ZetaCast

Ofcom
OFFICE OF COMMUNICATIONS

Review of DTT HD Capacity Issues

An Independent Report from ZetaCast Ltd
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Contents

1 EXECUTIVE SUMMARY AND CONCLUSIONS

This report provides a preliminary review of the Ofcom analysis into the possible restructuring of the DTT platform to facilitate the carriage of HD services. The main findings are:

1. To make the most efficient use of spectrum after analogue switchover, the author would recommend
   - Changing the transmission mode of all multiplexes to 64QAM
   - Performing frequent encoder upgrades and optimise the encoding parameters to maintain the best possible coding efficiency
   - Implementing full statistical multiplexing of all video services in a multiplex in a single group
   - Including all other components that are amenable to statistical multiplexing, such as sub-titling, in the stat. mux. group. Opportunistic data capacity should be used wherever possible for interactive and other non time-critical services
   - Audit the bit-rates used for all audio coding to ensure that unnecessarily high bit-rates have not been allocated to some services for historical reasons.
   - From a purely technical viewpoint, it would be preferable to gather all regional programmes together on a single multiplex, leaving all other multiplexes identical throughout the UK. If the BBC and ITV regional boundaries were aligned, regional variants of the complete statistical multiplex group could then be formed in the most cost-effective way. However, the commercial, legal and regulatory impediments to creating a single regional multiplex may well be insuperable and in the following analysis it is assumed that this radical re-configuration is not performed.

2. In the most probable scenario, it should be possible to clear Mux B after analogue switchover by moving all services onto Mux 1 and Mux 2 whilst maintaining current quality levels.

3. In a pessimistic scenario, clearing Mux B would only be possible by also transferring some radio services to Mux A.

4. In an optimistic scenario, it should be possible to clear Mux B after analogue switchover by moving services onto Mux 1 and Mux 2 with capacity to spare. This scenario would allow one of the commercial multiplexes (A, C or D) to also be cleared for new services, whilst maintaining the current number and quality of SDTV services.

5. A reasonably conservative assumption would be to plan on DVB-T2 being practical to launch by late 2009 / early 2010 and offering the minimum commercial target of a 30% capacity increase. Applying DVB-T2 modulation to Mux B would therefore increase the total capacity to 31.4 Mbit/s.

6. H.264/AVC video compression and HE-AAC audio compression should be combined with DVB-T2 modulation on the cleared Mux B to give the most efficient use of the capacity.

7. Mux B could be used to carry either additional SDTV channels or else HDTV services. In both cases, the viewer would require a new set-top box to access these services.

8. A reasonable set of mid-range assumptions for HDTV services coded in 720px1280 50Hz with HE-AAC five channel audio (at 160kbit/s), subtitling and audio description is:

Year	End-to-end Progressive System (e.g. 1080p production)	Hybrid system (e.g. 1080i production)
2010	8 Mbit/s	11 Mbit/s
2012	7 Mbit/s	10 Mbit/s

9. The creation of HDTV content by up-conversion of SDTV material is an inefficient use of capacity and should be discouraged. If it is used, a reasonable assumption would be that up-converted SDTV would need a slightly lower bit-rate than 720p native content; the inefficiencies caused by interlace and up-conversion should be more than offset by the almost five times lower information rate.

10. It is probable that 4 HDTV services can be carried on Mux B in 2010, provided all content is either produced progressively as HDTV or else is up-converted SDTV.

11. It is probable that 5 HDTV services can be carried on Mux B in 2012.

12. The author recommends the following next steps to help verify these preliminary conclusions:
    - Engage in discussion with the broadcasters to verify that the assumed current multiplex configurations are correct
    - Engage with broadcasters in identifying and attempting to overcome any barriers to implementing statistical multiplexing fully
    - Engage with broadcasters in confirming the feasibility of clearing Mux B as planned, particularly with regard to the potential of improved encoding efficiency by upgrading to a state-of-the-art MPEG-2 encoders in 2010
    - Monitor progress on the development of DVB-T2 to confirm that the date and performance assumptions are valid
    - Verify assumptions on H.264/AVC coding efficiency performance through evaluating the results of formal subjective tests, such as those recently performed by the EBU
    - Seek input from manufacturers on their product roadmaps to help validate the assumptions on performance evolution
    - Investigate best practice in other European countries, particularly those (such as France) with advanced plans to implement terrestrial HDTV

2 INTRODUCTION

This report provides a review of the possible restructuring of the DTT platform to allow more efficient use of the terrestrial multiplex capacity. It then describes how such an increase of efficiency could be used to facilitate the carriage of HD services whilst providing an opportunity for all of the existing platform services to continue to be delivered.

Since bit-rate is a limited resource, there is a natural tension between the desire to increase video quality and the desire to increase the number of channels. It is noticeable that significantly different video quality levels are applied to different channels today. This report assumes that the trade-off that broadcasters have currently chosen for each channel will continue to be valid in the future, i.e. the requirement is to maintain quality at today's levels for each channel.

The multiplex configuration is complicated by some programmes being specific to individual regions or nations within the UK. The basic assumption of this report is that in the future statistical multiplexing will be performed at a single point for each multiplex, using uncompressed (or very lightly compressed) video feeds. This will require multiple regional variants of the complete statistical multiplex group to be created. Any deviation from this architecture will inevitably result in some loss of compression efficiency.

This report concentrates on the technical issues and does not attempt to consider any potential commercial or contractual barriers to the more efficient use of multiplex capacity.

3 DIGITAL MULTIPLEX CAPACITY

3.1 Current Multiplex Utilisation

The DVB-T specification has a range of different transmission parameters that can be chosen to give different trade-off points of robustness versus bit-rate. Two different parameter sets are currently in use in the UK:

Multiplexes 1, B, C and D use
- 16QAM modulation
- 1/32 Guard Interval
- 3/4 FEC Rate

giving a capacity of 18.10 Mbit/s each.

Multiplexes 2 and A use
- 64QAM modulation
- 1/32 Guard Interval
- 2/3 FEC Rate

giving a capacity of 24.13 Mbit/s each.

The utilisation of the multiplexes as of 13 June 2007 is summarised in Table 1 below. The bit-rates given for the TV programmes represent the total for the programme, including video, audio, subtitling and audio description. The situation is complicated by some programmes being specific to individual regions or nations within the UK. The full exploration of the consequences of regional programming is beyond the scope of this report, but the multiplex utilisation that is given in Table 1 effectively represents the worst case of bit-rate demands.

The bit-rates quoted are primarily based on measurements, rather than an examination of the multiplex configuration maps, so there may be some minor rounding errors. This is particularly the case with the bit-rate pools for the statistically multiplexed groups (see section 3.3). It is not possible to determine by measurement alone how much of the bit-rate used for null packets would have been potentially available for statistically multiplexed video, but was not required since all of the video channels happened to be easy to encode at the time that the measurement was made. There could also be small discrepancies due to bit-rate being set aside for programme components that were not present when the measurements were made (e.g. audio description or subtitling). Where additional information was available, this has been used to verify the assumed multiplex configuration.

Since bit-rate is a limited resource, it is normal commercial practice give greater priority to channels that are regarded as being more important. Sample measurements were taken on a channel-by-channel basis to investigate the relative bit-rates applied within each statistically multiplexed group. However, bit-rate sampling can only be regarded as being indicative of the quality levels that have been applied; it is not possible to obtain accurate information on the different quality levels without examining the encoder and multiplexer settings.

From the measurements, it appears that unequal priorities have been set in several of the statistically multiplexed groups, e.g. ITV1 and Channel 4 appear to be consistently assigned a higher bit-rate than other programmes in their respective groups on Mux 2. The lower priority channels also use sub-sampled video (only 544 pixels per line rather than 704 or 720 pixels). Variable quality factors also appear to be applied to the BBC channels.

Mux	Service	Service Type	Stat Mux Group	Bit-rate (Mbit/s)
Mux 1	BBC1 (15 regional versions)[1]	SDTV	-	4.9
BBC	BBC2 (4 national variants)	SDTV	3	10.7
	BBC3/CBBC	SDTV		
	BBC News 24	SDTV		
	BBCi	Text/Interactive	-	1.2
	EIT, PAT, PMT	DVB SI/PSI	-	0.3
	Null packets	Unused capacity	-	1.0
Total				**18.1**

Mux 2	ITV1 (28 regional variants)	SDTV	4	10.3
Digi3/4	ITV2	SDTV		
	ITV3	SDTV		
	ITV4/CITV	SDTV		
	C4 (6 regional variants)	SDTV	4	10.3
	E4	SDTV		
	More 4	SDTV		
	Film4 +1	SDTV		
	Teletext, Teletext on 4, Teletext Cars	Text/Interactive	-	1.2
	Teletext Holidays (Wales only)[2]	Audio/Interactive	-	0.5
	ITV1/2/3/CiTV, C4 More 4, E4	Text/Interactive	-	0.2
	Heart (except Scotland), Radio Music Shop (except Scotland)	2 Radio (except Scotland)	-	0.2
	EIT, PAT, PMT, CAT	DVB SI/PSI	-	0.5
	Null packets	Unused capacity	-	0.9
Total				**24.1**

Mux A[3]	five (4 variants)	SDTV	9	20.2

[1] In Scotland, Wales and Northern Ireland, the BBC1 SDTV service is incorporated in a group of 4 stat. mux. pool together with BBC2, BBC3/CBBC and BBC News 24. Extra capacity is released by this more efficient approach, which enables the transmission of two 2 Nations' radio services: BBC Radio Scotland (Scotland), BBC Radio nan Gaidheal (Scotland), BBC Radio Wales (Wales), BBC Radio Cymru (Wales), BBC Radio Ulster (NI), BBC Radio Foyle (NI)

[2] U105 radio service (NI only) is assumed to use part of this capacity in NI

Mux	Service	Service Type	Stat Mux Group	Bit-rate (Mbit/s)
SDN	QVC	SDTV		
	Bid TV	SDTV		
	Price-drop TV	SDTV		
	five life	SDTV		
	five US	SDTV		
	Setanta Sports	SDTV		
	UKTV Gold	SDTV		
	Thomas Cook TV	SDTV		
	Teletext Holidays (except Wales)	Audio/Interactive	-	0.5
	Teletext Games	Audio/Interactive	-	0.2
	Various MHEG services	Text/Interactive	-	0.6
	BBC Radio 1, 2, 3, 4	4 Radio	-	0.8
	Heat, Mojo (except Wales)	2 Radio	-	0.3
	EIT, PAT, PMT	DVB SI/PSI	-	0.6
	Null packets	Unused capacity	-	0.9
Total				**24.1**
Mux B	BBC4 / CBeebies	SDTV	5	13.9
BBC	BBC Parliament	SDTV		
	BBC 301	SDTV		
	BBC 302/Community	SDTV		
	BBC 305 (news multi-screen including 4 audio channels)	SDTV		
	BBCi MHEG, Community slate	Text/Interactive	-	1.6
	BBC Radio 5 Live, BBC 5 Live Extra, BBC 6 Music, BBC 7, BBC 1 Extra, BBC Asian Network	6 Radio	-	0.9
	EIT, PAT, PMT	DVB SI/PSI	-	0.4
	Null packets	Unused capacity	-	1.3
Total				**18.1**
Mux C	Sky 3	SDTV	5	14.5

[3] The configuration of Mux A is different in Wales, where it carries S4C and S4C2. TeleG is carried on Mux A in Scotland for part of the day.

Mux	Service	Service Type	Stat Mux Group	Bit-rate (Mbit/s)
NGW	Sky News	SDTV		
	Sky Sports News	SDTV		
	E4+1	SDTV		
	UKTV History	SDTV		
	Sky Text	Text/Interactive	-	0.9
	Various MHEG services (Sky, UKTV, Virgin, TVTV etc.)	Text/Interactive	-	0.2
	Talk Sport, Premier Radio, Virgin, 3C	4 Radio	-	0.4
	EIT, PAT, PMT	DVB SI/PSI	-	0.4
	Null packets	Unused capacity	-	1.7
Total				**18.1**

Mux D	The Hits	SDTV	6	15.7
NGW	TMF	SDTV		
	ITV2+1	SDTV		
	Ideal World	SDTV		
	Ftn/UKTV Bright Ideas	SDTV		
	Film Four	SDTV		
	Various MHEG services	Text/Interactive	-	0.2
	BBC World Service Kiss 100 The Hits Radio Smash Hits Q Magic 105.4 102.2 Smooth FM Oneword Kerrang!	9 Radio	-	1.1
	EIT, PAT , PMT	DVB SI/PSI	-	0.4
	Null packets	Unused capacity	-	0.7
Total				**18.1**

Table 1: Overview of Multiplex Utilisation as of 13 June 2007

3.2 DVB-T Mode Change from 16QAM to 64QAM

As noted in section 3.1, Multiplexes 1, B, C and D currently use 16 QAM modulation with 3/4 FEC Rate, giving a capacity of 18.10 Mbit/s each. The capacity of each of these four multiplexes would increase to 24.13 Mbit/s if they were reconfigured to 64 QAM with 2/3 FEC rate. This is represents an increase in capacity of 6.03 Mbit/s per multiplex, i.e. a total increase in capacity of 24.12 Mbit/s. The disadvantage of the mode change is that 64 QAM is a less robust modulation. However, the potential loss of coverage can be offset by an increase in transmission power or increased transmitter density.

3.3 Statistical Multiplexing

In a constant bit-rate system each video service in the multiplex has a fixed allocation of data rate regardless of the content. When statistical multiplexing is used, a lower data rate is allocated when the video is easy to encode, such as a head and shoulders shot of a news presenter sitting in a studio. A higher data rate is allocated when the video becomes more difficult, e.g. a sports clip within the news programme. The benefits obtained through the use of statistical multiplexing are greatest when there is a large ratio between the minimum and the maximum bit-rate required to give constant video quality.

The improved coding efficiency due to sharing the multiplex capacity increases with the number of channels, as the peaks and troughs of bit-rate demand across the channels average each other out better. To a first approximation, the savings are independent on whether the content is all SD or all HD and whether the compression is MPEG-2 or H.264/AVC.

The exact efficiency gain is dependent on both the nature of the video content and the details of the implementation, but gains can be typically expected to asymptotically approach a value between about 25 and 30% for large numbers of channels. The graph in Figure 1 below is indicative of the typical benefits that can be expected, based on statements from encoder manufacturers and the author's own experience.

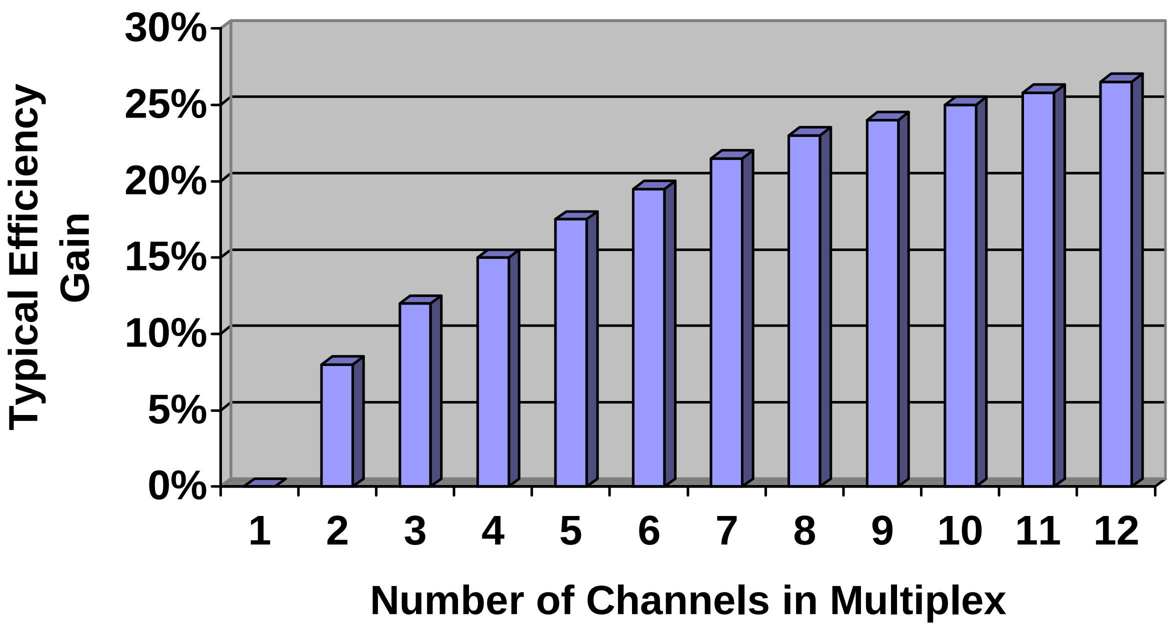

Figure 1: Typical Coding Efficiency Benefit due to Statistical Multiplexing

The graph will be used as the basis for the calculations of statistical multiplex gain in Chapter 4. For example, if 10 channels would require 28Mbit/s for a given quality at constant bit-rate, it will be assumed that the same quality can be achieved at a 25% lower bit-rate, i.e. 21Mbit/s, through the use of statistical multiplexing.

It is assumed that the content in each channel is uncorrelated and that each has similar bit-rate targets. There may be a very slight reduction in the benefit if unequal priority is used to give higher quality thresholds for some services than others (e.g. as currently appears to be the case with ITV1 and Channel 4 in Mux 2).

Statistically multiplexing a mix of HDTV and SDTV content is also possible, but this is likely to give significantly less benefit, as a demand peak on the HDTV channel will require several SDTV channels to reduce bit-rate to compensate. A particular case to avoid is multiplexing an HD and an SD version of the same programme on a single multiplex, as the peaks of demand will coincide.

3.4 Non-Video content in a Statistical Multiplex

Some time-critical data services, such as subtitles, have a variable data rate. It is preferable to include such services in a statistically multiplexed group as a high priority service, rather than assigning a fixed data rate (which would have to be high enough to cater for the worst case).

Capacity for low priority, opportunistic data becomes available during periods of time when several channels in a statistically multiplexed group are carrying relatively easy to encode video. Since the availability of this capacity cannot be guaranteed, it is not suitable for the carriage of any time-critical data. However, it could be usefully employed for the carriage of non time-critical services, such as downloading non real-time audio-visual content onto the hard disk of a PVR for subsequent playback. It could also be used to temporarily enhance the performance of some text or interactive services that had a guaranteed minimum delivery bandwidth.

The currently used audio coding schemes are fixed data rate and therefore audio does not benefit from statistical multiplexing. However, it is noticeable that a wide range of audio bit-rates are used for different services, including several that are significantly higher than the bit-rate used for DAB digital radio. It would be worthwhile performing an audit on the bit-rates used for all audio coding to ensure that unnecessarily high bit-rates have not been allocated to some services for historical reasons.

3.5 MPEG-2 Coding Developments

Compression coding specifications define the syntax and semantics of the bitstream, but not the encoder implementation. More complex or better tuned encoders can therefore give significant improvements whilst still working with the same decoder. This results in a noticeable trend of improving compression efficiency in the years following the publication of a specification, as the algorithm becomes better understood and it becomes practical to implement more processing power in the encoder.

The first MPEG-2 encoders in 1995 needed about 6Mbit/s to give reasonable quality, about double the bit-rate needed for a state-of-the-art video encoder operating at constant bit-rate today. The pace of development was initially very rapid, but as time has passed the rate of improvement in MPEG-2 encoding has decreased. The reduced rate of development is illustrated by only one of the major encoder manufacturers stating at IBC 2007 that it intends to launch new MPEG-2 encoding hardware in the next year; it estimates that this will give a coding efficiency improvement of around 10% compared to the current model. The other manufacturers appear to be aiming for more modest improvements in the next 12 months through software upgrades to their current hardware.

The aspects of the encoder that still give the most potential for further improvements are probably those that are least tightly coupled to the algorithm itself. More sophisticated means of performing adaptive pre-processing, motion estimation, multi-pass encoding and look-ahead statistical multiplexing all become practical with increasing processing power in the encoder. In these areas it is likely that some improvements developed for H.264/AVC encoding will be fed back into the MPEG-2 encoders.

There is also some scope for improving coding efficiency by using different coding parameters with the same equipment. For example, the time interval between intra-coded frames, which make no reference to other frames, can be varied to give different trade-off points between encoding efficiency and channel hopping time. The DVB audio-visual coding specification, TS 101 154, recommends a maximum interval of 0.5 seconds between intra-coded frames. The D-book strengthened this recommendation by making it a requirement. More recently, a DTG group was set up to examine the issue and proposed that the D-book requirement should be replaced by a recommendation for 0.75 seconds. The group estimated that changing from 0.5 to 0.75 seconds between intra-coded frames would result in a 2-3% improvement in coding efficiency, at the cost of an increase of an eighth of a second in average channel hopping time.

The terrestrial multiplexes currently use encoders from different manufacturers, some of which have been upgraded more recently than others. In the case of Mux 2, equipment from different manufacturers is mixed in the same multiplex. Some of these installations are closer to the current state-of-the-art than others, but it is beyond the scope of this report to perform a detailed analysis of each case.

The following three scenarios will be used in Chapter 4 when estimating improvements in coding efficiency that may be gained by installing a new state-of-the-art MPEG-2 encoding system in 2010 and optimising the encoding parameters:

1. Most probable Scenario: 10% gain in coding efficiency

2. Pessimistic Scenario: 5% gain in coding efficiency

3. Optimistic Scenario: 15% gain in coding efficiency

In each scenario, the gain in coding efficiency represents the combination of bringing each multiplex up to the level of the best achievable today plus the further improvements that can be expected between now and 2010.

3.6 Recommended Best Practice

To make the most efficient use of spectrum after analogue switchover, the author would recommend the following steps. This is based on purely technical analysis; potential commercial and regulatory impediments are not fully considered.

1. Change the transmission mode of all multiplexes to 64QAM

2. Carry out frequent encoder upgrades and optimise the encoding parameters to maintain the best possible coding efficiency.

3. Perform full statistical multiplexing of all video services in a multiplex in a single group. This requires there to be a single point where the encoding of uncompressed content and multiplexing of all services in a multiplex is performed. The cascading of compression encoders and the use of bit-rate transcoding should be avoided if at all possible.

4. Include any non-video service components that are amenable to statistical multiplexing, such as sub-titling, in the stat mux group. Opportunistic data capacity should be used wherever possible for interactive and other non time-critical services.

5. Audit the bit-rates used for all audio coding to ensure that unnecessarily high bit-rates have not been allocated to some services for historical reasons.

6. From a purely technical viewpoint, it would be preferable to gather all regional programmes together on a single multiplex, leaving all other multiplexes identical throughout the UK. If the BBC and ITV regional boundaries were aligned, regional variants of the complete statistical multiplex group could then be formed in the most cost-effective way. Even if the requirements for multiple regional variants of services or periods of regional opt-out made it impossible to perform full statistical multiplexing of all services, some restricted version of statistical multiplexing could be applied to this multiplex whilst leaving the other multiplexes running at full efficiency. Radio services do not readily benefit from statistical multiplexing and so all radio services could also be moved onto this “low efficiency” multiplex. Although this would represent a good technical solution, the commercial, legal and regulatory impediments to creating a single regional multiplex may well be insuperable. In the following analysis it is assumed that this radical re-configuration is not performed.

4 CLEARING MULTIPLEX B

4.1 Transfer from Multiplex B to Multiplex 1

4.1.1 Most probable Scenario

Assumptions for Multiplex 1:

- increase in capacity to 24.13 Mbit/s by mode change to 64 QAM with 2/3 FEC rate
- 23% gain in coding efficiency by using a full group of 8 statistical multiplex
- 10% improvement in coding efficiency due to developments in MPEG-2 coding
- 0.7 Mbit/s guaranteed bit-rate for BBCi, with further capacity obtained through the use of opportunistic data
- Residual null packet rate of 0.5 Mbit/s
- SI/PSI rate of 0.4 Mbit/s, the same as the present value on Mux B
- Target quality equivalent to today's BBC2 / BBC3 / News24 for the five main channels: BBC1, BBC2, BBC3, BBC4 and News24. Today 10.7 Mbit/s is used for a group of 3 on Mux 1, i.e. equivalent to about 4.0 Mbit/s per channel at constant bit-rate.
- Target quality equivalent to today's BBC 301 / 302 / 305/ Parliament for the three of these services in Mux 1: BBC 301, 302 and 305. Mux B currently has 13.9 Mbit/s for a group of 5, equivalent to a total of 16.8 Mbit/s at constant bit-rate. After allocating 4.0 Mbit/s to BBC4, this is equivalent to 3.2 Mbit/s constant bit-rate for the other channels.

A total of 29.6 Mbit/s constant bit-rate would be required today for the 8 SDTV services (5 services at 4.0 Mbit/s and 3 at 3.2 Mbit/s). After applying 23% stat mux gain and 10% coding gain, this is equivalent to a stat mux pool of 20.5 Mbit/s in 2010. The following configuration of Multiplex 1 can then be proposed:

Multiplex	Service	Service Type	Statistical Multiplex	Mean Bitrate (Mbit/s)
Mux 1	BBC1	SDTV	Group of 8	20.5
	BBC2	SDTV		
	BBC3	SDTV		
	BBC4/CBeebies	SDTV		
	BBC News 24	SDTV		
	BBC 301	SDTV		
	BBC 302/Community	SDTV		
	BBC 305 (multi-screen)	SDTV		
	BBCi	Text/Interactive	-	0.7
	Radio currently on Mux B	6 Radio	-	0.9
	Nations' Radio on Mux 1	2 Radio	-	0.3
	BBC Radio 1, 2, 3, 4	4 Radio	-	0.8
	EIT, PAT, PMT	DVB SI/PSI	-	0.4
	Null packets	-	-	0.5
Total				**24.1**

4.1.2 Pessimistic Scenario

Assumptions for Multiplex 1:

- increase in capacity to 24.13 Mbit/s by mode change to 64 QAM with 2/3 FEC rate
- 23% gain in coding efficiency by using a full group of 8 statistical multiplex
- 5% improvement in coding efficiency due to developments in MPEG-2 coding
- 1 Mbit/s guaranteed bit-rate for BBCi, with further capacity given by the use of opportunistic data
- Residual null packet rate of 1 Mbit/s
- SI/PSI rate of 0.4 Mbit/s, the same as the present value on Mux B
- Target quality equivalent to today's BBC2 / BBC3 / News24 for the five main channels: BBC1, BBC2, BBC3, BBC4 and News24. Today this is 10.7Mbit/s is used for a group of 3 on Mux 1, i.e. equivalent to about 4.0 Mbit/s per channel at constant bit-rate.
- Target quality equivalent to today's BBC 301 / 302 / 305/ Parliament for the three of these services in Mux 1: BBC 301, 302 and 305. Mux B currently has 13.9 Mbit/s for a group of 5, equivalent to a total of 16.8 Mbit/s at constant bit-rate. After allocating 4.0 Mbit/s to BBC4, this is equivalent to 3.2 Mbit/s constant bit-rate for each of the other channels.

A total of 29.6 Mbit/s constant bit-rate would be required today for the 8 SDTV services (5 services at 4.0 Mbit/s and 3 at 3.2 Mbit/s). After applying 21% stat mux gain and 5% coding gain, this is equivalent to a stat mux pool of 21.7 Mbit/s in 2010.

The following configuration of Multiplex 1 can then be proposed:

Multiplex	Service	Service Type	Statistical Multiplex	Mean Bitrate (Mbit/s)
Mux 1	BBC1	SDTV	Group of 8	21.7
	BBC2	SDTV		
	BBC3	SDTV		
	BBC4/CBeebies	SDTV		
	BBC News 24	SDTV		
	BBC 301	SDTV		
	BBC 302/Community	SDTV		
	BBC 305 (multi-screen)	SDTV		
	BBCi	Text/Interactive	-	1.0
	EIT, PAT, PMT	DVB SI/PSI	-	0.4
	Null packets	-	-	1.0
Total				**24.1**

4.1.3 Optimistic Scenario

Assumptions for Multiplex 1:

- increase in capacity to 24.13 Mbit/s by mode change to 64 QAM with 2/3 FEC rate
- 24% gain in coding efficiency by using a full group of 9 multiplex
- 15% improvement in coding efficiency due to developments in MPEG-2 coding
- 0.4 Mbit/s guaranteed bit-rate for BBCi, with further capacity given by the use of opportunistic data
- Residual null packet rate of 0.4 Mbit/s
- SI/PSI rate of 0.4 Mbit/s, the same as the present value on Mux B
- Target quality equivalent to today's BBC2 / BBC3 / News24 for the five main channels: BBC1, BBC2, BBC3, BBC4 and News24. Today this is 10.7Mbit/s for a group of 3, i.e. equivalent to about 4.0 Mbit/s per channel at constant bit-rate
- Target quality equivalent to today's BBC 301, BBC 302, BBC 305 and BBC Parliament for these four services. Mux B has 13.9 Mbit/s for a group of 5, equivalent to a total of 16.8 Mbit/s at constant bit-rate. After allocating 4.0 Mbit/s to BBC4, this is equivalent to 12.8 Mbit/s constant bit-rate for the four remaining channels.

A total of 32.8 Mbit/s constant bit-rate would be required today for the 9 SDTV services (5 services at 4.0 Mbit/s and 4 at 3.2 Mbit/s). After applying 24% stat mux gain and 15% coding gain, this is equivalent to a stat mux pool of 21.2 Mbit/s in 2010.

The following configuration of Multiplex 1 can then be proposed:

Multiplex	Service	Service Type	Statistical Multiplex	Mean Bitrate (Mbit/s)
Mux 1	BBC1	SDTV	Group of 9	21.2
	BBC2	SDTV		
	BBC3	SDTV		
	BBC4/CBeebies	SDTV		
	BBC News 24	SDTV		
	BBC 301	SDTV		
	BBC 302/Community	SDTV		
	BBC 305 (multi-screen)	SDTV		
	BBC Parliament	SDTV		
	BBCi	Text/Interactive	-	0.4
	Radio currently on Mux B	6 Radio	-	0.9
	BBC Radio 1, 2, 3, 4	4 Radio	-	0.8
	EIT, PAT, PMT	DVB SI/PSI	-	0.4
	Null packets	-	-	0.4
Total				**24.1**

4.2 Transfer to Multiplex 2

4.2.1 Most probable Scenario

Assumptions for Multiplex 2:

- 25% gain in coding efficiency by using a full group of 10 statistical multiplex. This compares with the likely 15% statistical multiplex benefit from the current arrangement of two groups of 4 channels each
- 10% improvement in coding efficiency due to developments in MPEG-2 coding
- 0.7 Mbit/s guaranteed bit-rate for all interactive services, with further capacity obtained through the use of opportunistic data. BBCi services currently carried in Mux B are substantially the same as those in Mux 1 and no repetition of these is required
- Null packet rate of 0.5 Mbit/s
- SI/PSI rate of 0.5 Mbit/s, the same as the present value on Mux 2
- Target quality for ITV and C4 channels the same as today, with target quality of BBC Parliament and five the average for these services. Four channels on Mux 2 share a 10.3 Mbit/s pool today, with some channels set to give higher quality than others. This is equivalent to a total constant bit-rate of 12.1 Mbit/s for the four channels.

A total of 30.3 Mbit/s constant bit-rate would be required today for the 10 SDTV services. After applying 25% stat mux gain and 10% coding gain, this is equivalent to a stat mux pool of 20.5 Mbit/s in 2010. The services on Mux 2 could be:

Multiplex	Service	Service Type	Statistical Multiplex	Mean Bitrate (Mbit/s)
Mux 2	ITV1	SDTV	Group of 10	20.5
	ITV2	SDTV		
	ITV3	SDTV		
	ITV4/CITV	SDTV		
	C4	SDTV		
	E4	SDTV		
	More 4	SDTV		
	Film4 +1	SDTV		
	BBC Parliament	SDTV		
	five	SDTV		
	Text, audio and Interactive	Text/Interactive	-	0.7
	Radio currently on Mux B	6 Radio	-	0.9
	Radio currently in Mux 2	2 Radio	-	0.2
	Radio from Mux A, C or D	Some Radio		0.8
	EIT, PAT, PMT, CAT	DVB SI/PSI	-	0.5
	Null packets		-	0.5
Total				**24.1**

4.2.2 Pessimistic Scenario

Assumptions for Multiplex 2:

- 25% gain in coding efficiency by using a full group of 10 statistical multiplex. This compares with the likely 15% statistical multiplex benefit from the current arrangement of two groups of 4 channels each
- 5% improvement in coding efficiency due to developments in MPEG-2 coding
- 1Mbit/s guaranteed bit-rate for all interactive services, with further capacity obtained through the use of opportunistic data. BBCi services currently carried in Mux B are substantially the same as those in Mux 1 and it is assumed that no repetition is required
- Null packet rate of 1.0 Mbit/s
- SI/PSI rate of 0.5 Mbit/s, the same as the present value on Mux 2
- Target quality for ITV and C4 channels the same as today, with target quality of BBC Parliament and five at the average for these services. Four 4 channels on Mux 2 share a 10.3Mbit/s pool today, with some channels set to give higher quality than others. This is equivalent to a total constant bit-rate of 12.1 Mbit/s for the four channels.

A total of 30.3 Mbit/s constant bit-rate would be required today for the 10 SDTV services. After applying 25% stat mux gain and 5% coding gain, this is equivalent to a stat mux pool of 21.6Mbit/s in 2010. The services on multiplex 2 could be:

Multiplex	Service	Service Type	Statistical Multiplex	Mean Bitrate (Mbit/s)
Mux 2	ITV1	SDTV	Group of 10	21.6
	ITV2	SDTV		
	ITV3	SDTV		
	ITV4/CITV	SDTV		
	C4	SDTV		
	E4	SDTV		
	More 4	SDTV		
	Film4 + 1	SDTV		
	BBC Parliament	SDTV		
	five	SDTV		
	Text, audio and Interactive services (using opportunistic data for additional capacity)	Text/Interactive	-	1.0
	EIT, PAT, PMT, CAT	DVB SI/PSI	-	0.5
	Null packets	Unused capacity	-	1.0
Total				**24.1**

With these pessimistic assumptions, capacity would need to be found on Mux A for the radio services currently on Mux 1, Mux 2 and Mux B, in addition to the BBC Radio 1, 2, 3 and 4 services already on Mux A.

4.2.3 Optimistic Scenario

Assumptions for Multiplex 2:

- 26% gain in coding efficiency by using a full group of 11 statistical multiplex. This compares with the likely 15% statistical multiplex benefit from the current arrangement of two groups of 4 channels each
- 15% improvement in coding efficiency due to developments in MPEG-2 coding
- 0.4 Mbit/s guaranteed bit-rate for all interactive services, with further capacity obtained through the use of opportunistic data. BBCi services currently carried in Mux B are substantially the same as those in Mux 1; it is assumed that no repetition is required
- Residual null packet rate of 0.4 Mbit/s
- SI/PSI rate of 0.5 Mbit/s, the same as the present value on Mux 2
- Target quality the same as today, with target quality of BBC 302, Parliament and five at the average for these services. Four channels on Mux 2 share a 10.3Mbit/s pool today, with some channels set to give higher quality than others. This is equivalent to a total constant bit-rate of 12.1 Mbit/s for the four channels.

A total of 33.3Mbit/s constant data rate would be required today for the 11 SDTV services. After applying 26% stat mux gain and 15% coding gain, this is equivalent to a stat mux pool of 20.9Mbit/s in 2010. The services on Mux 2 could be:

Multiplex	Service	Service Type	Statistical Multiplex	Mean Bitrate (Mbit/s)
Mux 2	ITV1	SDTV	Group of 11	20.9
	ITV2	SDTV		
	ITV3	SDTV		
	ITV4/CITV	SDTV		
	C4	SDTV		
	E4	SDTV		
	E4 +1	SDTV		
	More 4	SDTV		
	Film 4	SDTV		
	Film 4 +1	SDTV		
	five	SDTV		
	Text, audio and Interactive	Text/Interactive	-	0.4
	Radio currently on Mux 2	3 Radio	-	0.3
	Nations' Radio from Mux 1	2 Radio	-	0.3
	Radio from Mux A, C or D	Some Radio		1.3
	EIT, PAT, PMT, CAT	DVB SI/PSI	-	0.5
	Null packets	Unused capacity	-	0.4
Total				**24.1**

With these optimistic assumptions, the consolidation of all services from Muxes 1, 2 and B onto only Mux 1 and 2 has been achieved with capacity to spare. This has allowed three additional SDTV services and some radio services from Mux A, C or D to be transferred to Mux 2.

Applying the same optimistic assumptions to Mux A, C and D would then allow the remaining 18 SDTV services to be consolidated onto only two multiplexes, together with all of the other remaining services. This scenario would therefore allow one of these commercial multiplexes to also be cleared for use for DVB-T2 transmissions.

5 CAPACITY FOR NEW SERVICES ON MULTIPLEX B

5.1 Key Assumptions

5.1.1 DVB-T2

Since DVB-T was initially specified, there have been substantial developments in both modulation and error protection technologies. Furthermore, it is now feasible to include much more sophisticated technology at an acceptable cost in receivers, thus enabling a different balance to be struck between receiver complexity and bandwidth efficiency.

DVB recognised that these trends together with the increased capacity needs of High Definition TV (HDTV) gave rise to the need to specify a second generation enhanced terrestrial, DVB-T2. The Commercial Requirements for DVB-T2 require a minimum of 30% capacity increase relative to DVB-T.

The DVB-T2 technical group, chaired by Nick Wells (BBC), is working to define a versatile system intended primarily for reception at fixed receivers using existing antenna installations. It also aims to lay the foundations for MIMO extensions and extensions for mobile/handheld applications. These latter issues will be considered more fully in the next phase of activity, aiming to create a coherent family of standards.

Following a Study Mission phase, the DVB Project issued a call for technologies with a deadline of 4 June 2007. This resulted in 31 separate responses, which formed the basis of the subsequent technical work.

The goal is to have the DVB-T2 specification approved by the DVB Technical Module at its meeting in March 2008. The target is for services using DVB-T2 to be able to start in 2009.

A reasonably conservative assumption would be to plan on DVB-T2 being available for market deployment by late 2009 / early 2010 and offering the minimum 30% capacity increase. Applying DVB-T2 modulation to Mux B would therefore increase the total capacity to 31.4 Mbit/s.

5.1.2 H.264/AVC Video Compression

Since the viewer would require a new set-top box (or integrated TV set) to receive DVB-T2 transmissions, it is logical to make the most efficient use of the capacity by combining DVB-T2 with advanced video and audio compression, such as H.264/AVC and HE-AAC. This would apply regardless of whether the DVB-T2 multiplexes are used to carry SDTV or HDTV services. The remainder of section 5 focuses on the latter example.

The original version of the H.264/AVC specification was published in May 2003 by ITU-T as Recommendation H.264 and by ISO/IEC as 14496-10. Three Profiles were used to define sub-sets of the syntax and semantics: Baseline Profile, Extended Profile and Main Profile. The Fidelity Range Extensions Amendment of H.264/AVC, agreed in July 2004, added some additional tools and defined four new Profiles, including the High Profile.

The relationship between High Profile and the original three Profiles, in terms of the major tools from the toolbox that may be used, is illustrated by Figure 2 below.

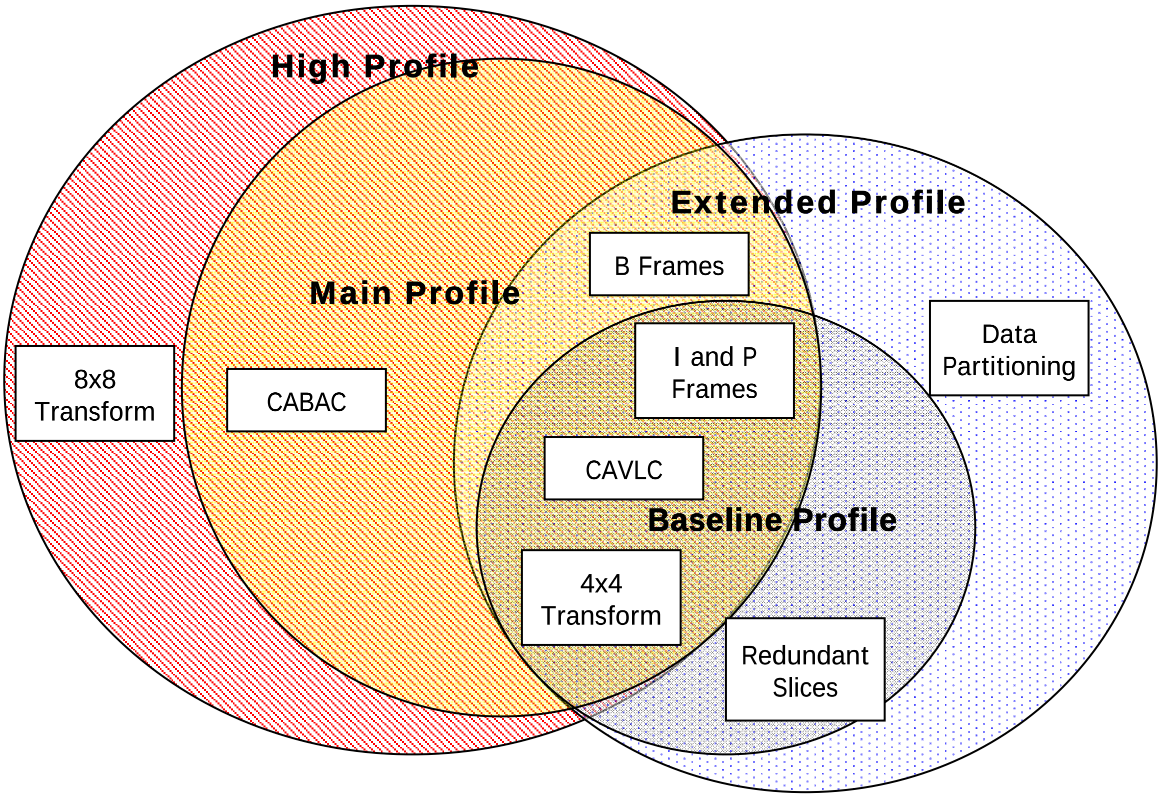

Figure 2: Relationship between High Profile and the three Original Profiles

Main Profile and High Profile both allow the use of the most powerful variable length coding scheme: Context Adaptive Binary Arithmetic Coding (CABAC). It has been estimated that this gives about 10 to 15% saving in bit-rate compared to the simpler alternative of Context Adaptive Variable Length Coding (CAVLC). In addition, the High Profile allows the use of an 8x8 transform and encoder-specified quantisation weighting matrices. It has been estimated that this gives about 10% improvement in coding efficiency compared to Main Profile when using progressive HDTV source material. In the DVB audio-visual coding specification, TS 101 154, High Profile support is required for HDTV decoders which implement H.264/AVC

Using a good non real-time software implementation, H.264/AVC High Profile showed about a factor of two improvement in coding efficiency compared to MPEG-2. However, this has been slow to appear in real-time hardware implementations, with the initial H.264/AVC encoders showing only a marginal improvement over MPEG-2.

The main reason for the initially disappointing results for H.264/AVC encoders was the desire to launch products as soon as possible. The fastest way to bring an H.264/AVC encoder onto the market was to base it on an existing MPEG-2 hardware design. However, this meant that some of the new tools were not fully exercised.

For example, MPEG-2 has only a single block size that is used for motion estimation, whilst H.264/AVC has extended this to provide 7 different options. This range of options gives noticeable benefit in allowing the edges of moving objects to be more efficiently encoded (even though 7 is probably more options than is really needed). However, virtually all of the early H.264/AVC encoders used only the single block size that is supported by MPEG-2. Another important new innovation in H.264/AVC is hierarchical B frames, but encoder manufacturers are only just starting to implement this now.

At the HD Masters conference in London in June, the author presented the following graph to illustrate how he thought that practical state-of-the-art coding efficiency had improved over the years, assuming 720p HDTV content.

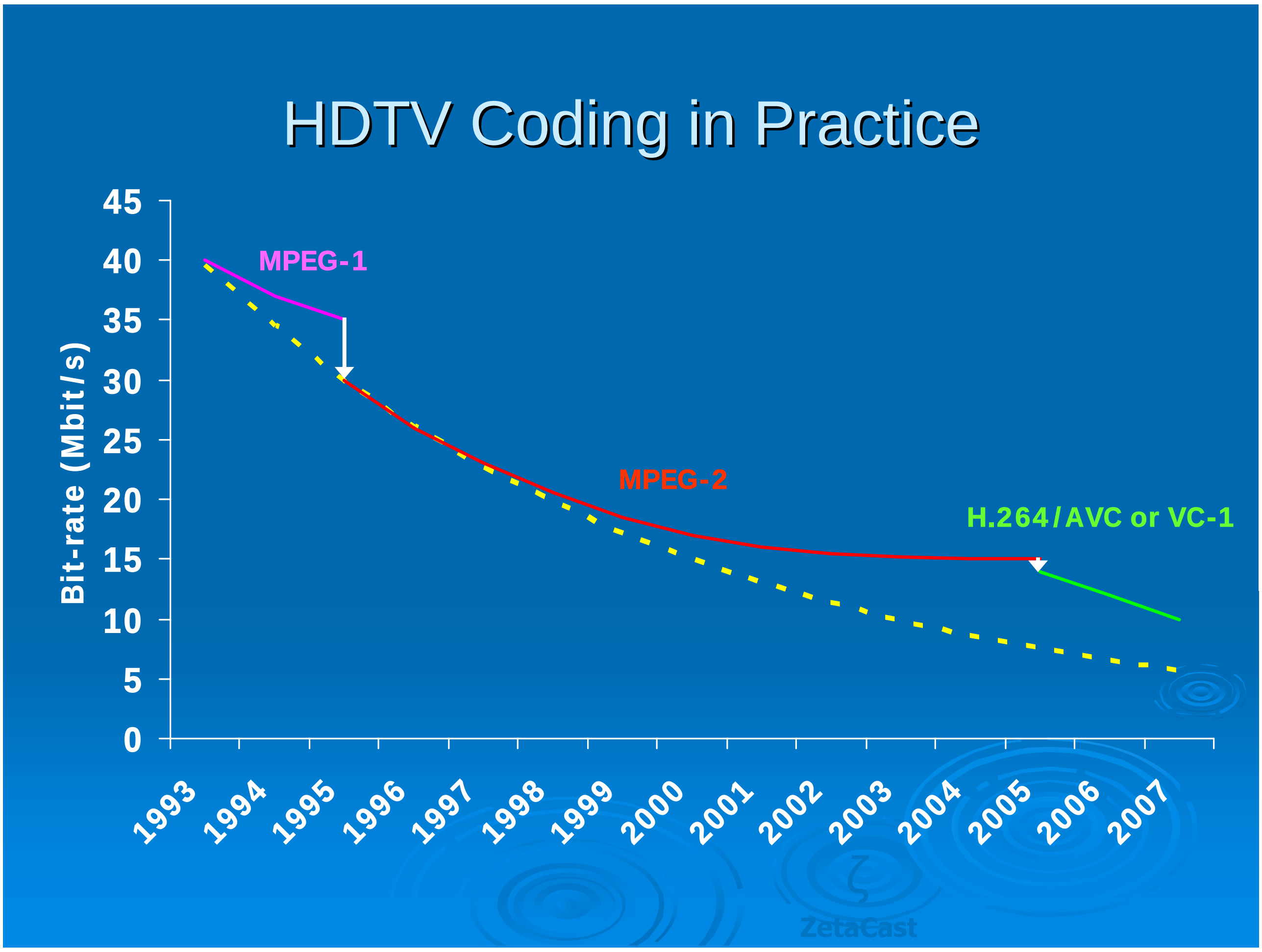

Figure 3: Bit-rates required for 720p HDTV

The dashed yellow trend line represents the prediction of "McCann's law". This predicts that the bit-rate required to achieve a given video quality halves every five years, assuming that both evolutionary improvements (within the same algorithm) and revolutionary improvements (changing algorithm) are implemented as early as possible. In the real world, improvements do not follow a smooth curve as legacy issues allow only infrequent changes of algorithm and budgetary constraints allow only infrequent changes of encoder hardware.

Although the general trend is fairly clear, it is a much more complex issue to say what bit-rate is actually needed in practice to get a reasonably good quality HDTV picture in a specific case. There are many factors to consider in addition to the choice of algorithm and the encoder implementation:

- Nature of content: a talk show will usually consist of fairly static, easy to encode video, whilst sports material has a lot of uncorrelated motion which is difficult to encode
- Interlaced or progressive video: interlace is a form of analogue compression that works fairly well when the video is static. However when there is motion, the effect of interlace is to mix the temporal and spatial information. Since digital compression coding works by removing spatial and temporal redundancy, this mixing makes the video much more difficult to encode. For this reason, 720p/50Hz video can be much more efficiently encoded than 1080i/25Hz.

- Use of Statistical multiplexing: allowing programmes within the multiplex to dynamically share bit-rate (see section 3.3)
- Quality expectations: is the primary customer proposition high quality or many channels?

A useful source of information is provided by the recent set of subjective tests carried out by the EBU, using 1080p/50, 1080i/25 and 720p/50 HDTV at 6, 8, 10, 13, 16, 18 Mbit/s. The testing used the newly developed 'Triple Stimulus Continuous Evaluation Scale' (TSCES) methodology. The encoding was performed using a non real-time software encoder from Fraunhofer HHI; this performance of this today is likely to be comparable to that of a real-time hardware encoder by 2010. The tests used seven sequences, four of which can be classified as “critical”, two as “medium critical” and one as “non-critical”. This mix is much more biased towards the critical end than normal broadcast content. In the overall results for all sequences, as shown by Hans Hoffmann (EBU) at the HD Masters conference in London in June 2007, the subjective assessment was above 60 (roughly equivalent to entering the “good” category of the traditional 5-point scale) at 8Mbit/s for 720p/50 and at 16Mbit/s for 1080i/25.

It is proposed that, to achieve the most efficient use of capacity, the HDTV video format for transmission should be 720p/50Hz at all times. However, a practical problem is that 1080i is currently the dominant format for HDTV content worldwide. The situation for 1080i content broadcast as 720p is different from that in the EBU tests, where the progressive or interlaced formats were maintained constant throughout the chain. The use of a motion-compensated professional de-interlacer prior to 720p encoding will mitigate, but not remove, the reduction in coding efficiency due to interlace.

The author is not aware of any formal subjective tests being carried out on the 720p encoding of de-interlaced 1080i video content. However, from the author’s experience a reasonable set of mid-range assumptions for HD services coded in 720px1280 with HE-AAC five channel audio (at 160kbit/s), mono audio description (also using HE-AAC) and sub-titling would be as shown below.

Year	End-to-end Progressive System (720p or 1080p production)	Hybrid system HDTV (i.e. 1080i production, 720p transmission)
2010	8 Mbit/s	11 Mbit/s
2012	7 Mbit/s	10 Mbit/s

These figures assume constant bit-rate encoding, so the efficiency improvements due to statistical multiplexing described in section 3.3 can be applied on top of these.

A potential issue for the transition phase is the use of up-converted SDTV content. The basic information rate of an SDTV (576i/25) signal is around 10 Mpixel/s, compared to 46 Mpixel/s for 720p/50 HDTV. Subsequent processing cannot create additional information, so the subjective quality will inevitably be significantly worse than that of true HDTV content. The creation of HDTV content by up-conversion of SDTV material is an inefficient use of capacity and should be discouraged. Such pseudo-HDTV content also risks damaging the public perception of HDTV quality.

The author is not aware of any formal subjective tests being carried out on the bit-rates required for up-converted SDTV content subsequently encoded as 720p. The basic information rate is about a fifth of that of HDTV content, but inefficiencies are introduced due to the interlaced nature of the source material and the up-conversion process. A safe assumption would be that the bit-rate required would be slightly lower than that for 720p native content.

5.2 Use of Multiplex B for HD Services

5.2.1 2010 Scenario

Assumptions:

- 31.4 Mbit/s multiplex capacity using DVB-T2
- Transmission of 720px1280 with HE-AAC five channel audio (at 160kbit/s) and AD
- No 1080i content; content is either produced progressively (e.g. 1080p) or else is just up-converted from SD
- Quality required equivalent to a CBR rate of 8 Mbit/s per programme in 2010
- 15% efficiency gain through use of statistical multiplexing
- 0.5 Mbit/s guaranteed bit-rate interactive with further capacity given by the use of opportunistic data
- Null packet rate of 0.5 Mbit/s
- SI/PSI rate of 0.4 Mbit/s

A total of 32.0 Mbit/s constant data rate would be required in 2010 for the 4 HDTV services. After applying 15% stat mux gain this is equivalent to a stat mux pool of 27.2 Mbit/s. This can result in a multiplex configuration as shown below, with 2Mbit/s spare for potential additional services.

Multiplex	Service	Service Type	Statistical Multiplex	Mean Bitrate (Mbit/s)
Mux B	HDTV1	HDTV	Group of 4	27.2
	HDTV2	HDTV		
	HDTV3	HDTV		
	HDTV4	HDTV		
	MHEG guaranteed rate	Text/Interactive	-	0.5
	EIT, PAT, PMT, CAT	DVB SI/PSI	-	0.4
	Spare	?		2.8
	Null packets	-	-	0.5
Total				**31.4**

5.2.2 2012 Scenario

Assumptions:

- 31.4 Mbit/s multiplex capacity using DVB-T2
- Transmission of 720px1280 with HE-AAC five channel audio (at 160kbit/s) and AD
- Content produced progressively (e.g. 1080p)
- Quality required equivalent to a CBR rate of 7 Mbit/s per programme in 2012
- 17.5% efficiency gain through use of statistical multiplexing

- 0.5 Mbit/s guaranteed bit-rate interactive with further capacity given by the use of opportunistic data
- Null packet rate of 0.5 Mbit/s
- SI/PSI rate of 0.4 Mbit/s

A total of 35.0 Mbit/s constant data rate would be required in 2012 for the 5 HDTV services. After applying 17.5% stat mux gain this is equivalent to a stat mux pool of 28.9 Mbit/s. This can result in a multiplex configuration as shown below:

Multiplex	Service	Service Type	Statistical Multiplex	Mean Bitrate (Mbit/s)
Mux B	HDTV1	HDTV	Group of 5	28.9
	HDTV2	HDTV		
	HDTV3	HDTV		
	HDTV4	HDTV		
	HDTV5	HDTV		
	MHEG guaranteed rate	Text/Interactive	-	0.5
	EIT, PAT, PMT, CAT	DVB SI/PSI	-	0.4
	Spare	?		1.1
	Null packets	-	-	0.5
Total				**31.4**

6 ABBREVIATIONS

MPEG-4 AVC	MPEG-4 Advanced Video Coding
DTT	Digital Terrestrial Television
DVB	Digital Video Broadcasting
DVB-AVC	DVB Audio-Visual Coding
DVB-T	DVB Terrestrial
FEC	Forward Error Protection
FFT	Fast Fourier Transform
HDTV	High Definition Television
I-frame	Intra-coded frame
MHEG	Multimedia and Hypermedia Experts Group
MPEG	Moving Pictures Expert Group
PID	MPEG-2 Transport Stream Packet Identifier
QAM	Quadrature Amplitude Modulation
SDTV	Standard Definition Television
TSCES	Triple Stimulus Continuous Evaluation Scale