (0:time_step:length(OFDM_tx) * time_step - time_step);
%%%%%%%%%%%%%%%%%%%%
%  Plot filtered in-phase data stream  %
%%%%%%%%%%%%%%%%%%%%
figure(4);clf;
plot(time,abs(OFDM))
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Plot power spectral density centred around baseband  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure(5);clf;
freq_points = 4096*16;
[Pxx, w] = periodogram( (abs(OFDM).^2)/2,[],'onesided',freq_points,(1 / time_step));
plot(w,10*log10(Pxx+0.00000000000000000000000000001))
%psdplot(Pxx,w,'Hz','dB')
%axis([-100e3 200e3 -300 -100])
title('OFDM Transmitter Spectrum at Baseband')
xlabel('Baseband Frequency, Hz')
ylabel('Power Spectral Density in dB/Hz')

%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Calculate channel power in 5MHz before HPA  %
%%%%%%%%%%%%%%%%%%%%%%%%%%
%channel_bandwidth = 5e6;
%frequency_resolution = freq_points / (1/time_step);
%bandwidth_correction = -10*log10(frequency_resolution);
%channel_power = sum(Dxx(round(freq_points/2-
frequency_resolution*channel_bandwidth/2):round(freq_points/2+frequency_resolution*channel_bandwidth/2)));
%channel_power_dB = 10*log10(channel_power) + bandwidth_correction;
%fprintf('channel power before HPA = %.4g\n',channel_power_dB)
%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Calculate adjacent channel power before HPA  %
%%%%%%%%%%%%%%%%%%%%%%%%%%
%channel_bandwidth = 3.84e6;
%adjacent_channel_offset = 5e6;
%frequency_resolution = freq_points / (1/time_step);
%bandwidth_correction = -10*log10(frequency_resolution);
%adjacent_channel_power = sum(Dxx(round(freq_points/2-adjacent_channel_offset*frequency_resolution-
frequency_resolution*channel_bandwidth/2):round(freq_points/2-
adjacent_channel_offset*frequency_resolution+frequency_resolution*channel_bandwidth/2)));
%adjacent_channel_power_dB = 10*log10(adjacent_channel_power) + bandwidth_correction;
%fprintf('adjacent_channel power before HPA = %.4g\n',adjacent_channel_power_dB)
%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Plot envelope in dB and display mean and peak  %
%%%%%%%%%%%%%%%%%%%%%%%%%%
%figure(6);clf;
%plot(20*log10(abs(quad_mod_output)))

%fprintf('ACPR before HPA = %.4g\n',channel_power_dB - adjacent_channel_power_dB)
%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Calculate and plot histogram of envelope in bins  %
%%%%%%%%%%%%%%%%%%%%%%%%%%
backoff = 16;
mean_power_dB = 10.*log10(( mean(    (abs(OFDM)).^2    )) ./2 +0.000000000000000000000001);
peak_power_dB = 10.*log10(( max (    (abs(OFDM)).^2    )) ./2 +0.000000000000000000000001);
envelope_rms = std(abs(OFDM));
peak_envelope = ( max (    (abs(OFDM))));
```

```
fprintf('mean power before HPA = %.4g\n',mean_power_dB - backoff)
%fprintf('envelope rms before HPA = %.4g\n',envelope_rms)
%fprintf('envelope peak before HPA = %.4g\n',peak_envelope)
fprintf('peak power before HPA = %.4g\n',peak_power_dB - backoff)
fprintf('peak to mean before HPA = %.4g\n',peak_power_dB - mean_power_dB)
%fprintf('ACPR before HPA = %.4g\n',channel_power_dB - adjacent_channel_power_dB)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Calculate and plot histogram of envelope  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

instantaneous_power_dB = 10.*log10( (  (abs(OFDM)).^2)./2 +0.000000000000000000000001);
figure(6);clf;
bins = -60:0.1:20;
hist(instantaneous_power_dB - mean_power_dB, bins);
axis([-60 20 0 2000])
title('Histogram of OFDM (mode III) Envelope')
xlabel('Bins (0.1dB width, 0dB = mean)')
ylabel('Quantity of samples in Bin')
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Calculate and plot pdf of envelope  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure(11);clf;
bins = -60:0.1:20;
[sample_bins,power_bins]=hist(instantaneous_power_dB - mean_power_dB, bins);
semilogy(power_bins,sample_bins/length(instantaneous_power_dB))
axis([-60 20 1e-6 1e-1])
title('Probability Density Function of OFDM (mode III) Envelope')
xlabel('Power, (0dB = mean power)')
ylabel('Probability')
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Create AM-AM and AM-PM interpolated curves from measured data  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
b_off = 34;
backoff = 100.28 - b_off;
Pin_dBW = instantaneous_power_dB - backoff;
r = sqrt((10.^(Pin_dBW./10)).*2);
%r = sqrt(r_W);
a = 1.6623e3;
b = 5.52e4;

A = (a.*r)./(1+b.*r.^2);
Pout_dBW = 20.*log10(A);

c = 1.533e5;
d = 3.456e5;
B = (c.*r.^2)./(1+d.*r.^2);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Apply WCDMA to non-linear amplifier curves and plot power spectral density  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
quad_mod_output_phase_rads = angle(OFDM);
HPA_output_phase_rads = quad_mod_output_phase_rads + B;
HPA_output = A .* exp(sqrt(-1) .* HPA_output_phase_rads);

mean_power_before_dBW = 10.*log10(( mean(    (abs(OFDM(100:end))).^2    )) ./2);
peak_power_before_dBW = 10.*log10(( max (    (abs(OFDM(100:end))).^2    )) ./2);
mean_power_after_dBW = 10.*log10(( mean(    (abs(HPA_output(100:end))).^2    )) ./2);
peak_power_after_dBW = 10.*log10(( max (    (abs(HPA_output(100:end))).^2    )) ./2);

fprintf('mean power before HPA = %.4g\n',mean_power_before_dBW)
fprintf('peak power before HPA = %.4g\n',peak_power_before_dBW)
fprintf('mean power after HPA = %.4g\n',mean_power_after_dBW)
fprintf('peak power after HPA = %.4g\n',peak_power_after_dBW)
figure(8);clf;
[Power_spectrum_quad_mod_output, frequency_quad_mod_output] =
periodogram(abs(OFDM).^2./2,[],'onesided',freq_points,(1 / time_step));
Power_spectrum_quad_mod_output_complex_baseband = zeros(1,freq_points);
```

```
Power_spectrum_quad_mod_output_complex_baseband(1:freq_points/2) =
Power_spectrum_quad_mod_output(freq_points/2+1:end);
Power_spectrum_quad_mod_output_complex_baseband(freq_points/2+1:end) =
Power_spectrum_quad_mod_output(1:freq_points/2);
frequency_quad_mod_output_shifted = frequency_quad_mod_output - (1 / time_step)/2;
plot(frequency_quad_mod_output,10.*log10(Power_spectrum_quad_mod_output+0.0000000000000000000000000
00001))
title('OFDM Transmitter Spectrum before and after HPA')
xlabel('Baseband Frequency, Hz')
ylabel('Power Spectral Density in dB/Hz')
hold on
[Power_spectrum_HPA_output, frequency_HPA_output] =
periodogram(abs(HPA_output).^2./2,[],'onesided',freq_points,(1 / time_step));
Power_spectrum_HPA_output_complex_baseband = zeros(1,freq_points);
Power_spectrum_HPA_output_complex_baseband(1:freq_points/2) =
Power_spectrum_HPA_output(freq_points/2+1:end);
Power_spectrum_HPA_output_complex_baseband(freq_points/2+1:end) =
Power_spectrum_HPA_output(1:freq_points/2);
frequency_HPA_output_shifted = frequency_HPA_output - (1 / time_step)/2;
plot(frequency_HPA_output,10.*log10(Power_spectrum_HPA_output+0.00000000000000000001),'m')
% NOTE:  Both plots have same frequency vector - problem with doppler
hold off
%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Calculate channel power in 1.6MHz before HPA  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%
channel_bandwidth = 1.6e6;
frequency_resolution = freq_points/2 / (1/time_step/2);
bandwidth_correction = -10*log10(frequency_resolution);
channel_power = sum(Power_spectrum_HPA_output(1:round(frequency_resolution*channel_bandwidth)));
channel_power_HPA_dB = 10*log10(channel_power) + bandwidth_correction;
fprintf('channel power in 1.6MHz after HPA = %.4g\n',channel_power_HPA_dB)
%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Calculate adjacent channel power after HPA  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%
channel_bandwidth = 1.536e6;
adjacent_channel_offset = 1.7e6;
frequency_resolution = freq_points/2 / (1/time_step/2);
bandwidth_correction = -10*log10(frequency_resolution);
adjacent_channel_power =
sum(Power_spectrum_HPA_output(round((channel_bandwidth/2+adjacent_channel_offset-
channel_bandwidth/2)*frequency_resolution:round((channel_bandwidth/2+adjacent_channel_offset+channel_ban
dwidth/2)*frequency_resolution))));
adjacent_channel_power_HPA_dB = 10*log10(adjacent_channel_power) + bandwidth_correction;
fprintf('adjacent_channel power = %.4g\n',adjacent_channel_power_HPA_dB)
%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Plot envelope in dB and display mean and peak after HPA %
%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure(9);clf;
plot(20*log10(abs(HPA_output)))
mean_power_HPA_dB = 20*log10(mean(abs(HPA_output)));
peak_power_HPA_dB = 20*log10(max(abs(HPA_output)));
%fprintf('mean power after HPA = %.4g\n',mean_power_HPA_dB)
%fprintf('peak power after HPA= %.4g\n',peak_power_HPA_dB)
%fprintf('peak to mean after HPA= %.4g\n',peak_power_HPA_dB - mean_power_HPA_dB)
fprintf('ACPR after HPA= %.4g\n',channel_power_HPA_dB - adjacent_channel_power_HPA_dB)
%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Calculate and plot histogram of envelope after HPA %
%%%%%%%%%%%%%%%%%%%%%%%%%%%
HPA_output_envelope_dB = 20*log10(abs(HPA_output));
figure(10);clf;
bins = -40:0.1:20;
hist(HPA_output_envelope_dB - mean_power_HPA_dB, bins)
title('Histogram of QPSK Envelope after HPA')
xlabel('Bins (0.1dB width, centred around mean)')
ylabel('Quantity of samples in Bin')
```

12 Appendix B – BER Simulation Test Bench

12.1 QPSK (DVB-S)

```
function BER=DVB_QPSK_AWGNrun(N,SNR_dB)
%  MSc Project: "DVB versus S-UMTS for broadcast/multicast"
%  Student:  Pete King
%  Supervisor:  Professor Barry Evans
%
%  MATLAB file name:  DVB_QPSK_AWGN.m
%
%  This file simulates the BER performance of coherent QPSK using monte carlo techniques.
%clear all;
%%%%%%%%%%%%%%%
%  Set up stream of data bits  %
%%%%%%%%%%%%%%%
number_of_bits = N;
bitstream = round(rand(1,number_of_bits));
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Convert from serial to parallel and make bipolar  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
i = 2 *bitstream(1:2:number_of_bits) - 1;
q = 2 *bitstream(2:2:number_of_bits) - 1;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Up-sample bit stream to enable filtering implementation  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
samples_per_bit = 1;
upsampled_i = zeros(1,length(i)*samples_per_bit);
upsampled_q = zeros(1,length(q)*samples_per_bit);
upsampled_i(1:samples_per_bit:end) = i;
upsampled_q(1:samples_per_bit:end) = q;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Calculate raised cosine impulse response and filter data  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%rrc_impulse = sqrt(samples_per_bit)*firrcos(501,1/samples_per_bit,0.35,2,'rolloff','sqrt');
% firrcos(n,F0,r,fs,'rolloff','sqrt')
scale = 1;
%rrc_data_i = scale.*filter(rrc_impulse,1,upsampled_i);
%rrc_data_q = scale.*filter(rrc_impulse,1,upsampled_q);
%%%%%%%%%%%%%%%%%%%%%%%%%
%  Plot IQ constellation with filtered data  %
%%%%%%%%%%%%%%%%%%%%%%%%%
%figure(1);clf;
transient_delay = 0;
%plot(rrc_data_i(1 + transient_delay:end),rrc_data_q(1 + transient_delay:end))
%title('QPSK Constellation Plot')
%xlabel('In-phase')
%ylabel('Quad-phase')
%hold on
%plot(rrc_data_i(1 + transient_delay:samples_per_bit:end),rrc_data_q(1 +
transient_delay:samples_per_bit:end),'m+')
%hold off
%%%%%%%%%%%%%%%%%%%%%%
%  Plot raised cosine impulse response  %
%%%%%%%%%%%%%%%%%%%%%%
%figure(3);clf;
%stem(rrc_impulse)
%title('FIR Raised Cosine Impulse Response')
%xlabel('Samples (10 times oversampling)')
%ylabel('Amplitude')
%axis([1 500 -0.1 0.4])
%%%%%%%%%%%%
%  Set up time vector  %
%%%%%%%%%%%%
```

```
quad_mod_output = i + sqrt(-1)*q;
bit_rate = 48e6;
symbol_rate = bit_rate / 2;
time_step = 1 / symbol_rate / samples_per_bit;
time = (0:time_step:length(quad_mod_output) * time_step - time_step);
%%%%%%%%%%%%%%%%
%  Satellite to Mobile Channel %
%%%%%%%%%%%%%%%%
%SNR_dB = 6;
SNR = 10.^(SNR_dB/10);
power = 2;
samples_per_symbol = 1;
bits_per_symbol = 2;
noise_variance = power*samples_per_symbol/(2*bits_per_symbol*SNR);
noise_std_dev = sqrt(noise_variance);
noise_i = noise_std_dev.*randn(1,number_of_bits ./ 2 .*samples_per_bit);
noise_q = noise_std_dev.*randn(1,number_of_bits ./ 2 .*samples_per_bit);
complex_noise = noise_i + sqrt(-1).*noise_q;
demod_input = complex_noise + quad_mod_output;
%%%%%%%%%%%%
%  Mobile Demodulator %
%%%%%%%%%%%%
rx_data_i = real(demod_input);
rx_data_q = imag(demod_input);
scale = 1;
rx_rrc_data_i = rx_data_i;
rx_rrc_data_q = rx_data_q;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Plot IQ constellation of received filtered data  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure(12);clf;
transient_delay = 0*2;
%plot(rx_rrc_data_i(1 + transient_delay:end),rx_rrc_data_q(1 + transient_delay:end))
%hold on
plot(rx_rrc_data_i(1 + transient_delay:samples_per_bit:end),rx_rrc_data_q(1 +
transient_delay:samples_per_bit:end),'m+')
title('QPSK Constellation Plot')
xlabel('In-phase')
ylabel('Quad-phase')
%hold off
%%%%%%%%%%%%%%%%%%%%
%  Decimate and slice using Gray coding %
%%%%%%%%%%%%%%%%%%%%
rx_sym = rx_rrc_data_i(1+transient_delay:samples_per_bit:end)+sqrt(-
1).*rx_rrc_data_q(1+transient_delay:samples_per_bit:end);
rx_sym_i = rx_rrc_data_i(1+transient_delay:samples_per_bit:end);
rx_sym_q = rx_rrc_data_q(1+transient_delay:samples_per_bit:end);

for num = 1:2:number_of_bits;% - 2.*(transient_delay - 1)./samples_per_bit;
if sign(rx_sym_i((num+1)./2)) >= 0 & sign(rx_sym_q((num+1)./2)) >= 0
   rx_bitstream(num) = 0; rx_bitstream(num+1)=0;
elseif sign(rx_sym_i((num+1)./2)) >= 0 & sign(rx_sym_q((num+1)./2)) < 0
   rx_bitstream(num) = 0; rx_bitstream(num+1)=1;
elseif sign(rx_sym_i((num+1)./2)) < 0 & sign(rx_sym_q((num+1)./2)) >= 0
   rx_bitstream(num) = 1; rx_bitstream(num+1)=0;
elseif sign(rx_sym_i((num+1)./2)) < 0 & sign(rx_sym_q((num+1)./2)) < 0
   rx_bitstream(num) = 1; rx_bitstream(num+1)=1;
else x=0;
end;end;
%%%%%%%%%%%%%%%%%%%%
%  Measures errors and calculate BER %
%%%%%%%%%%%%%%%%%%%%
rx_bitstream_inv = -1.*rx_bitstream + 1;
error = bitstream - rx_bitstream_inv;
total_errors = sum(abs(error));
format short e;
BER = total_errors ./ number_of_bits;
```

12.2 W-CDMA/QPSK (S-UMTS)

```
function BER=SUMTSBER(N,SNR_dB)
%  MSc Project: "DVB versus S-UMTS for broadcast/multicast"
%  Student:  Pete King
%  Supervisor:  Professor Barry Evans
%
%  MATLAB file name:  SUMTS_QPSK_AWGN.m
%
%  This file simulates the BER performance of W-CDMA / QPSK using monte carlo techniques.
%clear;
%%%%%%%%%%%%%%%%
%  Set up stream of data bits  %
%%%%%%%%%%%%%%%%
number_of_bits = N;
bit_streamCh1 = round(rand(1,number_of_bits));
bit_streamCh2 = round(rand(1,number_of_bits));
bit_streamCh3 = round(rand(1,number_of_bits));
bit_streamCh4 = round(rand(1,number_of_bits));
bit_streamCh5 = round(rand(1,number_of_bits));
bit_streamCh6 = round(rand(1,number_of_bits));
bit_streamCh7 = round(rand(1,number_of_bits));
bit_streamCh8 = round(rand(1,number_of_bits));
bit_streamCh9 = round(rand(1,number_of_bits));
bit_streamCh10 = round(rand(1,number_of_bits));
bit_streamCh11 = round(rand(1,number_of_bits));
bit_streamCh12 = round(rand(1,number_of_bits));
bit_streamCh13 = round(rand(1,number_of_bits));
bit_streamCh14 = round(rand(1,number_of_bits));
bit_streamCh15 = round(rand(1,number_of_bits));
bit_streamCh16 = round(rand(1,number_of_bits));
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Convert from serial to parallel and make bipolar  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
iCh1 = 2 *bit_streamCh1(1:2:number_of_bits) - 1;
qCh1 = 2 *bit_streamCh1(2:2:number_of_bits) - 1;
iCh2 = 2 *bit_streamCh2(1:2:number_of_bits) - 1;
qCh2 = 2 *bit_streamCh2(2:2:number_of_bits) - 1;
iCh3 = 2 *bit_streamCh3(1:2:number_of_bits) - 1;
qCh3 = 2 *bit_streamCh3(2:2:number_of_bits) - 1;
iCh4 = 2 *bit_streamCh4(1:2:number_of_bits) - 1;
qCh4 = 2 *bit_streamCh4(2:2:number_of_bits) - 1;
iCh5 = 2 *bit_streamCh5(1:2:number_of_bits) - 1;
qCh5 = 2 *bit_streamCh5(2:2:number_of_bits) - 1;
iCh6 = 2 *bit_streamCh6(1:2:number_of_bits) - 1;
qCh6 = 2 *bit_streamCh6(2:2:number_of_bits) - 1;
iCh7 = 2 *bit_streamCh7(1:2:number_of_bits) - 1;
qCh7 = 2 *bit_streamCh7(2:2:number_of_bits) - 1;
iCh8 = 2 *bit_streamCh8(1:2:number_of_bits) - 1;
qCh8 = 2 *bit_streamCh8(2:2:number_of_bits) - 1;
iCh9 = 2 *bit_streamCh9(1:2:number_of_bits) - 1;
qCh9 = 2 *bit_streamCh9(2:2:number_of_bits) - 1;
iCh10 = 2 *bit_streamCh10(1:2:number_of_bits) - 1;
qCh10 = 2 *bit_streamCh10(2:2:number_of_bits) - 1;
iCh11 = 2 *bit_streamCh11(1:2:number_of_bits) - 1;
qCh11 = 2 *bit_streamCh11(2:2:number_of_bits) - 1;
iCh12 = 2 *bit_streamCh12(1:2:number_of_bits) - 1;
qCh12 = 2 *bit_streamCh12(2:2:number_of_bits) - 1;
iCh13 = 2 *bit_streamCh13(1:2:number_of_bits) - 1;
qCh13 = 2 *bit_streamCh13(2:2:number_of_bits) - 1;
iCh14 = 2 *bit_streamCh14(1:2:number_of_bits) - 1;
qCh14 = 2 *bit_streamCh14(2:2:number_of_bits) - 1;
iCh15 = 2 *bit_streamCh15(1:2:number_of_bits) - 1;
qCh15 = 2 *bit_streamCh15(2:2:number_of_bits) - 1;
iCh16 = 2 *bit_streamCh16(1:2:number_of_bits) - 1;
```

```
qCh16 = 2 *bit_streamCh16(2:2:number_of_bits) - 1;
%%%%%%%%%%%%
walsh_row_length = 16;
%%%%%%%%%%%%
H2 = [0 0;0 1];
H4 = [H2 H2;H2 xor(1,H2)];
H8 = [H4 H4;H4 xor(1,H4)];
H16 = [H8 H8;H8 xor(1,H8)];
H16bipolar = 2.*H16-1;
%%%%%%%%%%%%
Ch1=[];Ch2=[];Ch3=[];Ch4=[];Ch5=[];Ch6=[];Ch7=[];Ch8=[];H16_2=[];
Ch9=[];Ch10=[];Ch11=[];Ch12=[];Ch13=[];Ch14=[];Ch15=[];Ch16=[];
for n = 1:length(iCh1)
Ch1 = [Ch1 iCh1(n) .* H16bipolar(1,:) + sqrt(-1) .* qCh1(n) .* H16bipolar(1,:)];
Ch2 = [Ch2 iCh2(n) .* H16bipolar(2,:) + sqrt(-1) .* qCh2(n) .* H16bipolar(2,:)];
Ch3 = [Ch3 iCh3(n) .* H16bipolar(3,:) + sqrt(-1) .* qCh3(n) .* H16bipolar(3,:)];
Ch4 = [Ch4 iCh4(n) .* H16bipolar(4,:) + sqrt(-1) .* qCh4(n) .* H16bipolar(4,:)];
Ch5 = [Ch5 iCh5(n) .* H16bipolar(5,:) + sqrt(-1) .* qCh5(n) .* H16bipolar(5,:)];
Ch6 = [Ch6 iCh6(n) .* H16bipolar(6,:) + sqrt(-1) .* qCh6(n) .* H16bipolar(6,:)];
Ch7 = [Ch7 iCh7(n) .* H16bipolar(7,:) + sqrt(-1) .* qCh7(n) .* H16bipolar(7,:)];
Ch8 = [Ch8 iCh8(n) .* H16bipolar(8,:) + sqrt(-1) .* qCh8(n) .* H16bipolar(8,:)];
Ch9 = [Ch9 iCh9(n) .* H16bipolar(9,:) + sqrt(-1) .* qCh9(n) .* H16bipolar(9,:)];
Ch10 = [Ch10 iCh10(n) .* H16bipolar(10,:) + sqrt(-1) .* qCh10(n) .* H16bipolar(10,:)];
Ch11 = [Ch11 iCh11(n) .* H16bipolar(11,:) + sqrt(-1) .* qCh11(n) .* H16bipolar(11,:)];
Ch12 = [Ch12 iCh12(n) .* H16bipolar(12,:) + sqrt(-1) .* qCh12(n) .* H16bipolar(12,:)];
Ch13 = [Ch13 iCh13(n) .* H16bipolar(13,:) + sqrt(-1) .* qCh13(n) .* H16bipolar(13,:)];
Ch14 = [Ch14 iCh14(n) .* H16bipolar(14,:) + sqrt(-1) .* qCh14(n) .* H16bipolar(14,:)];
Ch15 = [Ch15 iCh15(n) .* H16bipolar(15,:) + sqrt(-1) .* qCh15(n) .* H16bipolar(15,:)];
Ch16 = [Ch16 iCh16(n) .* H16bipolar(16,:) + sqrt(-1) .* qCh16(n) .* H16bipolar(16,:)];
H16_2 = [H16_2 H16bipolar(2,:)];
end
CDMAcomp =
Ch1+Ch2+Ch3+Ch4+Ch5+Ch6+Ch7+Ch8+Ch9+Ch10+Ch11+Ch12+Ch13+Ch14+Ch15+Ch16;%+Ch3+Ch4+Ch
5+Ch6+Ch7+Ch8+Ch9+Ch10+Ch11+Ch12+Ch13+Ch14+Ch15+Ch16;
CDMAcomp_i = real(CDMAcomp);
CDMAcomp_q = imag(CDMAcomp);

%figure(11);clf;
%plot(1:1000,CDMAcomp(1:1000))

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Up-sample bit stream to enable filtering implementation  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
samples_per_bit = 1;
%upsampled_i = zeros(1,length(CDMAcomp)*samples_per_bit);
%upsampled_q = zeros(1,length(CDMAcomp)*samples_per_bit);
%upsampled_i(1:samples_per_bit:end) = CDMAcomp_i;
%upsampled_q(1:samples_per_bit:end) = CDMAcomp_q;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Calculate raised cosine impulse response and filter data  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%rrc_impulse = sqrt(samples_per_bit)*firrcos(501,1/samples_per_bit,0.22,2,'rolloff','sqrt');
% firrcos(n,F0,r,fs,'rolloff','sqrt')
scale = 1;
%rrc_data_i = scale.*filter(rrc_impulse,1,upsampled_i);
%rrc_data_q = scale.*filter(rrc_impulse,1,upsampled_q);
%%%%%%%%%%%%%%%%%%%%%%%%
%  Plot IQ constellation with filtered data  %
%%%%%%%%%%%%%%%%%%%%%%%%
figure(1);clf;
transient_delay = 0;
plot(CDMAcomp_i(1 + transient_delay:end),CDMAcomp_q(1 + transient_delay:end))
title('WCDMA Constellation Plot')
xlabel('In-phase')
ylabel('Quad-phase')
%hold on
```

```
%plot(rrc_data_i(1 + transient_delay:samples_per_bit:end),rrc_data_q(1 +
transient_delay:samples_per_bit:end),'m+')
%hold off

%%%%%%%%%%%
%  Set up time vector  %
%%%%%%%%%%%
quad_mod_output = CDMAcomp_i + sqrt(-1)*CDMAcomp_q;
%chip_rate = 3.84e6;
%time_step = 1 / chip_rate / samples_per_bit;
%time = (0:time_step:length(quad_mod_output) * time_step - time_step);

%%%%%%%%%%%%%%%%%%%%%
%  Satellite to Mobile Channel - AWGN %
%%%%%%%%%%%%%%%%%%%%%
%SNR_dB = 6;
SNR = 10.^(SNR_dB/10);
power = (sqrt(2)*1)^2;
chips_per_bit = 16;
samples_per_symbol = 1;
bits_per_symbol = 2;
noise_variance = power*chips_per_bit*samples_per_symbol/(2*bits_per_symbol*SNR);
noise_std_dev = sqrt(noise_variance);

noise_i = noise_std_dev.*randn(1,length(quad_mod_output));
noise_q = noise_std_dev.*randn(1,length(quad_mod_output));
complex_noise = noise_i + sqrt(-1).*noise_q;
demod_input = complex_noise + quad_mod_output;

%%%%%%%%%%%
%  Mobile Demodulator %
%%%%%%%%%%%
rx_data_i = real(demod_input);
rx_data_q = imag(demod_input);
scale = 1;
rx_rrc_data_i = rx_data_i;%scale.*filter(rrc_impulse,1,rx_data_i);
rx_rrc_data_q = rx_data_q;%scale.*filter(rrc_impulse,1,rx_data_q);

rx_rrc_data = rx_rrc_data_i + sqrt(-1).*rx_rrc_data_q;

transient_delay = 0;

%%%%%%%%%%%%%%%
%  Demodulate Walsh row N %
%%%%%%%%%%%%%%%
%Ch2 = icdmaCh2 .* H16cdmaCh2 + sqrt(-1) .* qcdmaCh2 .* H16cdmaCh2;
rx_despread_i = rx_rrc_data_i .* H16_2;
rx_despread_q = rx_rrc_data_q .* H16_2;
rx_despread = rx_despread_i + sqrt(-1).*rx_despread_q;
power = mean(abs(rx_despread));


%%%%%%%%%%%%%
%  Correlate despread data  %
%%%%%%%%%%%%%

n=0;
for m = 1:16:length(rx_despread_i)-15
n=n+1;
rx_int_i(n) = sum(rx_despread_i(m:m+15));
rx_int_q(n) = sum(rx_despread_q(m:m+15));
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Plot IQ constellation of received filtered data  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure(2);clf;
```

```
plot(rx_int_i,rx_int_q,'m+')
title('Received QPSK Constellation Plot')
xlabel('In-phase')
ylabel('Quad-phase')
%hold on
%plot(rx_int_i(1 + transient_delay:samples_per_bit:end),rx_int_q(1 + transient_delay:samples_per_bit:end),'m+')
%hold off

%%%%%%%%%%%%%%%%%%%%
%  Decimate and slice using Gray coding %
%%%%%%%%%%%%%%%%%%%%

rx_sym = rx_despread_i+sqrt(-1).*rx_despread_q;
rx_sym_i = rx_int_i;
rx_sym_q = rx_int_q;

for num = 1:2:length(rx_sym_i)*2;
if sign(rx_sym_i((num+1)./2)) >= 0 & sign(rx_sym_q((num+1)./2)) >= 0
   rx_bitstream(num) = 0; rx_bitstream(num+1)=0;
elseif sign(rx_sym_i((num+1)./2)) >= 0 & sign(rx_sym_q((num+1)./2)) < 0
   rx_bitstream(num) = 0; rx_bitstream(num+1)=1;
elseif sign(rx_sym_i((num+1)./2)) < 0 & sign(rx_sym_q((num+1)./2)) >= 0
   rx_bitstream(num) = 1; rx_bitstream(num+1)=0;
elseif sign(rx_sym_i((num+1)./2)) < 0 & sign(rx_sym_q((num+1)./2)) < 0
   rx_bitstream(num) = 1; rx_bitstream(num+1)=1;
else x=0;
end;end;

%%%%%%%%%%%%%%%%%%%%
%  Measures errors and calculate BER %
%%%%%%%%%%%%%%%%%%%%

rx_bitstream_inv = -1.*rx_bitstream + 1;
error = bit_streamCh2(1:length(rx_bitstream_inv)) - rx_bitstream_inv;
total_errors = sum(abs(error));
format short e;
BER = total_errors ./ length(error);
```

12.3 W-CDMA/16QAM (S-UMTS)

```
function BER=SUMTS_16QAM_AWGN(N,SNR_dB)
%  MSc Project: "DVB versus S-UMTS for broadcast/multicast"
%  Student:  Pete King
%  Supervisor:  Professor Barry Evans
%
%  MATLAB file name:  SUMTS_16QAM_AWGN.m
%
%  This file simulates the BER performance of W-CDMA / 16QAM using monte carlo techniques.

%clear all;
%%%%%%%%%%%%%%%%
%  Set up stream of data bits  %
%%%%%%%%%%%%%%%%
number_of_bits = N;
bit_streamCh1 = round(rand(1,number_of_bits));
bit_streamCh2 = round(rand(1,number_of_bits));
bit_streamCh3 = round(rand(1,number_of_bits));
bit_streamCh4 = round(rand(1,number_of_bits));
bit_streamCh5 = round(rand(1,number_of_bits));
bit_streamCh6 = round(rand(1,number_of_bits));
bit_streamCh7 = round(rand(1,number_of_bits));
bit_streamCh8 = round(rand(1,number_of_bits));
bit_streamCh9 = round(rand(1,number_of_bits));
```

```
bit_streamCh10 = round(rand(1,number_of_bits));
bit_streamCh11 = round(rand(1,number_of_bits));
bit_streamCh12 = round(rand(1,number_of_bits));
bit_streamCh13 = round(rand(1,number_of_bits));
bit_streamCh14 = round(rand(1,number_of_bits));
bit_streamCh15 = round(rand(1,number_of_bits));
bit_streamCh16 = round(rand(1,number_of_bits));
%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Convert from serial to parallel and make bipolar  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%
iCh1M = 2 *bit_streamCh1(1:4:number_of_bits) - 1;
qCh1M = 2 *bit_streamCh1(2:4:number_of_bits) - 1;
iCh1S = 2 *bit_streamCh1(3:4:number_of_bits) - 1;
qCh1S = 2 *bit_streamCh1(4:4:number_of_bits) - 1;
iCh2M = 2 *bit_streamCh2(1:4:number_of_bits) - 1;
qCh2M = 2 *bit_streamCh2(2:4:number_of_bits) - 1;
iCh2S = 2 *bit_streamCh2(3:4:number_of_bits) - 1;
qCh2S = 2 *bit_streamCh2(4:4:number_of_bits) - 1;
iCh3M = 2 *bit_streamCh3(1:4:number_of_bits) - 1;
qCh3M = 2 *bit_streamCh3(2:4:number_of_bits) - 1;
iCh3S = 2 *bit_streamCh3(3:4:number_of_bits) - 1;
qCh3S = 2 *bit_streamCh3(4:4:number_of_bits) - 1;
iCh4M = 2 *bit_streamCh4(1:4:number_of_bits) - 1;
qCh4M = 2 *bit_streamCh4(2:4:number_of_bits) - 1;
iCh4S = 2 *bit_streamCh4(3:4:number_of_bits) - 1;
qCh4S = 2 *bit_streamCh4(4:4:number_of_bits) - 1;
iCh5M = 2 *bit_streamCh5(1:4:number_of_bits) - 1;
qCh5M = 2 *bit_streamCh5(2:4:number_of_bits) - 1;
iCh5S = 2 *bit_streamCh5(3:4:number_of_bits) - 1;
qCh5S = 2 *bit_streamCh5(4:4:number_of_bits) - 1;
iCh6M = 2 *bit_streamCh6(1:4:number_of_bits) - 1;
qCh6M = 2 *bit_streamCh6(2:4:number_of_bits) - 1;
iCh6S = 2 *bit_streamCh6(3:4:number_of_bits) - 1;
qCh6S = 2 *bit_streamCh6(4:4:number_of_bits) - 1;
iCh7M = 2 *bit_streamCh7(1:4:number_of_bits) - 1;
qCh7M = 2 *bit_streamCh7(2:4:number_of_bits) - 1;
iCh7S = 2 *bit_streamCh7(3:4:number_of_bits) - 1;
qCh7S = 2 *bit_streamCh7(4:4:number_of_bits) - 1;
iCh8M = 2 *bit_streamCh8(1:4:number_of_bits) - 1;
qCh8M = 2 *bit_streamCh8(2:4:number_of_bits) - 1;
iCh8S = 2 *bit_streamCh8(3:4:number_of_bits) - 1;
qCh8S = 2 *bit_streamCh8(4:4:number_of_bits) - 1;
iCh9M = 2 *bit_streamCh9(1:4:number_of_bits) - 1;
qCh9M = 2 *bit_streamCh9(2:4:number_of_bits) - 1;
iCh9S = 2 *bit_streamCh9(3:4:number_of_bits) - 1;
qCh9S = 2 *bit_streamCh9(4:4:number_of_bits) - 1;
iCh10M = 2 *bit_streamCh10(1:4:number_of_bits) - 1;
qCh10M = 2 *bit_streamCh10(2:4:number_of_bits) - 1;
iCh10S = 2 *bit_streamCh10(3:4:number_of_bits) - 1;
qCh10S = 2 *bit_streamCh10(4:4:number_of_bits) - 1;
iCh11M = 2 *bit_streamCh11(1:4:number_of_bits) - 1;
qCh11M = 2 *bit_streamCh11(2:4:number_of_bits) - 1;
iCh11S = 2 *bit_streamCh11(3:4:number_of_bits) - 1;
qCh11S = 2 *bit_streamCh11(4:4:number_of_bits) - 1;
iCh12M = 2 *bit_streamCh12(1:4:number_of_bits) - 1;
qCh12M = 2 *bit_streamCh12(2:4:number_of_bits) - 1;
iCh12S = 2 *bit_streamCh12(3:4:number_of_bits) - 1;
qCh12S = 2 *bit_streamCh12(4:4:number_of_bits) - 1;
iCh13M = 2 *bit_streamCh13(1:4:number_of_bits) - 1;
qCh13M = 2 *bit_streamCh13(2:4:number_of_bits) - 1;
```

```
iCh13S = 2 *bit_streamCh13(3:4:number_of_bits) - 1;
qCh13S = 2 *bit_streamCh13(4:4:number_of_bits) - 1;
iCh14M = 2 *bit_streamCh14(1:4:number_of_bits) - 1;
qCh14M = 2 *bit_streamCh14(2:4:number_of_bits) - 1;
iCh14S = 2 *bit_streamCh14(3:4:number_of_bits) - 1;
qCh14S = 2 *bit_streamCh14(4:4:number_of_bits) - 1;
iCh15M = 2 *bit_streamCh15(1:4:number_of_bits) - 1;
qCh15M = 2 *bit_streamCh15(2:4:number_of_bits) - 1;
iCh15S = 2 *bit_streamCh15(3:4:number_of_bits) - 1;
qCh15S = 2 *bit_streamCh15(4:4:number_of_bits) - 1;
iCh16M = 2 *bit_streamCh16(1:4:number_of_bits) - 1;
qCh16M = 2 *bit_streamCh16(2:4:number_of_bits) - 1;
iCh16S = 2 *bit_streamCh16(3:4:number_of_bits) - 1;
qCh16S = 2 *bit_streamCh16(4:4:number_of_bits) - 1;
%%%%%%%%%%%
walsh_row_length = 16;
%%%%%%%%%%%
H2 = [0 0;0 1];
H4 = [H2 H2;H2 xor(1,H2)];
H8 = [H4 H4;H4 xor(1,H4)];
H16 = [H8 H8;H8 xor(1,H8)];
H16bipolar = 2.*H16-1;
%%%%%%%%%%%
Ch1=[];Ch2=[];Ch3=[];Ch4=[];Ch5=[];Ch6=[];Ch7=[];Ch8=[];H16_2=[];
Ch9=[];Ch10=[];Ch11=[];Ch12=[];Ch13=[];Ch14=[];Ch15=[];Ch16=[];
for n = 1:length(iCh1M)
Ch1qam16(n) = graycode(iCh1M(n),qCh1M(n),iCh1S(n),qCh1S(n));
Ch1 = [Ch1 Ch1qam16(n) .* H16bipolar(1,:)];
Ch2qam16(n) = graycode(iCh2M(n),qCh2M(n),iCh2S(n),qCh2S(n));
Ch2 = [Ch2 Ch2qam16(n) .* H16bipolar(2,:)];
Ch3qam16(n) = graycode(iCh3M(n),qCh3M(n),iCh3S(n),qCh3S(n));
Ch3 = [Ch3 Ch3qam16(n) .* H16bipolar(3,:)];
Ch4qam16(n) = graycode(iCh4M(n),qCh4M(n),iCh4S(n),qCh4S(n));
Ch4 = [Ch4 Ch4qam16(n) .* H16bipolar(4,:)];
Ch5qam16(n) = graycode(iCh5M(n),qCh5M(n),iCh5S(n),qCh5S(n));
Ch5 = [Ch5 Ch5qam16(n) .* H16bipolar(5,:)];
Ch6qam16(n) = graycode(iCh6M(n),qCh6M(n),iCh6S(n),qCh6S(n));
Ch6 = [Ch6 Ch6qam16(n) .* H16bipolar(6,:)];
Ch7qam16(n) = graycode(iCh7M(n),qCh7M(n),iCh7S(n),qCh7S(n));
Ch7 = [Ch7 Ch7qam16(n) .* H16bipolar(7,:)];
Ch8qam16(n) = graycode(iCh8M(n),qCh8M(n),iCh8S(n),qCh8S(n));
Ch8 = [Ch8 Ch8qam16(n) .* H16bipolar(8,:)];
Ch9qam16(n) = graycode(iCh9M(n),qCh9M(n),iCh9S(n),qCh9S(n));
Ch9 = [Ch9 Ch9qam16(n) .* H16bipolar(9,:)];
Ch10qam16(n) = graycode(iCh10M(n),qCh10M(n),iCh10S(n),qCh10S(n));
Ch10 = [Ch10 Ch10qam16(n) .* H16bipolar(10,:)];
Ch11qam16(n) = graycode(iCh11M(n),qCh11M(n),iCh11S(n),qCh11S(n));
Ch11 = [Ch11 Ch11qam16(n) .* H16bipolar(11,:)];
Ch12qam16(n) = graycode(iCh12M(n),qCh12M(n),iCh12S(n),qCh12S(n));
Ch12 = [Ch12 Ch12qam16(n) .* H16bipolar(12,:)];
Ch13qam16(n) = graycode(iCh13M(n),qCh13M(n),iCh13S(n),qCh13S(n));
Ch13 = [Ch13 Ch13qam16(n) .* H16bipolar(13,:)];
Ch14qam16(n) = graycode(iCh14M(n),qCh14M(n),iCh14S(n),qCh14S(n));
Ch14 = [Ch14 Ch14qam16(n) .* H16bipolar(14,:)];
Ch15qam16(n) = graycode(iCh15M(n),qCh15M(n),iCh15S(n),qCh15S(n));
Ch15 = [Ch15 Ch15qam16(n) .* H16bipolar(15,:)];
Ch16qam16(n) = graycode(iCh16M(n),qCh16M(n),iCh16S(n),qCh16S(n));
Ch16 = [Ch16 Ch16qam16(n) .* H16bipolar(16,:)];
H16_2 = [H16_2 H16bipolar(2,:)];
end
```

```
CDMAcomp =
Ch1+Ch2+Ch3+Ch4+Ch5+Ch6+Ch7+Ch8+Ch9+Ch10+Ch11+Ch12+Ch13+Ch14+Ch15+Ch16;%+Ch
3+Ch4+Ch5+Ch6+Ch7+Ch8+Ch9+Ch10+Ch11+Ch12+Ch13+Ch14+Ch15+Ch16;
CDMAcomp_i = real(CDMAcomp);
CDMAcomp_q = imag(CDMAcomp);

%figure(11);clf;
%plot(1:1000,CDMAcomp(1:1000))


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Up-sample bit stream to enable filtering implementation  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
samples_per_bit = 1;
%upsampled_i = zeros(1,length(CDMAcomp)*samples_per_bit);
%upsampled_q = zeros(1,length(CDMAcomp)*samples_per_bit);
%upsampled_i(1:samples_per_bit:end) = CDMAcomp_i;
%upsampled_q(1:samples_per_bit:end) = CDMAcomp_q;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Calculate raised cosine impulse response and filter data  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%rrc_impulse = sqrt(samples_per_bit)*firrcos(501,1/samples_per_bit,0.22,2,'rolloff','sqrt');
% firrcos(n,F0,r,fs,'rolloff','sqrt')
scale = 1;
%rrc_data_i = scale.*filter(rrc_impulse,1,upsampled_i);
%rrc_data_q = scale.*filter(rrc_impulse,1,upsampled_q);

%%%%%%%%%%%%%%%%%%%%
%  Plot IQ constellation with filtered data  %
%%%%%%%%%%%%%%%%%%%%
figure(1);clf;
transient_delay = 0;
plot(CDMAcomp_i(1 + transient_delay:end),CDMAcomp_q(1 + transient_delay:end))
title('WCDMA Constellation Plot')
xlabel('In-phase')
ylabel('Quad-phase')
%hold on
%plot(rrc_data_i(1 + transient_delay:samples_per_bit:end),rrc_data_q(1 +
transient_delay:samples_per_bit:end),'m+')
%hold off

%%%%%%%%%%
%  Set up time vector  %
%%%%%%%%%%

quad_mod_output = CDMAcomp_i + sqrt(-1)*CDMAcomp_q;
%chip_rate = 3.84e6;
%time_step = 1 / chip_rate / samples_per_bit;
%time = (0:time_step:length(quad_mod_output) * time_step - time_step);

%%%%%%%%%%%%%%%%%%%%
%  Satellite to Mobile Channel - AWGN %
%%%%%%%%%%%%%%%%%%%%
%SNR_dB = 10;
SNR = 10.^(SNR_dB/10);
power = (sqrt(2.598))^2;
chips_per_bit = 16;
samples_per_symbol = 1;
```

```
bits_per_symbol = 4;
noise_variance = power*chips_per_bit*samples_per_symbol/(2*bits_per_symbol*SNR);
noise_std_dev = sqrt(noise_variance);

noise_i = noise_std_dev.*randn(1,length(quad_mod_output));
noise_q = noise_std_dev.*randn(1,length(quad_mod_output));
complex_noise = noise_i + sqrt(-1).*noise_q;
demod_input = complex_noise + quad_mod_output;

%%%%%%%%%%%%
%  Mobile Demodulator %
%%%%%%%%%%%%
rx_data_i = real(demod_input)./16;
rx_data_q = imag(demod_input)./16;
scale = 1/16;
%rx_rrc_data_i = scale.*filter(rrc_impulse,1,rx_data_i);
%rx_rrc_data_q = scale.*filter(rrc_impulse,1,rx_data_q);
%rx_rrc_data = rx_rrc_data_i + sqrt(-1).*rx_rrc_data_q;
transient_delay = 0;
%%%%%%%%%%%%%%
%  Demodulate Walsh row N %
%%%%%%%%%%%%%%
%Ch2 = icdmaCh2 .* H16cdmaCh2 + sqrt(-1) .* qcdmaCh2 .* H16cdmaCh2;
rx_despread_i = rx_data_i .* H16_2;
rx_despread_q = rx_data_q .* H16_2;
rx_despread = rx_despread_i + sqrt(-1).*rx_despread_q;
power = mean(abs(rx_despread));


%%%%%%%%%%%%
%  Correlate despread data  %
%%%%%%%%%%%%

n=0;
for m = 1:16:length(rx_despread_i)-15
n=n+1;
rx_int_i(n) = sum(rx_despread_i(m:m+15));
rx_int_q(n) = sum(rx_despread_q(m:m+15));
end

%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Plot IQ constellation of received filtered data  %
%%%%%%%%%%%%%%%%%%%%%%%%%%
figure(2);clf;
plot(rx_int_i,rx_int_q,'m+')
title('16QAM Constellation Plot')
xlabel('In-phase')
ylabel('Quad-phase')
%hold on
%plot(rx_int_i(1 + transient_delay:samples_per_bit:end),rx_int_q(1 +
transient_delay:samples_per_bit:end),'m+')
%hold off

%%%%%%%%%%%%%%%%%%%%
%  Decimate and slice using Gray coding %
%%%%%%%%%%%%%%%%%%%%
rx_sym = rx_despread_i+sqrt(-1).*rx_despread_q;
rx_sym_i = rx_int_i;
rx_sym_q = rx_int_q;
rx_off_i = zeros(1,length(rx_sym_i));
```

```
rx_off_q = zeros(1,length(rx_sym_q));
for num = 1:4:length(rx_sym_i)*4;
if sign(rx_sym_i((num+3)./4)) >= 0 & sign(rx_sym_q((num+3)./4)) >= 0
   rx_off_i((num+3)./4) = rx_sym_i((num+3)./4) - 1;
   rx_off_q((num+3)./4) = rx_sym_q((num+3)./4) - 1;
   if sign(rx_off_i((num+3)./4)) >= 0 & sign(rx_off_q((num+3)./4)) >= 0
   rx_bitstream(num) = 1; rx_bitstream(num+1) = 1;rx_bitstream(num+2) = 1;rx_bitstream(num+3) =
1;
   elseif sign(rx_off_i((num+3)./4)) >= 0 & sign(rx_off_q((num+3)./4)) < 0
   rx_bitstream(num) = 1; rx_bitstream(num+1) = 1;rx_bitstream(num+2) = 1;rx_bitstream(num+3) =
0;
   elseif sign(rx_off_i((num+3)./4)) < 0 & sign(rx_off_q((num+3)./4)) >= 0
   rx_bitstream(num) = 1; rx_bitstream(num+1) = 1;rx_bitstream(num+2) = 0;rx_bitstream(num+3) =
1;
   elseif sign(rx_off_i((num+3)./4)) < 0 & sign(rx_off_q((num+3)./4)) < 0
   rx_bitstream(num) = 1; rx_bitstream(num+1) = 1;rx_bitstream(num+2) = 0;rx_bitstream(num+3) =
0;
   else x=0;end;
elseif sign(rx_sym_i((num+3)./4)) >= 0 & sign(rx_sym_q((num+3)./4)) < 0
   rx_off_i((num+3)./4) = rx_sym_i((num+3)./4) - 1;
   rx_off_q((num+3)./4) = rx_sym_q((num+3)./4) + 1;
   if sign(rx_off_i((num+3)./4)) >= 0 & sign(rx_off_q((num+3)./4)) >= 0
   rx_bitstream(num) = 1; rx_bitstream(num+1) = 0;rx_bitstream(num+2) = 1;rx_bitstream(num+3) =
0;
   elseif sign(rx_off_i((num+3)./4)) >= 0 & sign(rx_off_q((num+3)./4)) < 0
   rx_bitstream(num) = 1; rx_bitstream(num+1) = 0;rx_bitstream(num+2) = 1;rx_bitstream(num+3) =
1;
   elseif sign(rx_off_i((num+3)./4)) < 0 & sign(rx_off_q((num+3)./4)) >= 0
   rx_bitstream(num) = 1; rx_bitstream(num+1) = 0;rx_bitstream(num+2) = 0;rx_bitstream(num+3) =
0;
   elseif sign(rx_off_i((num+3)./4)) < 0 & sign(rx_off_q((num+3)./4)) < 0
   rx_bitstream(num) = 1; rx_bitstream(num+1) = 0;rx_bitstream(num+2) = 0;rx_bitstream(num+3) =
1;
   else x=0;end;
elseif sign(rx_sym_i((num+3)./4)) < 0 & sign(rx_sym_q((num+3)./4)) >= 0
   rx_off_i((num+3)./4) = rx_sym_i((num+3)./4) + 1;
   rx_off_q((num+3)./4) = rx_sym_q((num+3)./4) - 1;
   if sign(rx_off_i((num+3)./4)) >= 0 & sign(rx_off_q((num+3)./4)) >= 0
   rx_bitstream(num) = 0; rx_bitstream(num+1) = 1;rx_bitstream(num+2) = 0;rx_bitstream(num+3) =
1;
   elseif sign(rx_off_i((num+3)./4)) >= 0 & sign(rx_off_q((num+3)./4)) < 0
   rx_bitstream(num) = 0; rx_bitstream(num+1) = 1;rx_bitstream(num+2) = 0;rx_bitstream(num+3) =
0;
   elseif sign(rx_off_i((num+3)./4)) < 0 & sign(rx_off_q((num+3)./4)) >= 0
   rx_bitstream(num) = 0; rx_bitstream(num+1) = 1;rx_bitstream(num+2) = 1;rx_bitstream(num+3) =
1;
   elseif sign(rx_off_i((num+3)./4)) < 0 & sign(rx_off_q((num+3)./4)) < 0
   rx_bitstream(num) = 0; rx_bitstream(num+1) = 1;rx_bitstream(num+2) = 1;rx_bitstream(num+3) =
0;
   else x=0;end;
elseif sign(rx_sym_i((num+3)./4)) < 0 & sign(rx_sym_q((num+3)./4)) < 0
   rx_off_i((num+3)./4) = rx_sym_i((num+3)./4) + 1;
   rx_off_q((num+3)./4) = rx_sym_q((num+3)./4) + 1;
   if sign(rx_off_i((num+3)./4)) >= 0 & sign(rx_off_q((num+3)./4)) >= 0
   rx_bitstream(num) = 0; rx_bitstream(num+1) = 0;rx_bitstream(num+2) = 0;rx_bitstream(num+3) =
0;
   elseif sign(rx_off_i((num+3)./4)) >= 0 & sign(rx_off_q((num+3)./4)) < 0
   rx_bitstream(num) = 0; rx_bitstream(num+1) = 0;rx_bitstream(num+2) = 0;rx_bitstream(num+3) =
1;
   elseif sign(rx_off_i((num+3)./4)) < 0 & sign(rx_off_q((num+3)./4)) >= 0
```

```
   rx_bitstream(num) = 0; rx_bitstream(num+1) = 0;rx_bitstream(num+2) = 1;rx_bitstream(num+3) =
0;
   elseif sign(rx_off_i((num+3)./4)) < 0 & sign(rx_off_q((num+3)./4)) < 0
   rx_bitstream(num) = 0; rx_bitstream(num+1) = 0;rx_bitstream(num+2) = 1;rx_bitstream(num+3) =
1;
   else x=0;end;
else x=0;
end;end;

%%%%%%%%%%%%%%%%%%%
%  Measures errors and calculate BER %
%%%%%%%%%%%%%%%%%%%
rx_bitstream_bip = 2.*rx_bitstream - 1;
bit_streamCh2_bip = 2.*bit_streamCh2 - 1;
error = bit_streamCh2_bip - rx_bitstream_bip;
total_errors = sum(abs(error));
format short e;
BER = total_errors ./ length(error)
```

12.4 OFDM/QPSK (DAB)

```
function BER=DAB_QPSK_AWGNrun(N,SNR_dB)
%  MSc Project: "DVB versus S-UMTS for broadcast/multicast"
%  Student:  Pete King
%  Supervisor:  Professor Barry Evans
%
%  MATLAB file name:  DAB_QPSK_AWGN.m
%
%  This file simulates the BER performance of OFDM / QPSK using monte carlo techniques.

%clear all;
%%%%%%%%%%%%%%%%%
%  Set up stream of data bits  %
%%%%%%%%%%%%%%%%%
no_of_carriers = 192;
number_of_bits = N*no_of_carriers;

bit_streamCh1 = round(rand(1,number_of_bits));

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Convert from serial to parallel and make bipolar  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
iCh1 = 2 *bit_streamCh1(1:2:number_of_bits) - 1;
qCh1 = 2 *bit_streamCh1(2:2:number_of_bits) - 1;
d1 = iCh1 + sqrt(-1)*qCh1;
d1 = 1.*d1;
%%%%%%%%%%%%%%%%%
%  Put bits into blocks of 10  %
%%%%%%%%%%%%%%%%%

no_of_symbols = length(d1)/no_of_carriers;
for i = 1:no_of_symbols %
   block(i,1:no_of_carriers) = d1((i-1)*no_of_carriers+1:(i-1)*no_of_carriers+no_of_carriers);
   %block(k+1,154:192) = zeros(1,(192-153));

end

ifftsize = 1024*2;
spacing=1;
offset=128;
start_carrier = 1;%ifftsize/2-no_of_carriers+1;
final_carrier = no_of_carriers;%ifftsize/4-1+1;
carriers = [1+offset:192+offset];
neg_carriers = [384+offset:-1:193+offset];
```

```
spectrum = zeros(no_of_symbols,ifftsize);

for k = 1:no_of_symbols
spectrum(k,carriers) = (block(k,1:192));
spectrum(k,neg_carriers) = conj(block(k,1:192));
end

%%%%%%%%%%%%%%%%%%%
%  Take Inverse DFT of each block  %
%%%%%%%%%%%%%%%%%%%

Sm = (ifft(spectrum.'));

%
%
%
window = hamming(ifftsize);
window2 = zeros(ifftsize,no_of_symbols);
for k = 1:no_of_carriers
   window2(:,k) = window;
end

%Sm = window2.*Sm;
%Sm = window2.*Sm;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Return blocks of time domain data back into series data  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
OFDM_tx = reshape(Sm,1,size(Sm,1)*size(Sm,2));
OFDM = 1.*(real(OFDM_tx) + sqrt(-1).*imag(OFDM_tx));
OFDM_i = real(OFDM);
OFDM_q = imag(OFDM);
%%%%%%%%%%%%%%%%%%%%%
%  Plot IQ constellation with filtered data  %
%%%%%%%%%%%%%%%%%%%%%
figure(1);clf;
transient_delay = 0;
plot(OFDM_i(1 + transient_delay:end),OFDM_q(1 + transient_delay:end))
title('OFDM Constellation Plot')
xlabel('In-phase')
ylabel('Quad-phase')
%hold on
%plot(rrc_data_i(1 + transient_delay:samples_per_bit:end),rrc_data_q(1 +
transient_delay:samples_per_bit:end),'m+')
%hold off
%%%%%%%%%%%
%  Set up time vector  %
%%%%%%%%%%%
T = 1/2048000;
Ts = 256*T;
symbol_rate = 1/Ts;
time_step = Ts/ifftsize*2;
time = (0:time_step:length(OFDM_tx) * time_step - time_step);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Plot power spectral density centred around baseband  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure(5);clf;
freq_points = 4096*16;
[Pxx, w] = periodogram( (abs(OFDM).^2)/2,[],'onesided',freq_points,(1 / time_step));
plot(w,10*log10(Pxx+0.000000000000001))
%psdplot(Pxx,w,'Hz','dB')
%axis([-100e3 200e3 -300 -100])
title('OFDM Transmitter Spectrum at Baseband')
xlabel('Baseband Frequency, Hz')
ylabel('Power Spectral Density in dB/Hz')
%%%%%%%%%%%%%%%
%  Add channel impairements  %
```

```
%%%%%%%%%%%%%%%%
OFDM = OFDM./1;
%%%%%%%%%%%%%%%%%%
%  Add channel noise impairements %
%%%%%%%%%%%%%%%%%%
%SNR_dB = 6;
SNR = 10.^(SNR_dB/10);
power = (sqrt(2))^2;
samples_per_bit = 2048;
samples_per_symbol = 1;
bits_per_symbol = 2;
noise_variance = power/samples_per_bit*samples_per_symbol/(2*bits_per_symbol*SNR);
noise_std_dev = sqrt(noise_variance);

noise_i = noise_std_dev.*randn(1,length(OFDM));
noise_q = noise_std_dev.*randn(1,length(OFDM));
complex_noise = noise_i + sqrt(-1).*noise_q;
demod_input = complex_noise + OFDM;

%%%%%%%%%%%%
%  Recover 192 carriers  %
%%%%%%%%%%%%
rx_s_p = reshape(demod_input,[ifftsize no_of_symbols]);
rx_symbol = (fft(rx_s_p)).';
%%%%%%%%%%%%
%  Recover bitstream  %
%%%%%%%%%%%%
for i = 1:no_of_symbols
   rx_block(i,1:192) = rx_symbol(i,carriers);
end
%
rx_data = rx_block.';
data = reshape(rx_data,1,no_of_symbols*length(carriers));
data_i = real(data);
data_q = imag(data);
%%%%%%%%%%%%%%%%%%%%%%%%
%  Plot IQ constellation of recovered data  %
%%%%%%%%%%%%%%%%%%%%%%%%
figure(10);clf;
plot(data_i,data_q,'m+')
title('Recovered QPSK Constellation Plot')
xlabel('In-phase')
ylabel('Quad-phase')


for num = 1:2:length(data)*2;
if sign(data_i((num+1)./2)) >= 0 & sign(data_q((num+1)./2)) >= 0
   rx_bitstream(num) = 0; rx_bitstream(num+1)=0;
elseif sign(data_i((num+1)./2)) >= 0 & sign(data_q((num+1)./2)) < 0
   rx_bitstream(num) = 0; rx_bitstream(num+1)=1;
elseif sign(data_i((num+1)./2)) < 0 & sign(data_q((num+1)./2)) >= 0
   rx_bitstream(num) = 1; rx_bitstream(num+1)=0;
elseif sign(data_i((num+1)./2)) < 0 & sign(data_q((num+1)./2)) < 0
   rx_bitstream(num) = 1; rx_bitstream(num+1)=1;
else x=0;
end;end;

%%%%%%%%%%%%%%%%%%%%
%  Measures errors and calculate BER %
%%%%%%%%%%%%%%%%%%%%
rx_bitstream_inv = -1.*rx_bitstream + 1;
error = bit_streamCh1 - rx_bitstream_inv;
total_errors = sum(abs(error));
format short e;
BER = total_errors ./ length(error);
```