# Beyond HDTV:
# Implications for Digital Delivery

An Independent Report by ZetaCast Ltd Commissioned by Ofcom

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# Contents

# 1 EXECUTIVE SUMMARY

## 1.1 Background

This report provides a review of next generation television display technology developments, in order to gain insight into the bit rates likely to be required to deliver such services in the future. It concentrates on the potential development of stereoscopic TV ("3D" TV) and Ultra High Definition television (UHDTV), although other issues such as higher frame rate, wider aspect ratio, greater bit depth, improved chrominance resolution and wider colour gamut are also considered.

The report explores some possible scenarios for the broadcasting of stereoscopic TV and UHDTV by terrestrial and satellite broadcasting, taking into account the likely developments in channel coding and modulation. Three scenarios for technology development are considered: most probable, pessimistic and optimistic. The pessimistic case is intended to be close to a worst case situation, which there is a 90% probability of exceeding. The optimistic scenario is intended to represent a best case situation, with only a 10% probability of exceeding.

In each scenario, predictions are made on the number of services that could be carried in an 8MHz terrestrial channel or a 36MHz satellite transponder in the year 2020. The year 2020 was chosen for the scenarios since by then stereoscopic TV is likely to have either matured to become a mainstream service or else been relegated to a niche market that is of little interest to broadcasters. Similarly, by 2020 UHDTV should have become practical to provide to the consumer at acceptable prices, if it is a service that is of mainstream interest.

With reference to the Gartner Hype Cycle [6], the current situation for stereoscopic TV displays has all the characteristics of a classic "Peak of Inflated Expectations", whilst UHDTV appears to be at the "Technology Trigger" stage. By 2020, both technologies should have reached the "Plateau of Productivity" stage.

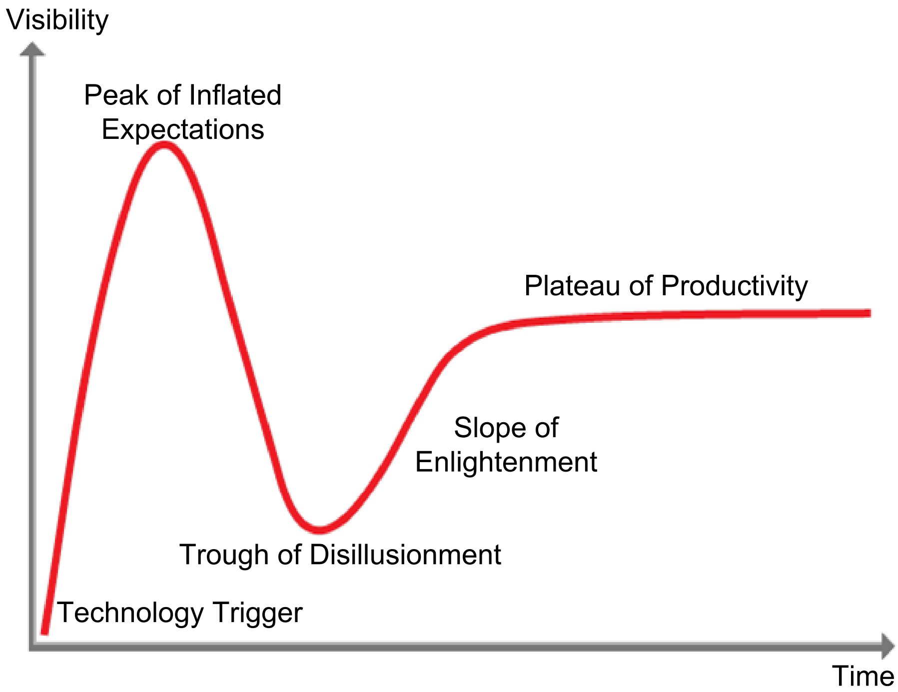



**Figure 1: Gartner Hype Cycle**

## 1.2 Explanation of the technology

### 1.2.1 Stereoscopic and 3D Display Techniques

The human vision system has no direct means of analysing the three-dimensional nature of a scene; the third dimension is inferred from various cues delivered through our binocular vision system. The most important of these cues is parallax, the difference between the views seen by the left and right eye, which is greater for the closer objects.

A stereoscopic effect can be obtained from video on a flat two-dimensional (2D) screen by employing some form of filtering to ensure that information representing a different perspective is presented to each eye. The filtering process may rely on glasses (filtering by colour, polarisation or temporal shutters) or may be inherent in the display itself (an auto-stereoscopic display). Such plano-stereoscopic displays are often referred to as "3D", but this is not strictly correct; in a true three dimensional display the scene observed would be dependent on the position of the viewer and would change if the viewer moved.

Each of the available display technologies has its own distinct advantages and disadvantages, which are summarised in Table 1 below.

| | Advantages | Disadvantages |
|---|---|---|
| Stereoscopic TV using Coloured glasses | Practical with most existing displays; already used on some Blu-Ray discs<br>Very low cost passive glasses | Colour reproduction problems<br>Poor quality "3D" results in a home viewing environment |
| Stereoscopic TV using Polarised glasses | Good quality "3D"<br>Good quality 2D<br>Low cost passive glasses | Requires new LCD display with micro-polarisation<br>Display cost increased due to micro-polarisation<br>Reduced spatial resolution when viewing "3D" |
| Stereoscopic TV using Shutter glasses | Good quality "3D"<br>Full quality 2D<br>Does not increase cost of display | Requires high-end plasma or DLP display with high display rate<br>Reduced temporal resolution when viewing "3D"<br>Relatively expensive active glasses |
| Auto-stereoscopic TV | No glasses | Requires very expensive new display<br>Currently offers a mediocre "3D" experience with limited viewing angles<br>Lenticular lens degrades viewing of 2D content |
| Head mounted stereoscopic display | Full quality "3D" without any filtering<br>Immersive viewing experience | Requires expensive individual display for each viewer<br>Not suitable for social viewing |
| Light Field, Holographic and Volumetric displays | True 3D (not just stereoscopic) | Unlikely to be available at consumer prices in the foreseeable future |

**Table 1: Stereoscopic and 3D Display Technologies**

### 1.2.2 Ultra High Definition TV

The current High Definition TV (HDTV) transmissions in Europe comply with the DVB Video and Audio Coding Specification [7] using one of two video formats:

- "720p", i.e. 1280 pixels x 720 lines at 50 frames/s (progressive)
- "1080i", i.e. 1920 pixels x 1080 lines at 25 frames/s (interlaced)

The best way to be able to provide content for transmission in either format is to produce it in a third format:

- "1080p", i.e. 1920 pixels x 1080 lines at 50 frames/s (progressive)

The latest revision of the DVB specification [8] also allows the broadcasting of 1080p video, to provide an improved quality HDTV service, but this has not yet been adopted by any broadcaster.

The term Ultra High Definition TV (UHDTV) is used to refer to resolutions higher that 1080p. Two main classifications are envisaged, representing 4 times and 16 times the resolution of 1080p respectively:

- "4Kx2K", i.e. 3840 pixels x 2160 lines
- "8Kx4K", i.e. 7680 pixels x 4320 lines

If the same nomenclature were applied to HDTV, then 1080p would be referred to as "2Kx1K".

## 1.3 Current state of the art

### 1.3.1 Stereoscopic and 3D Display Techniques

Several major display manufactures have shown progress towards introducing stereoscopic displays, either by demonstrating a prototype or by actually launching products to the market. The state of the market at the time of writing is summarised in Table 2 below.

| | Stereoscopic Polarised glasses | | | Stereoscopic Shuttered glasses | | | Auto-stereoscopic | |
|---|---|---|---|---|---|---|---|---|
| | LCD | Plasma | DLP | LCD | Plasma | DLP | Lenticular | Barrier |
| Hyundai | 46/24/22" | | | | | | | |
| Philips | | | | | | | 42" | |
| LG | 42" | | | | 55/60" | | 42" | |
| Samsung | | | | 22" | 42/50/58/63" | 50/56/61/67" | 52" | |
| Mitsubishi | | | | | | 60/65/73/82" | | |
| Panasonic | | | | | 103" | | | |
| JVC | 46" | | | | | | 50/72" | |
| Sony | | | | | | | | |
| Alioscopy (NEC) | | | | | | | | |
| Sharp | | | | | | | | |

Demonstration of Prototype
Launch announced/imminent
Commercially available

**Table 2: Current Market in Stereoscopic Display Devices (indicative)**

### 1.3.2 Ultra High Definition TV

Prototype 4Kx2K displays have been demonstrated since 2006. Several of the major display manufactures have started to introduce such UHDTV products on the market, using both plasma and LCD technologies:

| | LCD | Plasma |
|---|---|---|
| Samsung | 4Kx2K: 82" | 4Kx2K: 63" |
| Panasonic | | 4Kx2K: 150" |
| Sony | 4Kx2K: 82" | |
| Sharp | 4Kx2K: 64" | |
| Toshiba | 4Kx2K: 56" | |

Demonstration of Prototype
Launch imminent
Commercially available

**Table 3: Current Market in UHDTV Displays (indicative)**

## 1.4 Conclusions on Technology Development

### 1.4.1 Development of Stereoscopic TV and "3D" TV

Stereoscopic TV using anaglyph coding and coloured glasses is practical today, but the user experience is generally considered to be so poor that there is virtually no support for this as anything other than a very short-term solution.

In the medium term, implementation of stereoscopic TV is likely to be characterised by a proliferation of different broadcasting approaches whilst broadcasters and consumer equipment suppliers test the market. During this period, it is likely that the ability for an already deployed population of set-top boxes to decode the stereoscopic signal will be important to many broadcasters, even if that requires a reduction in the video resolution.

By the year 2020, it is assumed that and that the consumer demand for stereoscopic TV will be either proved or disproved. If there is confirmed consumer demand, it is assumed that both the broadcaster and the consumer would be willing to invest in the infrastructure and equipment necessary to deliver full 1080p/50 HDTV resolution video to each eye. The different options for achieving this in 2020 are summarised in the Table 4 below.

| | Broadcast Format | Able to be watched by viewer with 2D display | Required Bit-Rate Relative to 2D |
|---|---|---|---|
| Independent Left and Right Eye Views | 2 x 1080p/50 | Yes | 200% |
| Temporally Interleaved | 1080p/100 | Possible if scalable video coding is used | 170 – 190% |
| Spatially Interleaved | 2160p/50 (or other format at twice 1080p/50 resolution) | May be possible if scalable video coding is used | 170 – 190% |
| 2D plus Difference | 1080p/50 + metadata | Yes | 140 – 180% |
| 2D plus Depth | 1080p/50 + metadata | Yes | 120 – 160% |
| 2D plus DOT | 1080p/50 + metadata | Yes | 180 – 220% |

**Table 4: Possible Broadcasting Formats for Stereoscopic TV in 2020**

Broadcasting synchronised left and right eye views is straightforward, but is rather wasteful in bit-rate. Temporal and spatial interleaving both suffer from compatibility problems for 2D viewers so, although they are likely to have been used in the earlier market-testing phase, they are unlikely to continue to be used by 2020.

Of the "2D plus metadata" methods, "2D plus difference" is the most practical today. "2D plus depth" has the potential to reduce the required bit-rate further, but the depth map is likely to be difficult to create with any great precision, particularly for real-time events. The extension of the 2D plus depth approach to "2D plus DOT" would extend support from stereoscopic to multiview video, but it is unlikely that display devices capable of delivering multiview video will be available at consumer-friendly prices by 2020.

The scenarios are based on the assumptions summarised in Table 5 below:

| | Stereoscopic Broadcasting in 2020 | Assumed Bit-Rate Relative to 2D |
|---|---|---|
| Pessimistic (lowest decile) | Simulcast of left and right eye views | 200% |
| Most Probable | 2D plus Difference (with similar efficiency to that achievable today) | 180% |
| Optimistic (highest decile) | 2D plus Difference (with greater efficiency to that achievable today) | 160% |

**Table 5: Scenarios for Stereoscopic TV Broadcasting in 2020**

### 1.4.2 Development of UHDTV and Video Compression

The decade from 1995 to 2005 saw digital SDTV by terrestrial, cable and satellite being launched and then becoming commonplace in the majority of households in the UK. We appear to be in the midst of a similarly successful roll-out of HDTV in the decade from 2005 to 2015. A logical extrapolation would be to predict that an equivalent roll-out of 4Kx2K UHDTV will occur in the decade from 2015 to 2025. However, this is far from proven; an alternative view would be that consumers are sufficiently satisfied with the picture quality of HDTV that improving picture quality further is not a major driver.

Camera and storage media technologies appear to be progressing at a sufficiently rapid rate that they will not impede the launch of UHDTV. Furthermore, the capacity of packaged media and the increasing bit-rates available through wired and even wireless broadband networks implies that broadcasters will be in danger of being bypassed in picture quality by other delivery mechanisms if they do not embrace UHDTV.

The price of the few UHDTV displays that are available today is prohibitively high for consumer use. However, it is reasonable to assume that these prices will reduce dramatically over the next decade, following a similar pattern to prices of corresponding HDTV displays over the past decade.

The UHDTV scenarios are based on the following assumptions:

- The typical UHDTV video format will be 3840 pixels x 2160 lines
- Other display enhancements (e.g. enhanced colour gamut) will not require any increase in bit-rate.
- The broadcasting frame rate will remain 50Hz and the aspect ratio will remain 16:9

The assumed starting point in all scenarios is that 13Mb/s constant bit-rate is required today to give reasonable quality 1080p/50 HDTV video with a state-of-the-art encoder. A range of assumptions are then made for the bit-rate that would be required for 1080p/50 HDTV in the year 2020, depending on the rate of progress in video compression technology. Finally, different assumptions are made for the increase in compression efficiency, as measured in terms of bits per pixel, for UHDTV compared to HDTV; this is due to both the increased correlation between adjacent pixels at higher resolutions and a possible new compression algorithm that may be better matched to the statistics of higher resolution video.

The assumptions used in the various scenarios are summarised in Table 6 below:

| | 1080p/50 bit-rate | UHDTV bit-rate |
|---|---|---|
| Pessimistic (lowest decile) | 9.1 Mb/s<br>70% of today | 34.6 Mb/s<br>380% of 1080p/50 |
| Most Probable | 6.5 Mb/s<br>50% of today | 23.4 Mb/s<br>360% of 1080p/50 |
| Optimistic (highest decile) | 5.2 Mb/s<br>40% of today | 17.7 Mb/s<br>340% of 1080p/50 |

**Table 6: Scenarios for UHDTV Broadcasting in 2020**

### 1.4.3 Development of Channel Coding and Modulation

Significant advances have been made in all three of DVB's second generation transmission systems [12][14][16], compared to the equivalent first generation solutions [11][13][15]. However, the scope for further improvement appears to be more limited, with all three operating close to theoretical limits.

The greatest potential for further improvements appears to be the introduction of MIMO (multiple input multiple output) techniques in terrestrial transmission. With two antennas for both transmission and reception, this could yield as much as a doubling of data capacity. However, it would require changes to both the transmission infrastructure and the home installation, which would be both very disruptive and expensive to implement.

The scenarios are based on the assumptions summarised in Table 7 below:

| | Satellite Broadcasting in 2020 | Bit-rate from a 36MHz satellite transponder | Terrestrial Broadcasting in 2020 | Bit-rate from a 8MHz terrestrial channel |
|---|---|---|---|---|
| Pessimistic (lowest decile) | DVB-S2<br>0% improvement | 46.0Mb/s | DVB-T2<br>0% improvement | 35.9Mb/s |
| Most Probable | DVB-S3<br>15% improvement | 52.9Mb/s | DVB-T3 (no MIMO)<br>20% improvement | 43.1Mb/s |
| Optimistic (highest decile) | DVB-S3<br>25% improvement | 57.5Mb/s | DVB-T3 inc. MIMO<br>100% improvement | 71.8Mb/s |

**Table 7: Scenarios for Satellite and Terrestrial Broadcasting in 2020**

## 1.5 Conclusions on Scenarios

### 1.5.1 Delivery of "3D" TV by Terrestrial Broadcasting in 2020

The second column of Table 8 below predicts the number of "3D" services that can be expected to be carried in an 8MHz terrestrial channel in the pessimistic, most probable and optimistic scenarios. The calculation is based on the bit-rate available in the channel, the bit-rate required per service and the assumed gain from the use of statistical multiplexing specified in the fifth column. The final column is intended to confirm that there is sufficient residual bit-rate available for audio, SI/PSI, interactive services, etc.

| | "3D" TV Required Bit-rate (CBR) | No. "3D" services in 8MHz channel | Stat Mux Gain | Total video bit-rate | Bit-rate in a 8MHz terrestrial channel | Residual bit-rate for audio, SI, etc. |
|---|---|---|---|---|---|---|
| Pessimistic | 18.2 Mb/s | **2** | 8% | 33.5 Mb/s | 35.9Mb/s | 2.4 Mb/s |
| Most Probable | 11.7 Mb/s | **4** | 15% | 39.8 Mb/s | 43.1Mb/s | 3.3 Mb/s |
| Optimistic | 8.3 Mb/s | **11** | 26% | 67.7 Mb/s | 71.8Mb/s | 4.1 Mb/s |

**Table 8: Terrestrial Broadcasting of "3D" TV**

In the most probable scenario, four "3D" TV services could be expected to be carried in an 8MHz terrestrial channel by 2020. In the pessimistic scenario this decreases to two, whilst in the optimistic scenario it increases to eleven. The wide range between the scenarios is largely due to the potential doubling of bit-rate that could be provided by a future DVB-T3 channel if MIMO techniques were used, amplified by the "virtuous circle" effect of statistical multiplexing; the larger the number of channels, the less bit-rate is required per channel.

### 1.5.2 Delivery of "3D" TV by Satellite Broadcasting in 2020

The second column of Table 9 below predicts the number of "3D" services that can be expected to be carried in a 36MHz satellite transponder.

| | "3D" TV Required Bit-rate (CBR) | No. "3D" services in 36MHz transponder | Stat Mux Gain | Total video bit-rate | Bit-rate in a 36MHz satellite transponder | Residual bit-rate for audio, SI, etc. |
|---|---|---|---|---|---|---|
| Pessimistic | 18.2 Mb/s | **2** | 8% | 33.5 Mb/s | 46.0 Mb/s | 12.5 Mb/s |
| Most Probable | 11.7 Mb/s | **5** | 17.5% | 48.3 Mb/s | 52.9 Mb/s | 4.6 Mb/s |
| Optimistic | 8.3 Mb/s | **8** | 23% | 51.3 Mb/s | 57.5 Mb/s | 6.2 Mb/s |

**Table 9: Satellite Broadcasting of "3D" TV**

In the most probable scenario, five "3D" TV services could be expected to be able to be carried in a 36MHz satellite transponder by 2020. In the pessimistic scenario this decreases to two, whilst in the optimistic scenario it increases to eight. The differences between the scenarios are much less pronounced than in the terrestrial case, because even in the most optimistic scenario, the capacity achievable by DVB-S3 channel coding and modulation cannot exceed the Shannon limit.

### 1.5.3 Delivery of UHDTV by Terrestrial Broadcasting in 2020

The second column of Table 10 below predicts the number of UHDTV services that can be expected to be carried in an 8MHz terrestrial channel.

| | UHDTV Required Bit-rate (CBR) | No. UHDTV services in 8MHz channel | Stat Mux Gain | Total video bit-rate | Bit-rate in a 8MHz terrestrial channel | Residual bit-rate for audio, SI, etc. |
|---|---|---|---|---|---|---|
| Pessimistic | 34.6 Mb/s | **1** | 0% | 34.6 Mb/s | 35.9Mb/s | 1.3 Mb/s |
| Most Probable | 23.4 Mb/s | **2** | 8% | 43.1 Mb/s | 43.1Mb/s | 0.04 Mb/s |
| Optimistic | 17.7 Mb/s | **4** | 15% | 60.1 Mb/s | 71.8Mb/s | 11.7 Mb/s |

**Table 10: Terrestrial Broadcasting of UHDTV**

In the most probable scenario, two UHDTV video services would just fit in an 8MHz terrestrial channel, but with insufficient residual capacity for audio or SI/PSI. In the pessimistic scenario there is capacity for only one UHDTV services, whilst in the optimistic scenario four could be provided.

### 1.5.4 Delivery of UHDTV by Satellite Broadcasting in 2020

The second column of Table 11 below predicts the number of UHDTV services that can be expected to be carried in a 36MHz satellite transponder.

| | UHDTV Required Bit-rate (CBR) | No. UHDTV services in 36 MHz Transponder | Stat Mux Gain | Total video bit-rate | Bit-rate in a 36MHz satellite transponder | Residual bit-rate for audio, SI, etc. |
|---|---|---|---|---|---|---|
| Pessimistic | 34.6 Mb/s | **1** | 0% | 34.6 Mb/s | 46.0 Mb/s | 11.4 Mb/s |
| Most Probable | 23.4 Mb/s | **2** | 8% | 43.1 Mb/s | 52.9 Mb/s | 9.8 Mb/s |
| Optimistic | 17.7 Mb/s | **3** | 12% | 46.7 Mb/s | 57.5 Mb/s | 10.8 Mb/s |

**Table 11: Satellite Broadcasting of UHDTV**

In the most probable scenario, two UHDTV services could be expected to be carried in a 36MHz satellite transponder by 2020. In the pessimistic scenario this decreases to only one, whilst in the optimistic scenario it increases to three.

# 2 INTRODUCTION

Ofcom asked ZetaCast to review ongoing next generation television display developments in order to gain qualitative and quantitative insight into the bit rates likely to be required to deliver such services in the future.

ZetaCast used two approaches in parallel to address these issues. Firstly, it performed desk research to determine the current state of the art and likely direction of future developments by reviewing published papers and analysing the progress of relevant standardisation activities. Secondly, it conducted a series of carefully targeted interviews with some leading members of the broadcasting industry and consumer electronics manufacturers to evaluate their opinions on future developments. However, it should not be assumed that the organisations interviewed endorse the conclusions of this report, since the conclusions were not discussed with them.

The report explores some possible scenarios for the broadcasting of stereoscopic TV and UHDTV by terrestrial and satellite broadcasting, taking into account the likely developments in channel coding and modulation. Three scenarios for technology development are considered: most probable, pessimistic and optimistic. The pessimistic case is intended to be close to a worst case situation, which there is a 90% probability of exceeding. The optimistic scenario is intended to represent a best case situation, with only a 10% probability of exceeding.

In each scenario, predictions are made on the number of services that could be carried in an 8MHz terrestrial channel or a 36MHz satellite transponder in the year 2020. The year 2020 was chosen for the scenarios since by then stereoscopic TV is likely to have either matured to become a mainstream service or else been relegated to a niche market that is of little interest to broadcasters. Similarly, by 2020 UHDTV should have become practical to provide to the consumer at acceptable prices, if it is a service that is of mainstream interest.

If there is consumer demand for both types of new services then they would compete for the available bandwidth. However, any such competition is likely to be driven by commercial issues that are beyond the scope of this analysis, which focuses on issues of technical feasibility.

With reference to the Gartner Hype Cycle [6], the current situation for stereoscopic TV displays the characteristics of a classic "Peak of Inflated Expectations", whilst UHDTV appears to be at the "Technology Trigger" stage. By 2020 both technologies should have reached the "Plateau of Productivity" stage.

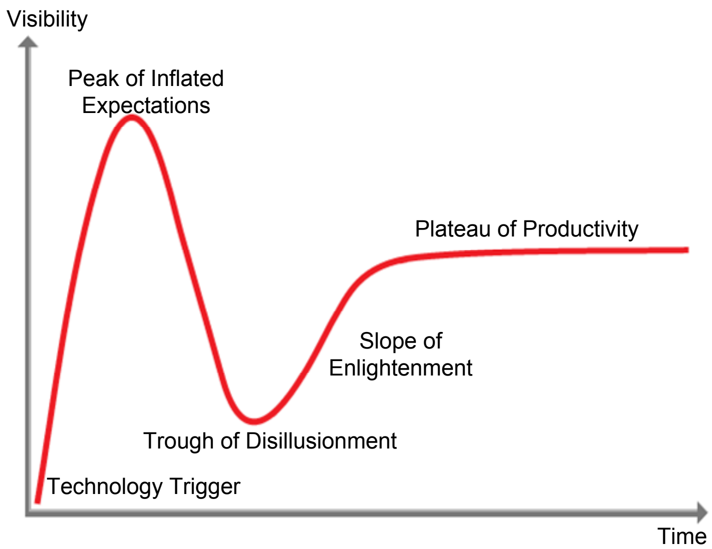



**Figure 2: Gartner Hype Cycle**

# 3 "3D" TELEVISION

## 3.1 Stereoscopic and 3D Display Techniques

### 3.1.1 Overview of Display Techniques

The human vision system has no direct means of analysing the three-dimensional nature of a scene; the third dimension is inferred from various cues delivered through our binocular vision system. The most important of these cues is parallax, the difference between the views seen by the left and right eye, which is greater for the closer objects.

A stereoscopic effect can be obtained from video on a flat two-dimensional (2D) screen by employing some form of filtering to ensure that information representing a different perspective is presented to each eye. The filtering process may rely on glasses (filtering by colour, polarisation or temporal shutters) or may be inherent in the display itself (an auto-stereoscopic display). Each of these approaches has its own distinct advantages and disadvantages, which are discussed below.

Such plano-stereoscopic displays are often referred to as "3D", but this is not strictly correct; in a true three dimensional display the scene observed would be dependent on the position of the viewer and would change if the viewer moved. However, the "3D" terminology is a convenient short-hand that will be used in places in this report.

In the real world, parallax is not the only visual cue to the distance of an object; other cues such as the point of focus of the eye ("accommodation") also contribute to the impression of depth. When using parallax alone to create the illusion of depth, care must be taken to ensure that the viewer does not suffer from eyestrain. In extreme cases, conflicting depth cues may produce a feeling similar to motion sickness.

### 3.1.2 Stereoscopic TV using Coloured glasses

Anaglyph images can be used to provide a stereoscopic effect when viewed using simple coloured glasses where each lens is an opposite colour (typically red/green or red/cyan). Each eye sees a different image and the brain tries to accommodate the difference in colour to create a normally coloured stereograph image.

This is the oldest of all of the stereoscopic projection systems; the first confirmed public showing of a stereoscopic movie was in 1922 using a red/green anaglyph. In movie theatres, the left and right eye images were originally projected separately through two coloured filters. However, it is now simpler to use image processing software to create the superposition effect, which allows any type of display device to be used.

An inherent problem with all anaglyph images is the trade-off between the stereoscopic effect and the accurate reproduction of colours. With the typical red/cyan anaglyph this tends to be particularly visible as a loss of saturation in reds. A compensating technique, known as Anachrome, attempts to reduce this impairment by using a slightly more transparent cyan filter.

Despite the colour reproduction problems, an anaglyph approach using simple red/cyan glasses has the advantage of being possible to implement today without requiring any significant additional expenditure by the viewer. For this reason, a number of movies have already been released in "3D" on Blu-Ray. Disney has been particularly prolific in releasing such Blu-Ray titles, starting with "Hannah Montana & Miley Cyrus: Best of Both Worlds Concert" in August 2008. Disposable red/cyan glasses with cardboard frames are generally included with the "3D" Blu-Ray disc. These can also be purchased individually for less than £1, whilst reusable anaglyph glasses with plastic frames are available for about £5 to £10. The same approach could be used to provide stereoscopic content using an existing HDTV broadcasting channel today. However, apart from a small number of special events, there is little sign of interest from any broadcaster in offering such a service, perhaps due to concerns over the perceived quality.

**Figure 3: Red/Cyan Plastic Framed Anaglyph Glasses**

A more advanced form spectral-multiplexing, sometimes called a "super-anaglyph", is to use a well-defined triplet of narrow frequency bands within each primary colour. A slightly different triplet of shades of red, green and blue is used to construct the left and right eye images. This allows stereoscopic images to be viewed with only slight colour differences between the two eyes, hence largely avoiding the colour reproduction problems of traditional anaglyphs. The viewing glasses have advanced filters that pass only the appropriate colour triplet to each eye, e.g. by use of interference filter technology ("Infitec"). They are therefore more expensive than the simple red/cyan glasses, costing about £30, so they are marketed as re-usable rather than disposable. This technology is used by both Dolby and Barco, who each have over 300 "3D" cinema installations worldwide. However, the requirement to have very precisely defined colours is likely to make it impractical for use in home displays for the forseable future.

### 3.1.3 Stereoscopic TV using Polarised glasses

A stereoscopic effect can be created by presenting orthogonally polarised images corresponding to each eye's view on the display, either simultaneously or sequentially. Glasses with corresponding orthogonally polarised filters (either linear or circular) restrict the light that reaches each eye so that each eye sees only its intended image.

This technique has been used in movie theatres since the 1930s, using two synchronised projectors with opposite polarising filters and a silvered projection screen (to maintain polarisation of the reflected light). Orthogonal linear polarisation (e.g. horizontal/vertical or +45°/-45°) requires the viewer to keep his head level, as tilting of the viewing filters will cause the images of one channel to bleed over to the opposite channel resulting in "ghosting". Orthogonal circular (clockwise/anticlockwise) polarisation avoids this problem and is more commonly used today. Polarised glasses are relatively cheap, retailing at about £1 with cardboard frames, whilst more robust versions with plastic frames are available from about £10. Of all of the types of stereoscopic glasses, polarised would probably trigger the least resistance from the public for aesthetic reasons, since they can look similar to sunglasses.


**Figure 4: RealD Circularly Polarised Glasses**

The "RealD" projection technology, backed by Disney, is an alternative approach which avoids the need for twin polarised projectors in the cinema. A single projector operates at an overall rate of 144 frames per second, six times the normal movie frame rate, to project the left and right eye frames three times each. There is an electronic polarising screen in front of the projector that switches between clockwise and anti-clockwise polarisation in synchronisation with the switch between left and right eye frames. RealD is currently the most widely deployed stereoscopic projection system worldwide.

It is also possible to use a projector approach with polarising filters to create a "3D" home theatre environment for enthusiasts. For example, the "GeoWall" is a stereoscopic projection system that consists of a computer with a dual-output graphics card, two projectors, polarising filters and a silver screen.

A more mass-market polarising display device for the home is a flat panel liquid crystal display (LCD) with micro-polarisation arranged such that opposite direction of circular polarisation is used over pixels intended for the left and right eye. Typically, a horizontally interlaced stereoscopic format is used and the polarisation alternates between each line; the vertical resolution is then effectively halved in order to achieve the stereoscopic effect. Other micro-polarisation patterns are also possible.

The display needs to be brighter than normal when viewing "3D" material in order to compensate for the effect of the dark glasses. The micro-polarisation also results in a slight reduction in brightness when using the display without glasses for viewing normal 2D material, as well as increasing the manufacturing cost of the display. For example, the Hyundai S465D 46" 1080p stereoscopic LCD TV currently retails for the equivalent of about £3,500 in Japan.

### 3.1.4 Stereoscopic TV using Shutter glasses

Shutter glasses can be used to provide temporal filtering, which creates a stereoscopic effect by presenting different perspectives to each eye through alternate frame sequencing; the display alternates between left and right eye views whilst the glasses blank each eye alternately in synchronisation with the screen.

The shutter glasses are typically based on liquid crystal materials that have the property to become dark when voltage is applied, but are otherwise transparent. Unlike coloured glasses or polarised glasses, these are active devices that require synchronisation with the display through wireless or infra-red communication. For this reason, LCD shutter glasses are more expensive than simple coloured or polarised glasses, typically costing around £80.

XpanD is currently the world leader in supplying shutter glasses systems for cinemas, deployed in around 500 movie theatres worldwide. The XpanD X101 Series shutter glasses have built-in batteries, for which they claim a lifetime of 300 hours, whilst other manufacturers offer glasses with replaceable batteries.

**Figure 5: XpanD X101 Series shutter glasses**

The shutter glasses approach can be used to create a projector-based "3D" home theatre environment for enthusiasts. Only a single projector is needed and a standard white screen can be used, which gives a wider viewing angle than the silver screen required for systems based on polarisation.

A similar shutter glasses technique can be applied to flat-screen TV displays, provided that the attack and decay of the display is rapid enough to avoid information intended for one eye from bleeding into the image for the other. Historically, rapid attack and decay has tended to be a problem when liquid crystal display (LCD) technology is used, so that currently shutter glasses are generally used in conjunction with plasma display panel (PDP) or digital light processing (DLP) displays. However, the continual improvements in LCD technology may overcome this problem; the response times of today's LCD displays have already improved to the extent that the smearing and blurring of rapidly moving 2D images that was commonly seen a decade ago is no longer evident.

Displays intended to be used with shutter glasses all tend to support 100Hz or higher display rates; flicker is noticeable when using shutter glasses unless the display has a high refresh rate, as the display's nominal refresh rate is effectively halved by the operation of the shutter. They also require a brighter than normal display, since the glasses pass light for only half of the time and are slightly dark even when in "transparent" mode. However, there is no compromise to the quality that is obtained when using the display without glasses for viewing normal 2D material.

Synchronisation of the shutter glasses can be achieved using either an infra-red (or wireless) transmitter built into the TV or else via an interface to an external transmitter. A Video Electronics Standards Association (VESA) standard interface for stereoscopic display hardware was defined in 1997 to support the connection of shutter glasses to computer systems, using a 3 pin DIN plug [26].

### 3.1.5 Auto-stereoscopic TV

An auto-stereoscopic display is one which provides a stereoscopic effect without requiring any form of glasses. The display itself is designed to present different information when viewed from slightly different angles, so if the viewer positions their head correctly they will perceive a different image with each eye, giving a stereo image.

Unlike the glasses-based systems, the cinema experience with auto-stereoscopic displays does not really help to illustrate the way that displays in the home could develop. There have been some attempts to develop an auto-stereoscopic projection system for use in cinemas since the 1930s, using techniques such as projecting onto an array of vertical piano wires, but without any great success. A few such movie theatres existed in the Soviet Union in the 1960s, but none remain today.

There are two main auto-stereoscopic techniques that are currently used with flat panel displays: parallax barrier and lenticular lens. In both systems, the spatial resolution of the base 2D display is reduced in order to gain the stereoscopic effect.

In the parallax barrier system, some form of mask is placed over the display which directs light from alternate pixel columns to each eye. Parallax barrier displays can allow dynamic switching between 2D and "3D" modes if the barrier is constructed from a layer of liquid crystal which can become completely transparent, allowing the display to function as a conventional 2D monitor. A single-user auto-stereoscopic display can use eye tracking systems to automatically adjust the two displayed images to follow the viewer's eyes as they move their head.

The best performing of the current auto-stereoscopic displays use the lenticular lens system. In this system, an array of cylindrical lenses directs light from alternate pixel columns to a defined viewing zone. These displays typically have a central viewing zone of about 10 to 15 degrees wide, with additional viewing zones to the sides. These additional viewing zones allow multiple users to view the image at the same time, as long as they are correctly positioned. They can also provide a limited degree of horizontal motion parallax, where the scene changes as the viewer moves horizontally, but with a noticeable "jump" between views.

Prior to the March 2009 announcement that it intended to scale down its activities, Philips appeared to be the market leader for auto-stereoscopic displays. For example, the Philips 42-3D6W02, a 42" LCD with native 1080p resolution and a lenticular lens system providing 9 views, was on sale for about £7,500.

### 3.1.6 Head mounted stereoscopic display

A personalised stereoscopic display system can be created by a head-mounted display, with a separate dedicated display device for each eye. Because there is no form of filtering, this approach has the potential to give a better stereoscopic effect than any of the glasses-based systems.

Since the displays are so close to the eye, they subtend as large an angle as a very large flat panel display viewed from a normal viewing angle, to provide a very immersive viewing experience. For example, the TDVisor-HD is claimed to offer the equivalent viewing angle to a 108" TV screen seen from a distance of 10 feet. It supports 720p HDTV and the pre-order price in the USA is around £1,000 per headset.

**Figure 6: TDVisor**

Apart from the cost of having to buy individual headsets, one of the main drawbacks of this approach is the loss of the normal social interaction between family and friends sharing a TV viewing experience. However, headsets are likely to be used in professional applications (such as military, governmental, medicine and sports) and in applications for solitary use, particularly for playing stereoscopic video games. In the longer term, a headset could be combined with a tracking system to alter the views depending on head and eye movements, thus providing a fuller three dimensional environment.

### 3.1.7 True 3D displays

There have been numerous attempts to create some form of holographic or volumetric display that gives a true three dimensional representation of an object, in the manner popularised by science fiction films such as Star Wars.

There are already some commercially available devices that attempt to mimic this effect with 2D content, for example the "FogScreen" projection screen produces a thin curtain of fog that serves as a translucent projection screen, allowing the display of "pseudo-holographic" images that appear to float in the air. This is adequate for attention-grabbing displays at public events, although the image quality is degraded by any turbulent air flow.

**Figure 7: "FogScreen" Display**

True 3D representation is rather more difficult. Despite the advances that have been made in the use of holography and laser-created volumetric displays, the use of such displays for general entertainment in the home is likely to remain in the realm of science fiction for the foreseeable future.

A more promising approach may be to implement the principles of the light field, the mathematical function that describes the amount of light travelling in every direction through every point in space, using non-laser illumination. Researchers at the University of Southern California (USC) Institute for Creative Technologies have produced a 3D display system based on light field principles that can be viewed through 360°.

The display uses a high-speed video projector aimed at a spinning mirror covered by a holographic diffuser to give a horizontally multiview auto-stereoscopic display, with vertical head tracking to produce the correct vertical parallax for tracked users. Figure 8 below, taken from a paper [27] written by University of Southern California researchers in the ACM SIGGRAPH proceedings, shows photographs of eight frames from an animated light field sequence of a running man.

**Figure 8: Photographs of an animated Light Field sequence**

A small Hungarian company called Holografika has developed commercial products based on light field techniques which use a scalable array of digital light projectors and a projection screen augmented with micro-lenses [28]. Each projector module emits light beams towards specific points of the screen, not necessarily illuminating the whole screen, whilst each point of the holographic screen is hit by light beams arriving from different modules. The result is that there is continuous horizontal motion parallax, without the "jumping" between views that is characteristic of auto-stereoscopic displays based on lenticular lens or parallax barrier techniques.

However, these products are not really targeted at the consumer market: the cheapest model is the 32" Holovizio 128WLD, which sells for around £25,000.

### 3.1.8 Industry Trends

Most major display manufactures have made some move towards introducing stereoscopic displays, either by demonstrating a prototype or by actually launching products to the market.

| | Stereoscopic Polarised glasses | | | Stereoscopic Shuttered glasses | | | Auto-stereoscopic | |
|---|---|---|---|---|---|---|---|---|
| | LCD | Plasma | DLP | LCD | Plasma | DLP | Lenticular | Barrier |
| Hyundai | 46/24/22" | | | | | | | |
| Philips | | | | | | | 42" | |
| LG | 42" | | | | 55/60" | | 42" | |
| Samsung | | | | 22" | 42/50/58/63" | 50/56/61/67" | 52" | |
| Mitsubishi | | | | | | 60/65/73/82" | | |
| Panasonic | | | | | 103" | | | |
| JVC | 46" | | | | | | 50/72" | |
| Sony | | | | | | | | |
| Alioscopy (NEC) | | | | | | | | |
| Sharp | | | | | | | | |

Demonstration of Prototype

Launch announced and imminent

Commercially available

**Table 12: Current Market in Stereoscopic Display Devices (indicative)**

The manufacturers' solution for "3D" TV tends to be driven by their preferred display technology. For example, Samsung, Mitsubishi and Panasonic are offering stereoscopic TV using shutter glasses, because it works well with their high end plasma and DLP screens. On the other hand, Hyundai, LG and JVC may lean towards stereoscopic TV with polarised glasses because they are a more natural fit for LCD screens.

Similarly, in terms of video input formats, manufacturers are backing those formats that better match their preferred display technology. For example, Hyundai and JVC displays are both compatible with Line Interleaving and Side-by-Side formats, Panasonic supports Frame Interleaving, whilst Samsung supports a diversity of formats such as Checkerboard and Line Interleaving.

LCD manufacturers have largely supported stereoscopic TV using polarized glasses. Hyundai's S465D 46" was the first LCD display with micro-polarisation to be commercially available on the consumer market. It is currently for sale at an equivalent of about £3,500, but only for the Japanese market. JVC has announced it will launch its GD-463D10 46" display (for about £4,500) in the UK in July 2009. Several other manufacturers have also shown an interest in stereoscopic TV using polarised glasses, with LG, Panasonic and Sony all demonstrating LCD polarised displays in the past year.

Developments in the Plasma and DLP for the home market have leaned towards stereoscopic TV using shutter glasses. Many of these displays sold over recent years from manufacturers such as Samsung, Mitsubishi and Panasonic have high refresh rates and can be upgraded to support stereoscopic shutter glasses. The upgrade is possible by adding a hardware plug-in and infra-red remote control. The Panasonic 103" Full HD plasma display has been demonstrated working together with their Blu-ray Disc player to give stereoscopic playback of packaged media from a Blu-ray disc. Samsung's range of plasmas and DLPs launched since 2008 can be upgradable to stereoscopic viewing using a hardware add-on that costs about £150. Similarly, Mitsubishi's DLP displays will have an attachment from Nvidia at a comparable cost, launching later in 2009. LG has also demonstrated stereoscopic TV using shutter glasses.

LG, Alioscopy (NEC), Philips and Sharp have developed auto-stereoscopic displays based on lenticular lens technology. However, these displays are not particularly good for 2D viewing and their cost is high; they tend to be aimed primarily for use in digital signage, rather than home use. Philips appeared to be the market leader for auto-stereoscopic displays, selling a 42" LCD with native 1080p resolution and 9 viewing angles, the 42-3D6W02, for about £7,500. It had also demonstrated a prototype 56" auto-stereoscopic display with 46 viewing angles and a native resolution of 4096×2160. However in March 2009 Philips announced that it intended to scale down its "3D" activities, quoting the impact of the current economic climate on industry developments. This withdrawal by the current industry leader in auto-stereoscopic displays casts some doubt over the long-term viability of the lenticular lens approach.

Philips stated that:

> *"Because of current market developments, the point in time where mass adoption of no-glasses based 3D TV will occur has shifted significantly. Therefore, Philips has decided to stop the 3D Solutions venture. Philips has been marketing its leading no-glasses based 3D technologies through a pro-active approach for a long time, because it believes that over time, no-glasses based 3D TVs will bring the ultimate 3D experience to the home. Unfortunately, the current market developments no longer justify such a pro-active approach. As a consequence of this, Philips has decided to scale down its investments in this area. In practice, this means that the 3D Solutions venture will be discontinued."*

The first commercially available 3D display using light field principles are starting to appear, aimed at niche professional applications. Holografika has announced that three sizes of auto-stereoscopic "Holovizio" displays are commercially available: the 32" 128WLD, 45" 240P and 72" 720RC. These displays are not aimed at the consumer market, with the smallest of them having a price tag of around £25,000.

The most commonly used interface for connecting the video decoder to the display is HDMI (High-Definition Multimedia Interface). In May 2009, HDMI Licensing issued a press release announcing that the HDMI specification ver. 1.4 was now available to Adopters. The features incorporated in the new HDMI 1.4 specification include support for resolutions up to 1080p/50 (and 1080p/60) in "3D" and it conveys information on a wide range of "3D" display formats, including:

- Field, Frame and Line Interleaved
- Side-by-Side
- 2D + depth

The HDMI specification is currently available for download by Adopters at the www.HDMI.org site. It is expected that the first products supporting this specification will be launched on the market by the end of 2009.

### 3.1.9 Conclusions on "3D" Display Techniques

There are various means of providing stereoscopic or 3D displays. Each of the available display technologies has its own distinct advantages and disadvantages, which are summarised in Table 13 below.

| | Advantages | Disadvantages |
|---|---|---|
| Stereoscopic TV using Coloured glasses | Practical with most existing displays; already used on some Blu-Ray discs<br>Very low cost passive glasses | Colour reproduction problems<br>Poor quality "3D" results in a home viewing environment |
| Stereoscopic TV using Polarised glasses | Good quality "3D"<br>Good quality 2D<br>Low cost passive glasses | Requires new LCD display with micro-polarisation<br>Display cost increased due to micro-polarisation<br>Reduced spatial resolution when viewing "3D" |
| Stereoscopic TV using Shutter glasses | Good quality "3D"<br>Full quality 2D<br>Does not increase cost of display | Requires high-end plasma or DLP display with high display rate<br>Reduced temporal resolution when viewing "3D"<br>Relatively expensive active glasses |
| Auto-stereoscopic TV | No glasses | Requires very expensive new display<br>Currently offers a mediocre "3D" experience with limited viewing angles<br>Lenticular lens degrades viewing of 2D content |
| Head mounted stereoscopic display | Full quality "3D" without any filtering<br>Immersive viewing experience | Requires expensive individual display for each viewer<br>Not suitable for social viewing |
| Light Field, Holographic and Volumetric displays | True 3D (not just stereoscopic) | Unlikely to be available at consumer prices in the foreseeable future |

**Table 13: Stereoscopic and 3D Display Technologies**

Stereoscopic TV using anaglyph coding and coloured glasses is the only solution for that can be deployed directly with most existing displays; the other stereoscopic solutions all require some form of supporting technology to be implemented in the display. However, the user experience that is achieved with anaglyph coding is generally considered to be so poor that there is virtually no support for this format as a long-term solution.

Whilst the requirement to wear glasses is not ideal for most consumers, the stereoscopic effect achieved by polarised or shutter technologies is the best currently available. In addition, as these technologies can be implemented in existing broadcast transmission networks, it is likely that they will dominate the market for "3D" capable displays in the medium term. Stereoscopic TV using polarised glasses has good industry support, particularly for LCD displays under 50". There are already first-generation displays with micro-polarisation commercially available in Japan, where BS11 channel broadcasts "3D" programs 4 times a day. Stereoscopic TV using shutter glasses also has good industry support, particularly for plasma and DLP displays over 50", with typical frame rates of 100/120Hz.

Ultimately, glasses-based approaches are likely to be superseded by glasses-free solutions, when such technologies become viable. The current quality of auto-stereoscopic displays based on lenticular lens or parallax barrier technology is not good enough for home viewing, and some doubt has been cast on the viability of this technology as a result of Philips, the market leader, withdrawing from the market. It is possible that some form of light field based display device would be a better long-term solution, although the current cost of such displays is prohibitively high for the domestic market.

## 3.2 Broadcasting of Stereoscopic TV

### 3.2.1 Overview of Broadcasting Considerations

This section concentrates on the options for broadcasting stereoscopic TV that are likely to be practical in the medium term, i.e. by the year 2020. Anaglyph coding is not considered as the user experience that can be achieved with this technique is not adequate for general consumer acceptance. On the other hand, it is assumed that longer term glasses-free and true 3D solutions will not be practical in the timescale under consideration. The focus is therefore on means of broadcasting stereoscopic TV for viewing using some form of glasses.

A number of different approaches to broadcasting a stereoscopic TV signal are possible, each with their own distinct advantages and disadvantages. The choice between these approaches is likely to depend on the relative importance of the various, and often conflicting, commercial drivers. Some of these conflicting requirements are:

- Maximum technical quality for stereoscopic version of content
- Maximum technical quality for 2D version of content
- Maximum artistic quality for stereoscopic version of content
- Maximum artistic quality for 2D version of content
- Minimum bit-rate
- Minimum additional cost to broadcaster
- Minimum additional cost to consumer
- Ability to use existing decoder for stereoscopic content
- Ability to use existing decoder for 2D content
- Practical to implement immediately
- Widely supported international standard
- Interfaces to all possible stereoscopic displays
- Supports multi-view displays

It is likely to be a long time before the population of stereoscopic display devices is so large that broadcasters would not wish to also supply the content to viewers with 2D displays. A technically straightforward approach would be to simply broadcast the content by completely independent 2D and "3D" signals. This would also provide full artistic freedom to optimise the content for viewing in each mode.

However, in many broadcasting systems, particularly for terrestrial transmission, bit-rate is a scarce resource. If it is artistically acceptable to constrain the 2D version by the "grammar" of shooting for "3D", e.g. reducing the frequency of scene cuts and avoiding shooting 3D objects that overlap the edge of the screen, then considerable overall bit-rate savings may be made by encoding the stereoscopic image on top of the 2D signal. The most straightforward way of doing this would be to just broadcast the left and right eye views as completely independent video streams. Another option is broadcasting the 2D video plus some form of metadata to represent the information in the third dimension, in order to reduce the total bit-rate further.

If the ability for an already deployed population of set-top boxes to decode the stereoscopic signal is of paramount importance, as it is currently appears to be for BSkyB, then the stereoscopic TV signal would have to be broadcast as if it were a conventional 720p/50 or 1080i/25 HDTV signal. However, this means that either the frame rate seen by each eye is halved (by shutter glasses) or else the resolution perceived by each eye is halved (by polarised glasses). The overall subjective impression of resolution of such a system is not actually reduced by quite as much as a factor of two, due to the effect of different information from each eye being processed as increased resolution by the brain.

All of the above considerations imply that the short and medium term implementation of stereoscopic TV is likely to be characterised by a proliferation of different broadcasting formats, in many cases directly linked to the display formats. If the broadcast signal is required to be displayed on a range of different forms of display devices, then some form of display-agnostic coding would be required for the broadcast signal.

### 3.2.2 Broadcasting Independent Left and Right Eye Views

The most straightforward way of broadcasting stereoscopic video would be to broadcast two totally independent, but synchronised, HDTV streams; one representing the left eye view and one representing the right eye view. Since there would be no linkage between the compression coding for the left and right eye views, the total bit-rate required would be twice that of a 2D HDTV signal at the same resolution as each eye.

The existing HDTV broadcast infrastructure could carry the signal without any significant modification, since it would appear as two conventional HDTV signals. Assuming the SI was correctly configured, a viewer who had only a 2D display could display the view intended for one eye (say the left eye). A consumer who wished to view the content stereoscopically would need a dual HDTV decoder interfaced to a suitable display arrangement.

### 3.2.3 Broadcasting a Temporally Interleaved Stereoscopic Signal

A variant of the independent approach would be to encode the stereoscopic signal as alternating frames of left and right eye view. This signal could be encoded as if it was a conventional 2D 100Hz HDTV signal, allowing prediction between the left and right eye view. The required bit-rate would still be considerably more than a 50Hz HDTV signal, but less than twice as much. A reasonable estimate would be that the stereoscopic signal would require about 1.7 to 1.9 times the bit-rate of a 2D HDTV signal at the same resolution.

The existing HDTV broadcast infrastructure would need to be upgraded to carry this signal; it would appear to be of conventional HDTV resolution, but at 100Hz frame rate. It would be possible to use scalable video coding with temporal scalability so that (say) the left eye view was the base layer, encoded as a conventional 50Hz HDTV signal which could be decoded and displayed by a viewer with a conventional 2D decoder and display. To view the content stereoscopically, a viewer would need a scalable video decoder operating at 100Hz, together with a display capable of accepting and displaying 100Hz video and synchronised shutter glasses.

If full HDTV quality for each eye is not required, it would be possible to use temporal interleaving within the constraints of a conventional HDTV signal for the broadcast stereoscopic signal. This would allow the existing HDTV broadcast infrastructure to carry the signal, but without backwards compatibility for viewers with a conventional 2D decoder and display.

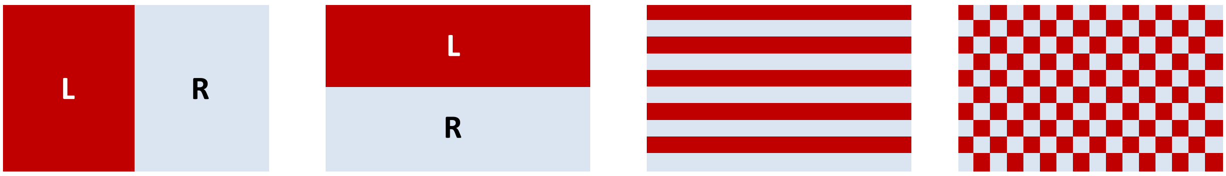
One option would be to transmit the stereoscopic signal as 720p/50 and use frame-synchronised shutter glasses so that each eye would see 720p/25 video. Another option would be to broadcast the stereoscopic signal as a 1080i/25 video signal and use field-synchronised shutter glasses. The odd lines would be seen by one eye and the even lines by the other eye, effectively halving the vertical resolution; each eye would see 540p/25 video, but with full HDTV horizontal resolution.

There is no inherent ability for an interleaved signal to be capable of being watched by a viewer with 2D display. However, it would be possible to use scalable video coding to add this ability, although this would then require a slightly higher overall bit-rate.

### 3.2.4 Broadcasting a Spatially Interleaved Stereoscopic Signal

An alternative means of fitting a pair of reduced quality left and right eye images within the constraints of a conventional HDTV signal is to use spatial interleaving. There is a variety of different ways in which the stereoscopic data can be organised for display on a monitor with matching micro-polarisation, for viewing with polarised glasses, but all effectively represent a halving of the native spatial resolution.

In a "side-by-side" arrangement, the left hand half of the screen displays the video intended for the left eye, the right hand half displays the video intended for the right eye, halving the horizontal resolution. In a "top-and-bottom" arrangement, the top half of the screen displays the video intended for one eye, the bottom half displays the video intended for the other eye, halving the vertical resolution. The "line interleaved" arrangement also results in a halving of the vertical resolution. In the "checkerboard" arrangement, sometimes referred to as "mosaic", the loss of resolution is shared between vertical and horizontal, but the overall effect is still a halving of the spatial resolution.




Side-by-Side Top-and-Bottom Line Interleaved Checkerboard

**Figure 9 Common Polarisation Patterns (indicative)**

These arrangements all allow the existing HDTV broadcast infrastructure to carry the stereoscopic signal, but with the disadvantage that the broadcast format is linked to the display format. Transformation from one format to another is possible, but this results in a significant loss of quality. For example, a side-by-side format has half the horizontal resolution of HDTV, together with full vertical resolution. Transforming this to a top-and-bottom format will then half the vertical resolution, i.e. the overall resolution will be reduced to 25% that of HDTV.

If spatial interleaving were to be used to carry a full resolution stereoscopic HDTV signal for each eye, then the native spatial resolution would need to be twice that of HDTV (in a direction appropriate for the method of spatial interleaving used). A reasonable estimate would be that such a stereoscopic signal would require about 1.7 to 1.9 times the bit-rate of a 2D HDTV signal at the same resolution.

### 3.2.5 Broadcasting 2D plus Stereoscopic Metadata

#### 3.2.5.1 2D plus Difference

In a "2D plus Difference" (or "2D plus Delta") approach, either the left or the right eye view is chosen as the 2D video, which is encoded conventionally. Assuming the SI is correctly configured, a viewer who has only a 2D decoder can view the 2D video normally.

In a stereoscopic decoder, the difference signal is used to modify the 2D video to re-create the view from the other eye. The output from the decoder to the display would normally be a full HDTV resolution stereo pair, although it could also be transcoded to one of the interleaved formats if required for interfacing reasons.

The difference signal can be compressed using either a standard video encoder, e.g. using the MPEG-4 Stereo High Profile [34], or else some other form of data compression. A reasonable estimate would be that the total bit-rate would be about 1.4 to 1.8 times that of the 2D video alone.

A current commercial example of this approach is the TDVision codec [30].

#### 3.2.5.2 2D plus Depth

In a "2D plus Depth" (or "2D+Z") approach, a conventional 2D video representation is broadcast together with a depth map. Assuming the SI is correctly configured, a viewer who has only a 2D decoder can view the 2D video normally. In a stereoscopic decoder, the depth map is used to modify the 2D image to create the left and right eye views of the stereoscopic video.

Figure 10 below shows an example of a 2D video sequence and the corresponding depth map. A dark depth pixel indicates that the collocated video pixel is in the background, a bright depth pixel indicates that the collocated video pixel is in the foreground.

**Figure 10: A video frame and its depth map**

An advantage of the 2D plus depth approach for the stereoscopic viewer is the ability to adjust the degree of depth perception to match their preferences, which could help minimise eye fatigue. A disadvantage of the approach is that the depth map is difficult to create with any great precision, particularly for real-time events. Also, with some implementations the depth tends to look rather unnatural, due to quantisation. However, this quantisation also implies that the overhead of carrying the depth information is relatively low. A reasonable estimate would be that the 2D plus depth signal would require about 1.2 to 1.6 times the bit-rate of a 2D HDTV signal alone, depending on the resolution of the depth information.

A form of 2D plus Depth approach is supported by the MPEG standards; MPEG-C part 3 [5] allows a depth map to be treated as "auxiliary video" and compressed by existing video coding techniques (e.g. H.264/AVC).

### 3.2.6 Broadcasting 2D plus DOT

An extension of the 2D plus depth approach is "2D plus DOT"; a 2D image plus depth, occlusion and transparency data. This additional information adds support for carrying multiview video, i.e. information on how the scene would look from a range of viewpoints, not just static left and right eye views. The resulting multiview data set would, in principle, allow a viewer with a suitable decoding and display device get more of a true 3D experience, where the scene would change when the viewer moves his head from side to side to change his perspective.

The compression techniques required to support this data representation efficiently are still at an early stage development. Assuming that they are successfully developed, the total bit-rate required is likely to be about twice that of the bit-rate of a 2D signal.

However, data compression is only part of the problem. It is even more difficult to create accurate depth, occlusion and transparency data in real-time than a simple depth map. Furthermore, it is likely to be some time before a display device that is capable of supporting more than stereoscopic viewing becomes available at consumer prices.

### 3.2.7 Conclusions on Broadcasting of Stereoscopic TV

The short and medium term implementation of stereoscopic TV is likely to be characterised by a proliferation of different broadcasting approaches whilst broadcasters and consumer equipment suppliers test the market. During this period, it is likely that the ability for an already deployed population of set-top boxes to decode the stereoscopic signal will be important to many broadcasters. The stereoscopic TV signal would therefore be broadcast as if it were a conventional 720p/50 or 1080i/25 HDTV signal using some form of spatial interleaving; temporal interleaving using 720p/50 would also be possible. Regardless of how the interleaving is performed, the overall effect is to half the pixel rate seen by each eye. A better experience for stereoscopic viewers would be obtained if the left and right eye views were independently broadcast at full resolution, but these viewers would then require a new dual decoder set-top box.

By the year 2020, it is assumed that and that the consumer demand for stereoscopic TV will be either proved or disproved. If there is confirmed consumer demand, it is reasonable to assume that both the broadcaster and the consumer would be willing to invest in the infrastructure and equipment necessary to broadcast and display good quality "3D" content. It is therefore assumed in the scenarios explored in Section 7 that full 1080p/50 HDTV resolution will required for each eye in order to meet consumer expectations in this timescale. The subjective impression of resolution of such a system is actually slightly greater than for a 2D 1080p/50 HDTV due to the effect of different information from each eye being processed by the brain.

Broadcasting synchronised left and right eye views is straightforward, and may avoid complicating the production environments for live events, but is rather wasteful in bit-rate.

Temporal and spatial interleaving both suffer from compatibility problems for 2D viewers so, although they are likely to have been used in the earlier market-testing phase, they are unlikely to continue to be used by 2020.

Of the "2D plus metadata" methods, "2D plus difference" is the most practical today. "2D plus depth" has the potential to reduce the required bit-rate further, but the depth map is likely to be difficult to create with any great precision, particularly for real-time events. The extension of the 2D plus depth approach to "2D plus DOT" would extend support from stereoscopic to multiview video, but it is unlikely that display devices capable of delivering multiview video will be available at consumer-friendly prices by 2020.

The different options for stereoscopic 1080p/50 HDTV in a 2020 timeframe are summarised in Table 14 below.

| | Broadcast Format | Able to be watched by viewer with 2D display | Likely Required Bit-Rate Relative to 2D |
|---|---|---|---|
| Independent Left and Right Eye Views | 2 x 1080p/50 | Yes | 200% |
| Temporally Interleaved | 1080p/100 | Possible if scalable video coding is used, but the required bit-rate would then increase | 170 – 190% |
| Spatially Interleaved | 2160p/50 (or some other format at twice spatial resolution of 1080p/50) | May be possible if scalable video coding is used, but the required bit-rate would then increase | 170 – 190% |
| 2D plus Difference | 1080p/50 + metadata | Yes | 140 – 180% |
| 2D plus Depth | 1080p/50 + metadata | Yes | 120 – 160% |
| 2D plus DOT | 1080p/50 + metadata | Yes | 180 – 220% |

**Table 14: Possible Broadcasting Formats for Stereoscopic TV in 2020**

In the scenarios explored in Section 7, the assumptions summarised in Table 15 below will be made for Stereoscopic Broadcasting in 2020. The pessimistic scenario is arguably overly-pessimistic, since forms of 2D plus difference coding are practical today; this scenario is intended to capture a situation in which production issues for live events prevent techniques which are perfectly applicable to non real-time processing being used in general broadcasting.

| | Stereoscopic Broadcasting in 2020 | Assumed Bit-Rate Relative to 2D |
|---|---|---|
| Pessimistic (lowest decile) | Simulcast of left and right eye views | 200% |
| Most Probable | 2D plus Difference (with similar efficiency to that achievable today) | 180% |
| Optimistic (highest decile) | 2D plus Difference (with greater efficiency to that achievable today) | 160% |

**Table 15: Scenarios for Stereoscopic Broadcasting in 2020**

## 3.3 "3D" Content

### 3.3.1 Feature Films

"3D" films have been available in cinemas since the 1920's, with a very distinct peak in popularity around 1953. The popularity declined very rapidly after 1954 and remained low until just before the turn of this century, when the current revival of "3D" began. From 2007 onwards this trend gained considerable momentum, particularly for films using computer graphics (CGI). Twenty-three "3D" films planned to be released in 2009 and the number of "3D" releases in 2010 is expected to exceed those of the 1953 peak.

There is growing support for "3D" in the film industry led by Disney and DreamWorks Animation, who account for about 42% of "3D" productions released or announced to date. DreamWorks Animation has announced that it will produce all of its films in "3D" format from 2009 onwards.

Viewing a new "3D" film in a cinema in the UK currently costs about 20% more than the 2D version. With older films, the premium is even larger, up to 70%. "3D" therefore has the potential to generate significantly more revenue for the cinemas than 2D releases. Cineworld Cinemas, which has the largest portfolio of digital screens of any cinema operator in the UK, has announced that it is installing the RealD stereoscopic system in 144 of its digital screens. Odeon has also partnered with RealD and has "3D" films available at cinemas in 48 cities in the UK. RealD has announced that by July 2009, a total of 300 screens in the UK would have been installed with its system.

The graph in Figure 11 below summarises the annual releases of "3D" films, based on publicly available data [31][32]. It includes confirmed schedules as well as potential releases; future dates are subject to change.

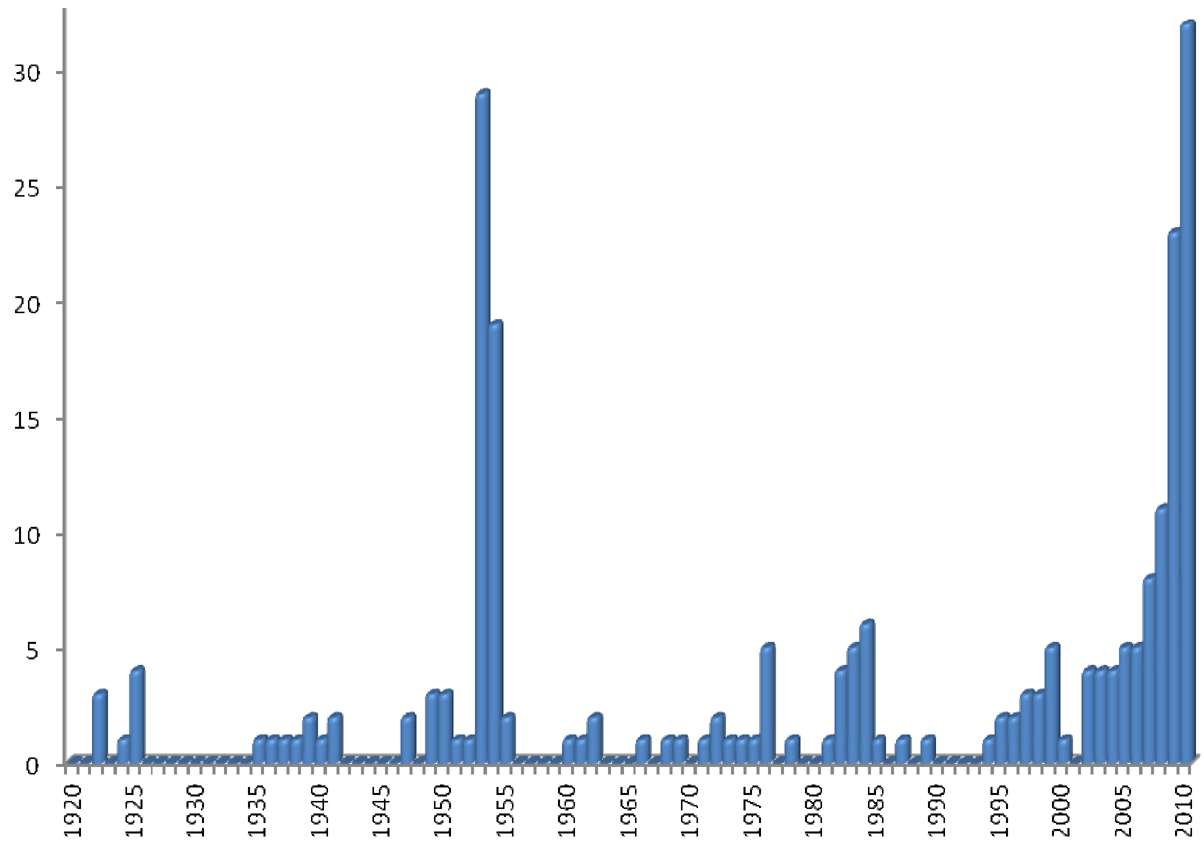



**Figure 11: "3D" feature film releases over time**

### 3.3.2 Packaged Media

A number of movies have already been released in "3D" on both DVD and Blu-ray Disc using a anaglyph techniques. Disney has been particularly prolific in releasing such Blu-ray titles, starting with "Hannah Montana & Miley Cyrus: Best of Both Worlds Concert" in August 2008. However, these suffer from the usual anaglyph colour reproduction problems.

In May 2009, the Blu-ray Disc Association announced that it had formed a 3D task force to study the integration of 3D technology into the Blu-ray Disc format. Studios, consumer electronics manufacturers and information technology companies are all represented in the task force, which will work toward creating a "universal 3D home entertainment specification". One of the initial objectives is to integrate a glasses-based stereoscopic viewing system which will allow 2D video to be extracted when a "3D" disk is played in a current Blu-ray player. The current candidate video codec for this is Multiview Video Coding (MVC) within the H.264/AVC specification [4] (see section 3.4.1).

Panasonic has been particularly active in this work, proposing the use of a stereoscopic system based on its preferred technology of shutter glasses and high refresh-rate displays. In February 2009 Panasonic set up the Hollywood Laboratory Advanced Authoring Center to accelerate the establishment of a "3D Full HD" (3D FHD) Blu-ray format and to work with Hollywood studios in providing development services for 3D FHD Blu-ray titles.

### 3.3.3 Broadcasting

Despite a number of experimental transmissions, there is currently still very little regular "3D" television being broadcast.

In February 2007 in the USA, the National Basketball Association offered live sports events in "3D" with footage delivered via fibre optics to the Mandalay Bay Hotel in Las Vegas.

In Japan, the public broadcaster NHK has started real-time "3D" broadcasting via satellite in December 2007. NHK is now regularly transmitting daily "3D" programming to homes in Japan on one of its satellite channels, BS11.

In March 2008 in the UK, the BBC performed a live test screen of the Rugby Six Nations match between Scotland and England in "3D", delivered via satellite to a small audience. The event was a joint venture between BBC Sport and the3DFirm (a consortium made of Can Communicate, Inition and Axis Films).

In February 2009, NBC in the USA distributed over 100 million "3D" glasses and aired a stereoscopic episode of "Chuck vs. the Third Dimension", subsequently making the episode available both in "3D" and the regular 2D versions for streaming on NBC.com, free of charge. Viewers of the broadcast episode were encouraged to keep their glasses to re-use them for the streamed viewing.

In April 2009, BSkyB test screened a live "3D" broadcast, a performance by the band Keane, as part of a "3D" music event co-produced by Sky, Nineteen Fifteen Productions and Island Records. It was delivered via satellite to a "3D" enabled Vue cinema. BSkyB has not made any announcement regarding "3D" service launch; however in press interviews it confirmed that it was working with TV manufacturers, broadcasters, studios and other content owners to establish the potential for commercial "3D" TV services.

### 3.3.4 Games

There are about 350 games in "3D" format already available that can be played on current game consoles and PCs, including popular titles such as Call of Duty and Tomb Raider. For example, NVidia [33] provides a kit comprising its active shutter glasses and IR emitter for about £140; however a compatible monitor and graphics card would also be required.

The prevalence of early adopters in the games market, the higher acceptance by gamers to use peripherals such as glasses and relative ease of equipment upgrade, may lead to "3D" content achieving mass market adoption for gaming much sooner than for TV broadcasting.

## 3.4 Standardisation Work

### 3.4.1 MPEG

MPEG video coding standards have provided various means of supporting stereoscopic and multiview video for some time; further mechanisms are currently been developed.

Firstly, any of the MPEG video coding standards can be used for the broadcasting of two independent HDTV streams, one representing the left eye view and one representing the right eye view. The synchronisation mechanisms provided by the MPEG-2 Transport Stream [1] are sufficiently accurate to allow the two views to be combined to give stereoscopic effect.

In 1996, the Multiview Profile of MPEG-2 [2] was defined. This profile extended the existing MPEG-2 temporal scalability tools to allow the exploitation of redundancies between views when two (or more) cameras were used. The video from one camera could be defined as the base layer, encoded using the normal MPEG-2 Main Profile, whilst the video from the other camera could be defined as an enhancement layer, encoded using the Multiview Profile to improve the compression efficiency. The base layer provided compatibility for a normal 2D decoder.

In 2007, MPEG-C part 3 [5] was published, which allows a "2D plus depth" approach to be used. MPEG-C part 3 provides a representation format for Auxiliary Video and Supplemental Information, such as depth maps, to allow them to be compressed by normal video coding techniques. An amendment to MPEG-2 Systems was also made to define a new stream type and a specific descriptor for auxiliary video, so that legacy 2D decoders would decode and display only the 2D video component of a 2D plus depth broadcast.

In 2008, an amendment of the H.264/AVC specification [4] was made to support Multiview Video Coding (MVC). This includes the encoding of multiple synchronised views, as would be required for viewing using light field or holographic display, to provide "free-viewpoint TV". The Amendment made no changes to the lower levels of the H.264/AVC syntax, but some backwards compatible changes were introduced at a higher level, e.g. to specify view dependency. Inter-view prediction is enabled through flexible reference picture management, to allow decoded pictures from other views to be inserted and removed from the reference picture buffer.

The general multiview compression problem is considerably more complex than just stereoscopic compression; it is characterised by a huge amount of raw data with a high level of redundancy. It had been hoped that the MVC specification would allow the number of available views to be increased without requiring a significant increase in the total bit-rate over stereoscopic viewing. However, the preliminary results for large numbers of views are rather disappointing; it appears that the required bit-rate remains approximately proportionate to the number of views. In one experiment with up to 8 views, the average improvement in bit-rate relative to simulcasting all of the individual views was only 20%. It is therefore likely that MVC will be better suited to short-term stereoscopic applications, such as with Blu-ray Disc, than as a solution to the longer-term multiview problem.

As with other MPEG standards, profiles are used to define subsets of the syntax and semantics. The first profile to be defined was the MVC High Profile, which supports the same subset of coding tools for inter-view prediction as the existing High Profile of AVC, but not interlaced video formats. More recently, MPEG has defined the Stereo High Profile [34], which was agreed to be put to final draft amendment ballot at the MPEG meeting in London in July 2009. In Stereo High Profile the number of coded views was limited to two, in order to focus on the immediate stereoscopic video applications. Support for interlaced coding tools is also included, to increase backwards compatibility with existing 2D content. The preliminary experimental results show that Stereo High Profile will allow a stereoscopic pair to be encoded at about 170% to 180% of the bit-rate required for a 2D view when progressive video content is used, increasing to about 180% to 190% when interlaced video content is used.

MPEG is continuing to investigate further improvements in coding stereoscopic and 3D content. It issued a "vision statement" on 3D [35] at its February 2009 meeting in Lausanne, followed by an "applications and requirements" [36] document at its July 2009 meeting in London. This stated that MPEG is initiating a new phase of standardization to be completed within the next two years, as a second phase of the free-viewpoint TV framework begun with MVC. The vision is of a "*new 3D Video (3DV) format that goes beyond the capabilities of existing standards to enable both advanced stereoscopic display processing and improved support for auto-stereoscopic N-view displays, while enabling interoperable 3D services*."

The 3DV format targets two specific application scenarios:

- *"Enabling stereo devices to cope with varying display types and sizes, and different viewing preferences. This includes the ability to vary the baseline distance for stereo video to adjust the depth perception, which could help to avoid fatigue and other viewing discomforts."*
- *"Support for high-quality auto-stereoscopic displays, such that the new format enables the generation of many high-quality views from a limited amount of input data, e.g. stereo and depth*."

It is assumed that, due to limitations in the production environment, the 3DV data format will be based on a limited number of camera inputs, possibly as few as two. The intention is that a much larger number of output views would be supported, but without requiring an increase in the transmitted data rate. This de-coupling of the number of views from the transmitted data rate was illustrated as follows:

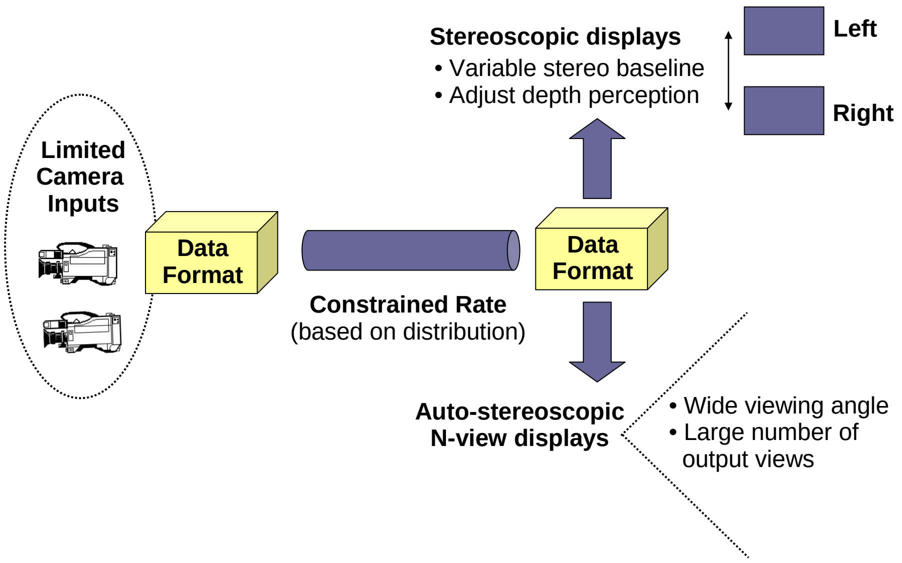



**Table 16: MPEG 3D Video Format Usage**

The overall goal of the 3DV format is to improve the quality of 3D rendering beyond that supported by MPEG-C Part 3, but without requiring the relatively high bit-rates of MVC. One possible approach would be some form of "2D plus DOT"; a 2D image plus depth, occlusion and transparency data. The goal is illustrated as follows in the vision paper:

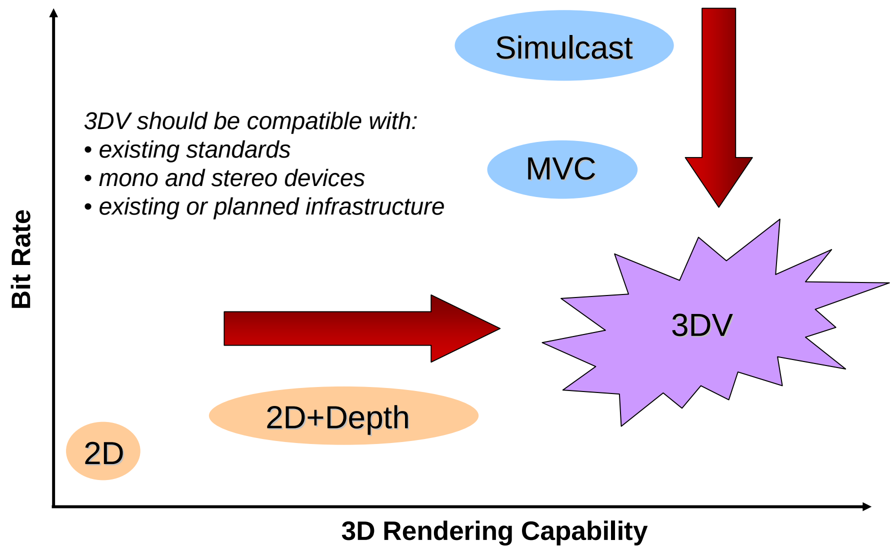



**Table 17: Goal of MPEG 3D Video Format**

### 3.4.2 ITU-T

The video coding experts from ITU-T Study Group 16 Question 6 (VCEG) formed the Joint Video Team (JVT) in collaboration with the MPEG video group in 2001 in order to jointly develop the H.264/AVC standard. More recently, there was some strain in this collaboration arrangement, resulting in MPEG terminating it in February 2009.

There was a meeting between VCEG and the MPEG video group during the June/July MPEG meeting in London to discuss potential future collaboration; it now appears probable that a new joint Collaborative Team will be set up.

### 3.4.3 ITU-R

The ITU-R has begun a study programme on 3D TV to determine the steps that the ITU-R can usefully take to help the broadcasting community. The objective is to agree worldwide Recommendations for standards "*drawing on, but not duplicating, the work done by other relevant bodies*".

ITU-R Study Group 6 has begun work on a new "Study Question" on 3D Television, under Working Party 6C. It has developed a classification system, where 3D technology is defined as first, second or third generation.

- First Generation systems are two-channel systems giving a purely stereoscopic display, e.g. systems based on polarised or shutter glasses.
- Second Generation systems are those that provide a multiview display where more than two views are possible. An example of this would be an autostereoscopic display with a lenticular lens system viewing providing multiple views.
- Third Generation systems include all of the systems based on object wave recording or approximations to object wave recording. Examples of these would include light field or holographic display devices.

### 3.4.4 SMPTE

The Society of Motion Picture and Television Engineers (SMPTE) set up a task force on "3D Home Display Formats". The task force held its first meeting in Los Angeles in August 2008 and published a report in April 2009 [37].

The task force was chartered with defining "*what standards would be needed to establish rapid adoption of stereoscopic A/V content from content mastering to consumption in the home via multiple types of distribution channels (e.g., packaged, broadcast, satellite, cable, internet) with consideration for downward scalability (e.g., portable/mobile).*"

During its initial phase of work, the task force redefined its scope and goals to focus on addressing the standards needed for a "3D Home Master". This is a common intermediate format, based on 1080p resolution, that would be distributed after post production to the ingest points of the various distribution channels for TV content: satellite, cable, terrestrial, mobile TV, broadband and removable media. It is deliberately different from the "3D Cinema Master" for distribution to movie theatres.

The role of the 3D Home Master is illustrated in the diagram below, taken from the report of the Task Force.

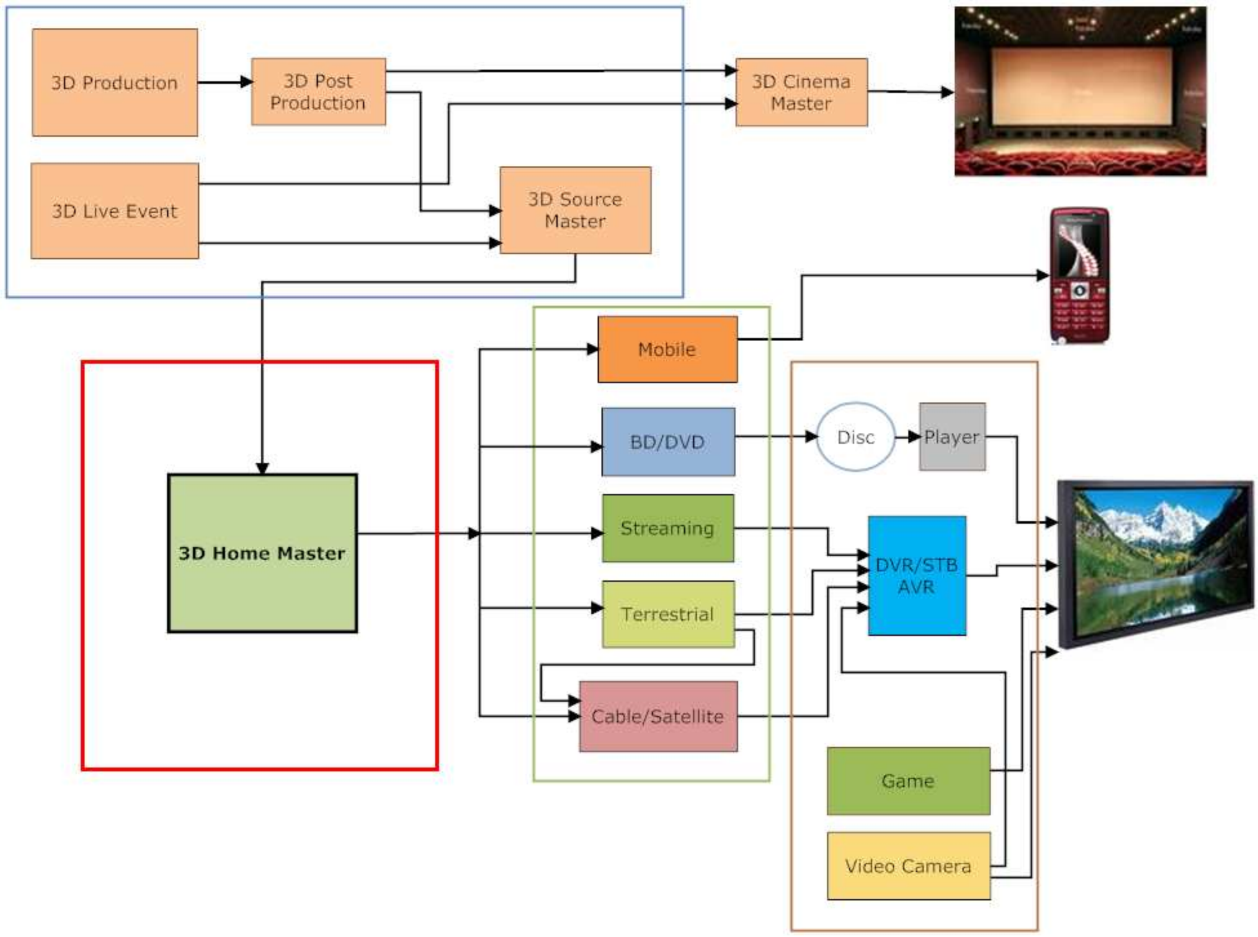



**Table 18: SMPTE 3D Home Master**

The ingest point in each of the types of distribution networks are expected to convert the content in the 3D Home Master into the appropriate format as needed by the distribution system. The 3D Home Master is defined to be an "uncompressed and unencrypted image format or file package derived from a 3D Source Master. The 3D Home Master is intended to be used in the creation of 3D Distribution Data."

The task force first identified various use cases from the perspective of the various entities in the supply chain of the "3D" content to the home, and those use cases that had an impact on the format of the master were used to generate requirements. In generating use cases, priority was given to distribution via physical media, broadcast channels, and online mechanisms.

The task force recommended that:

*SMPTE should undertake standardization effort to generate specifications for the 3D Home Master that meet the requirements listed above. The intent of the standards creation should be to create a single 3D Home Master versus multiple masters. SMPTE should establish liaisons as needed with other relevant Standards Development Organizations (SDOs), as well as industry consortia and forums to:*

*(a) ensure compatibility/interoperability with the technical solution/specifications /standards being developed by those organizations,*

*(b) to foster the use of the 3D Home Master (resulting from future SMPTE standardization activity) for content creation, storage and ingest in downstream authoring and distribution,*

*(c) align terminology and concepts with the work of these organizations, and*

*(d) identify gaps in standards required that fall within SMPTE's charter and generate solutions for these gaps.*

The plan is for the core SMPTE standards to be completed in 2010, potentially leading to compliant equipment in the home in about 2012.

### 3.4.5 EBU

The EBU is holding a series of workshops on 3D jointly with ITU-R and SMPTE. The first of these, entitled "Toward worldwide standards for first and second Generation 3D TV", was hosted by the EBU in Geneva on 30 April 2009.

### 3.4.6 DVB

In November 2008 the DVB Technical Module set up a Study Group on Stereoscopic TV and 3D to gather views on what the DVB might usefully do in this area.

The group reported to the DVB Technical Module in June 2009, with a recommendation that the DVB Commercial Module should be asked to develop a clearer view of the commercial drivers. The DVB Commercial Module, meeting later in June, agreed to set up such a Commercial Study Mission. The initial task will be to gather information from DVB members; it may subsequently generate commercial requirements.

This activity may, or may not, subsequently lead to the inclusion of stereoscopic coding in a future DVB standard. If it does, then the detailed work on adapting the video coding specification for the DVB environment will be performed by the TM-AVC group.

# 4 INCREASING SPATIAL RESOLUTION

## 4.1 HDTV and 1080p

The current High Definition TV (HDTV) transmissions in Europe comply with the DVB Video and Audio Coding Specification [7] using one of two video formats:

- "720p", i.e. 1280 pixels x 720 lines at 50 frames/s (progressive)
- "1080i", i.e. 1920 pixels x 1080 lines at 25 frames/s (interlaced)

There has been fierce debate on the relative merits of the two formats over the years, with advocates of 720p pointing to its better motion portrayal and more efficient compression, whilst proponents of 1080i highlight its superior static resolution. From the point of view of a content provider, the existence of the two formats is an unwanted complication. The best way to be able to provide content for transmission in either format is to produce it in a third format:

- "1080p", i.e. 1920 pixels x 1080 lines at 50 frames/s (progressive)

1080p provides good quality down-sampling to either 720p or else 1080i, hence maintaining the value of a content provider's archive. The latest revision of the DVB Video and Audio Coding Specification [8] also allows the direct transmission of 1080p video to provide an improved quality HDTV service, but this has not yet been adopted by any broadcaster.

Recent top-of-the-range screens will display 1080p, but the limitations of the decoder act as major a barrier to using 1080p for transmission. A 1080p decoder requires double the memory bandwidth of 1080i, which was a significant technical problem when the current HDTV standards were devised. Although no great technical challenge today, this has created a legacy problem with all of the currently deployed set-top-boxes.

A recent evaluation [18] of the options for a future launch of 1080p HDTV within DVB has shown that this is a situation where the use of scalable video coding (SVC) tools may be beneficial. There are three basic approaches that could be followed when launching 1080p services: single layer, simulcast or scalable video. Single layer H.264/AVC 1080p would require the lowest bit-rate; 13Mbit/s was found to give reasonable quality with the software-based encoder used in the evaluation. However, today's 720p/1080i HDTV receivers would be incapable of decoding this signal at all. Adding a reasonable quality 720p simulcast signal to provide backwards compatibility required a further 8Mbit/s, giving a total of 21Mbit/s. Alternatively, 15.4Mbit/s was found to be sufficient when using SVC tools to provide backwards compatibility with a two-layer 720p/1080p signal of the same subjective quality with the same encoder.

On the other hand, it may be that 1080p would not give enough of a step change in quality to justify launching a service using a new video format.

## 4.2 Ultra High Definition TV (UHDTV)

In this document, resolutions higher that 1080p will be generically referred to as ultra high definition TV (UHDTV). A number of other names are used elsewhere: Super Hi-Vision (SHV), Ultra High Definition Video (UHDV), Extreme Definition Video, etc.

Two main classifications are envisaged, representing 4 times and 16 times the resolution of 1080p respectively:

- "4Kx2K", e.g. 3840 pixels x 2160 lines
- "8Kx4K", e.g. 7680 pixels x 4320 lines

The 4Kx2K format was first proposed in the Digital Cinema Initiative (DCI); it offers a resolution comparable to that of 35mm film. The 8Kx4K format was first introduced by NHK in Japan for the "Super Hi-Vision" system [38]; it gives similar resolution to IMAX film.

There are also some variants of these formats, so that "4Kx2K" may also be used to refer to 4096 pixels x 2048 lines, 4096 pixels x 2304 lines or 4112 pixels x 2168 lines. It is not envisaged that any of the UHTV formats will allow the use of interlace.

If the same shorthand nomenclature were extended down to HDTV, then 1080p would be referred to as "2Kx1K".

## 4.3 Perceptual Limit to Resolution

The generally accepted rule of thumb for the smallest object that a person with normal vision can discern is about 1 minute of arc. This was confirmed by a test performed by the BBC in 2004 [24] which measured an average value of 1.054 for 18 observers. The implication is that the pixel structure of a 1080p system would not be visible unless the screen occupied an angle of more than about 18° vertically, corresponding to just over 30° horizontally for a 16:9 screen.

However, there is some evidence that detail that is not consciously discernable is still perceptible, increasing the feeling of reality of the viewing experience. Some recent research by NHK [25] has implied that the threshold for being able to perceive the difference between resolutions may correspond to only about 2/3 of a pixel per minute of arc, depending on the visual acuity of the observers. The NHK tests used 45 observers, all with 20/20 vision or better, who were asked to judge which of a pair of images was of higher resolution.

| | Approximate Horizontal viewing angle for 1 pixel per arc minute | Approximate Horizontal viewing angle for 2/3 pixel per arc minute |
|---|---|---|
| 720p: 1280 pixels x 720 lines | 20° | 13° |
| 1080p: 1920 pixels x 1080 lines | 30° | 20° |
| 4Kx2K: 3840 pixels x 2160 lines | 60° | 40° |
| 8Kx4K: 7680 pixels x 4320 lines | 100° | 70° |

**Table 19: Maximum Horizontal Viewing Angle**

A BBC study of domestic viewing arrangements [23] found that the viewer sat at an average of about 2.7m from the screen. From this distance, the pixel structure of a 1080p system would be assumed to be invisible unless the diagonal screen size was greater than about 65 inches, if 1 pixel per arc minute is used as the threshold. However, if 2/3 pixel per arc minute is used as the threshold for perceptibility, then it implies that the improved resolution of UHDTV would still be perceptible with screen sizes as small as 43 inches.

## 4.4 Industry Trends towards UHDTV

### 4.4.1 Camera Technology

The range of available UHDTV cameras is rather limited at this stage in the market. One of the most popular 4Kx2K cameras at the moment is the "Red One". It can record at several combinations of resolution and frame rates (all progressive scan), as listed in Table 20 below:

| | 16:9 resolution | 2:1 resolution | Frame Rate Range (variable) |
|---|---|---|---|
| 4K x 2K | 4096x2304 | 4096x2048 | 1 – 30 frame/s |
| 3K x 1.5K | 3072x1728 | 3072x1536 | 1 – 60 frame/s |
| 2K x 1K | 2048x1152 | 2048x1024 | 1 – 120 frame/s |

**Table 20: Resolutions currently supported by the "Red One" camera**

The camera does not currently allow full 4Kx2K resolution to be shot at full 50 frames/s frame rate. However, an upgrade to support 4Kx2K at frame rates up to 125 frames/s has been announced for later in 2009.

In June 2008, Aptina Imaging, a division of Micron Technology Inc., announced the MT9E501 [40], a high performance CMOS image sensor designed to support the 8Kx4K "Super High Definition" projects for NHK. The sensor has a resolution of 4112 pixels x 2168 lines and delivers 60 frames per second. It can be used either as a single chip colour sensor for a 4Kx2K camera or else as a monochrome sensor in a multi-chip 8Kx4K camera.

At NAB 2009, JVC announced the KY-F4000 [41], a real-time 4Kx2K, 60 frames per second camera, developed in collaboration with NHK Engineering Services Inc. The camera head has a single 1.25-inch CMOS image sensor of 3840 x 2160 pixels and is separated from the signal processing unit. This has allowed the weight of the camera head unit to be reduced to 3kg, increasing its portability. The camera head and signal processing units can be installed up to 100m away from each other, with interface via a fibre optic cable. It is expected to be used for a range of professional applications such as corporate or military video conferencing, monitoring/control, education and medical services. The KY-F4000 is expected to be available by April 2010 and priced at under $200,000.


**Figure 12: JVC 4K x 2K real-time Camera (KY-F4000)**

### 4.4.2 Displays

Prototype 4Kx2K displays have been demonstrated since around 2006. Several of the major display manufactures have made some move towards introducing such UHDTV products on the market, using both plasma and LCD technologies:

- Toshiba's P56QHD 56" 4Kx2K LCD display is commercially available for about £25,000
- Sharp has announced that the commercial launch of the LK636R3LA19 64" 4Kx2K LCD display is imminent
- Sony and Samsung have both demonstrated prototype 4Kx2K 82" LCD displays
- Samsung has demonstrated a prototype 4Kx2K 63" plasma display
- Panasonic has demonstrated a prototype 4Kx2K 150" plasma display

| | LCD | Plasma |
|---|---|---|
| Samsung | 4Kx2K: 82" | 4Kx2K: 63" |
| Panasonic | | 4Kx2K: 150" |
| Sony | 4Kx2K: 82" | |
| Sharp | 4Kx2K: 64" | |
| Toshiba | 4Kx2K: 56" | |

| | |
|---|---|
| Yellow | Demonstration of Prototype |
| Orange | Launch imminent |
| Red | Commercially available |

**Table 21: Current Market in UHDTV Displays (indicative)**

The current price of the few UHDTV displays that are available is well above the levels required for consumer acceptance. However, it is reasonable to assume that these prices will reduce dramatically over the next decade, following a similar pattern to the corresponding HDTV display technologies over the past decade.

The Japan Ministry of Economy, Trade and industry Technology Roadmap (2007), predicted that consumer 4Kx2K displays would be commercially available from 2011, whilst 8Kx4K displays would be available commercially from 2015 onwards.

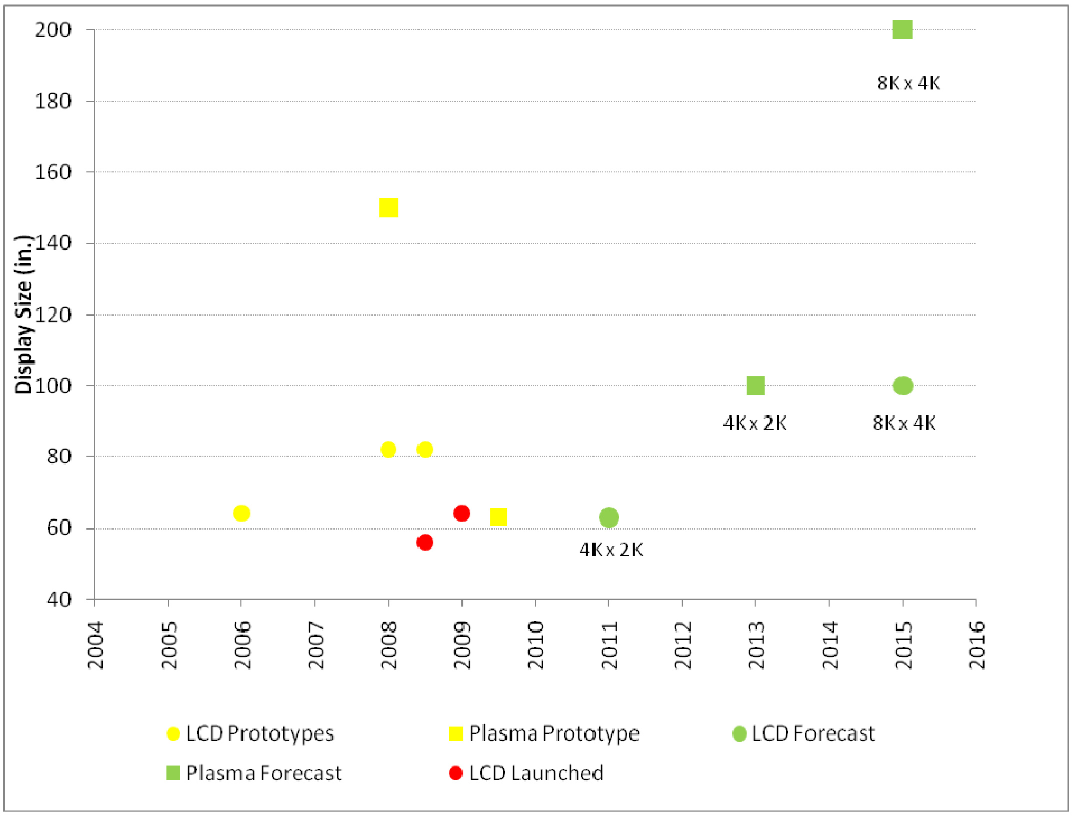



**Figure 13: UHDTV Displays distribution over time (indicative)**

### 4.4.3 Broadcasters

NHK provided the first public demonstration of a prototype ultra-high definition video system back in 2002. Since then, several tests have been carried out in conjunction with other broadcasters such as the BBC and the RAI, including a demonstration of a live 8Kx4K link between London and Amsterdam at IBC 2008.

NHK aims to begin experimental satellite 8Kx4K broadcasts in 2015, building up to full public transmissions in time for the 2016 Olympic Games.

## 4.5 Standardisation Work

### 4.5.1 MPEG

MPEG published a Vision Statement [21] on a possible new High-Performance Video Coding (HVC) codec at its February 2009 meeting in Lausanne. This stated that:
"*MPEG has concluded that video bitrate (when current compression technology is used) will go up faster than the network infrastructure will be able to carry economically, both for wireless and wired networks. Therefore a new generation of video compression technology that has sufficiently higher compression capability than the existing AVC standard in its best configuration (the High Profile), is needed.*"
The goal in compression performance was stated to be "*substantially greater bitrate reduction over MPEG-4 AVC High Profile*" and the range of picture formats would include 4Kx2K and potentially also 8Kx4K.

At its April 2009 meeting in Maui, MPEG issued a Call for Evidence [22] on High-Performance Video Coding (HVC). This stated that:

"*A study has been started on the feasibility of HVC, which is mainly intended for high quality applications, in particular expecting*

- *Performance improvements in terms of coding efficiency at higher resolution,*
- *Applicability to entertainment-quality services such as HD mobile, home cinema and Ultra High Definition (UHD) TV.*

*First results that were reported to MPEG indicate that compression technology giving higher compression performance than AVC might exist for such application cases. It is therefore planned to enter a more rigorous evaluation phase, with a Call for Evidence on new high-performance video compression technology potentially followed by a formal Call for Proposals.*"

Submitters were requested to submit results for various classes of video sequence, including 1080p and 4Kx2K as well as lower resolutions.

A total of 9 responses to the Call for Evidence at 1080p resolution were received by the deadline for analysis at the June/July 2009 MPEG meeting in London; there were a smaller number of responses at other resolutions.

The better performing responses showed bit-rate savings of around 25% to 30% compared to H.264/AVC, when measured by picture signal-to-noise ratio (PSNR), for the three 1080p sequences. However, PSNR measurements can only be regarded as a fairly crude indication of the actual subjective quality. An expert viewing session was therefore arranged to confirm that the better PSNR figures did indeed translate into superior subjective quality. The results of this formal expert viewing, and also various informal viewing sessions, confirmed that there was indeed evidence that a significant improvement in coding efficiency could be achieved by the use of new coding tools.

It was not required to disclose the details of the new coding methods at this stage. However, all of the submissions appear to have retained a fairly conventional top-level architecture, based on a hybrid motion-compensated block transform. The new tools that were mentioned include:

- Extended range of block transform options, including larger block transform sizes (e.g. up to 16x16)
- Extended range of macroblock options, including larger macroblock sizes (e.g. up to 32x32 or even 64x64)
- Enhanced adaptive loop filter (e.g. quadtree-based Wiener filter)
- Increased internal bit depth to reduce rounding errors (e.g. up to 12 bit internal representation)
- Improved variable length coding
- Decoder-side motion vector derivation

After reviewing the results of the Call for Evidence, MPEG issued a Draft Call for Proposals as the first stage of the development of a new compression standard. It did not issue the Call for Proposals publically at this stage, although it did share it with ITU-T VCEG. The next stage will be to finalise the Call for Proposals, probably in collaboration with VCEG. This is likely to lead to a joint analysis of responses in January or April 2010, and consequently to a new video compression standard in about 2013.

### 4.5.2 ITU-T

The video coding experts from ITU-T Study Group 16 (VCEG) formed the Joint Video Team (JVT) together with the MPEG video group in 2001 in order to jointly develop the H.264/AVC standard. More recently, there was some strain in this collaboration arrangement, resulting in MPEG terminating its participation in the JVT in February 2009.

As a sign of the strained state of relations, VCEG began drafting its own requirements for a successor to the H.264/AVC, separately from MPEG, in January 2009. The primary target was very similar to that of MPEG's HVC: a bit-rate requirement of about 50% of H.264/AVC at the same subjective quality and support for video resolutions up to 8Kx4K. However, one difference in emphasis was that VCEG had a greater concern over decoder complexity; VCEG have an explicit secondary target of the new codec being capable of operating at 50% of the complexity of H.264/AVC and still providing a 25% bit rate saving compared to H.264/AVC High Profile at equivalent subjective quality. Another difference in emphasis is that VCEG appears to have a more relaxed attitude towards the timeline for the development of the standard.

There was a meeting between VCEG and the MPEG video group during the June/July 2009 MPEG meeting in London, to discuss what form of collaboration, if any, there may be in the future. The conclusion was that a new joint Collaborative Team should be set up, with the current working title of Enhanced Performance Video Coding (EPVC JCT).

### 4.5.3 SMPTE

SMPTE produced standard 2036-1 [42] on "Ultra High Definition Television - Image Parameter Values for Program Production" in 2007. It added the companion standard 2036-2 [43], "Ultra High Definition Television - Audio Characteristics and Audio Channel Mapping for Program Production" in 2008.

# 5 OTHER DISPLAY ENHANCEMENTS

## 5.1 Increasing Frame Rate

The 50Hz field rate (i.e. 25Hz frame rate) used for analogue TV in Europe was originally chosen more because of its convenient linkage with the frequency used for mains electrical power, rather than for any consideration of psycho-visual optimisation. Although mains frequency is no longer an important issue with digital TV technology, the historical frame rates have been maintained, so that the world is now divided into areas that use the 50Hz family and those that use the 60Hz family of frame rates.

When moving from interlaced SDTV to progressive HDTV formats such as 720p or 1080p, the frame rates are doubled from 25Hz to 50Hz by the removal of interlace. This provides more realistic motion portrayal, which is particularly noticeable with sports material.

When introducing UHDTV, it would be possible to consider doubling the frame rates again, to 100Hz. Many top of the range HDTV sets today already use internal frame doubling to 100Hz to reduce the visibility of flicker. This technique works satisfactorily in static areas, but operating the entire broadcast chain at 100Hz would extend this benefit to further improving the motion portrayal.

Alternatively, UHDTV could be used as an opportunity to launch a new family of frame rates. A 75Hz, 150Hz and 300Hz family of frame rates could provide a convergence point for the traditional 50Hz and 60Hz families.

## 5.2 Increasing Aspect Ratio

The old 4:3 format for analogue TVs was replaced by the 16:9 "widescreen" format with the move to digital TV and HDTV.

However, 16:9 corresponds to an aspect ratio 1.78, whilst most movie titles use an ultra widescreen aspect ratio of 2.33 or 2.35. The viewer looking at movies filmed in an ultra widescreen format such as CinemaScope on a 16:9 HDTV therefore has to accept either black bars at the top and bottom of the screen or else cropping of the right and left of the picture.

In principle, there is no reason why there could not be a future transition of domestic displays from 16:9 to an ultra widescreen. An appropriate time for this might be to combine it with the transition from HDTV to UHDTV, particularly if viewing movies was an important driver for the transition.

To date, there has been limited industry support for ultra-widescreen consumer televisions. JVC announced an ultra-widescreen prototype TV in 2007, but it never materialised commercially. LG has produced ultra-widescreen displays for commercial use, but only at low resolutions of up to 1366 x 480.

More recently however, at CES 2009, Philips demonstrated a prototype 56" LCD TV (Cinema 21:9) that displays 2.33 movie material in high definition (2560×1080), with the aim giving a true anamorphic cinematic viewing experience in the home. It has to either stretch traditional 16:9 HDTV content to fill in the screen or else add black bars on the sides. Commercial release for this TV has been announced for summer 2009, at prices of about £3,500. It remains to be seen if this is any more of a commercial success than previous attempts at introducing ultra widescreen displays.

## 5.3 Increasing Chrominance Resolution

Established broadcasting practice is to transmit video which represents chrominance information with half the resolution, in both the horizontal and vertical direction, as that of the luminance information. For historical reasons, this format is designated as 4:2:0 (where the first number represents the sampling frequency of the luminance, whilst the second and third numbers represent the sampling frequency of the chrominance on odd and even lines respectively).

Video content is generally originally shot with the same vertical chrominance resolution as that of luminance, but with half the horizontal resolution, designated as 4:2:2. Film content is generally shot with the same chrominance and luminance resolution, designated as 4:4:4.

In principle, a future broadcasting standard could increase the relative resolution of the chrominance information to 4:2:2 or even 4:4:4. However, the disparity between the luminance and chrominance resolution represented by current practice appears to be well-matched to the characteristics of the human eye.

## 5.4 Increasing Bit depth

The video information in digital broadcasting transmissions is currently represented with 8 bit accuracy, although 10 or 12 bit representation is generally used in digital production. The quantisation due to 8 bit representation becomes most visible when there is a gradual but consistent variation of colour, e.g. in an area of clear sky at sunset.

The quantisation effects are likely to become more apparent as video resolution is increased. The introduction of UHDTV is therefore likely to be combined with an improvement of the bit depth. However, it is likely that some form of adaptive quantisation could be used. Since contouring due to quantisation is often most visible on relatively easy to encode video, this is unlikely to require any significant increase in bit-rate.

## 5.5 Improving Colour space

The colour space for HDTV systems has been based on ITU-R Recommendation BT.709 [20], "Basic parameter values for the HDTV standard for the studio and for international program exchange", since its adoption in 1990. Rec. 709 represented a major step forward in replacing the range of different colour gamuts previously in use with various SDTV systems worldwide, which was subsequently also endorsed by the computer industry as "sRGB". However, it was still designed around the limitations of the phosphors in CRT-based display technologies and hence it does not allow all real-world colours to be reproduced.

Many modern consumer display devices are already capable of displaying a wider colour gamut than is permitted by Rec.709. In 2006, IEC adopted the "xvYCC" colour gamut [44] , IEC 61966-2-4, which is backwards-compatible with ITU-R Rec. 709 but which allows a wider range of colours to be reproduced. There are some areas of colour-space where the differences are quite noticeable, e.g. shades of deep rose-red. This standard is supported by several consumer display manufacturers and it is expected that there will be increasing momentum behind its wider adoption.

## 5.6 Standardisation Work

The majority of the display enhancements discussed in this section are already supported by the current generation video coding standards, although they are not widely adopted in the current generation of encoding hardware.

For example, the H.264/AVC coding standard already supports frame rates up to 172 frames per second, 4:2:2 and 4:4:4 chrominance representation, up to 12 bit representation and the use of the xvYCC colour gamut.

## 5.7 Conclusions on Other Display Enhancements

If and when UHDTV is launched, there are a number of other display enhancements that could be included at the same time. In the scenarios explored in Section 7, the following assumptions will be made for UHDTV broadcasting in 2020:

- The normal frame rate used for broadcasting will remain 50Hz
- The aspect ratio will remain 16:9 and the typical UHDTV video format will be 3840 pixels x 2160 lines
- The overall chrominance resolution will continue to be a quarter that of luminance in the transmitted signal, i.e. 4:2:0
- Increased bit depth will be used, but in an adaptive manner so that there is no resultant increase in bit-rate
- Enhanced colour gamut will be used, but will not require any significant increase in bit-rate.

# 6 CONTENT DELIVERY

## 6.1 Storage

### 6.1.1 Hard Disk

Hard disk storage is a key component in a Personal Video Recorder (PVR), to allow the consumer to record digital television programming for subsequent viewing. For typical consumer use, a capacity corresponding to about 20 to 40 hours of programming is probably required, regardless of whether the content is SDTV, HDTV or UHDTV.

The first commercially available hard disk system was the IBM 350 disk storage unit, launched in 1956 as a data storage component for an IBM accounting computer. It was leased for an annual fee of about £25,000 and it contained a stack of 50 disks giving a total capacity of around 4.4 MB.

Since then, hard disk capacities have rapidly increased whilst prices have steadily decreased, so that a 1TB drive currently retails for under £100. Han-Kwang Nienhuys [45] has plotted the following graph of hard disk capacity over time, showing an approximately exponential rate of increase of capacity over a 40 year period.

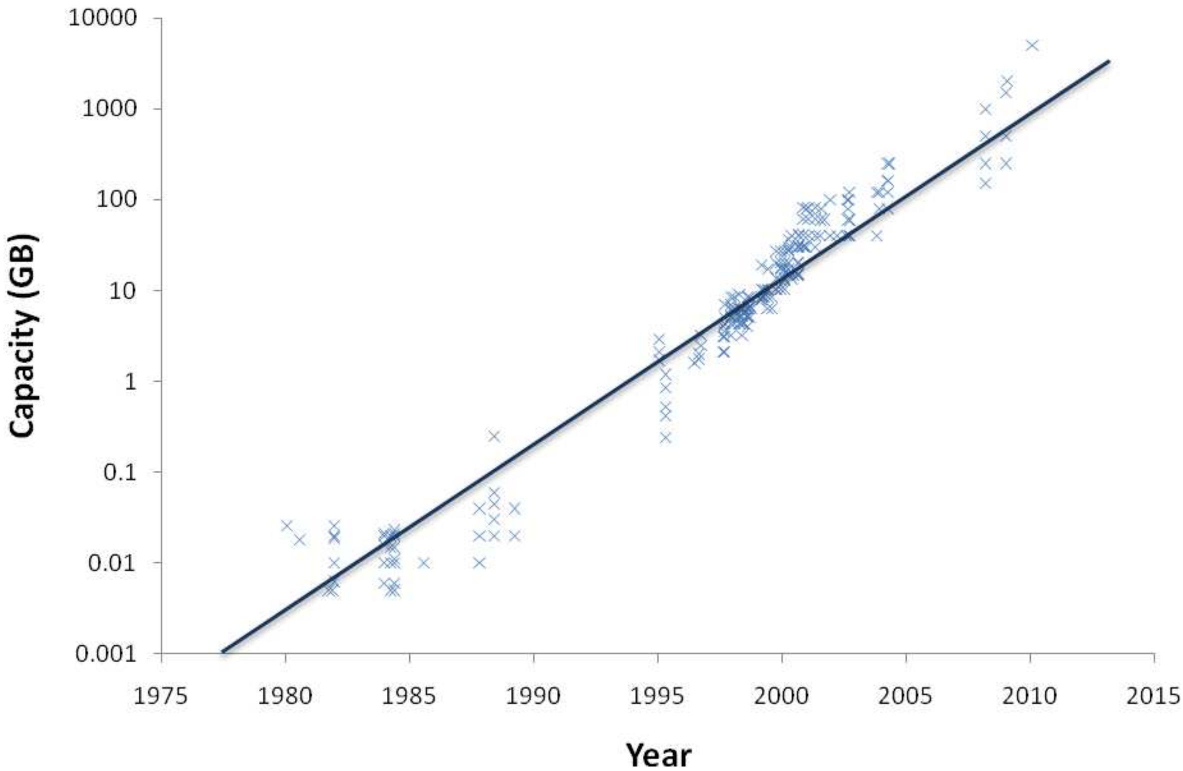



**Figure 14: Hard drive capacity over time**

It is reasonable to expect that the trends of increasing capacity and decreasing cost will continue in the future. There are some indications that the rate of increasing capacity may start to decrease after about 2015, as the physical limits of magnetic storage start to become more evident, but it may be that new technological approaches will allow these limits to be overcome.

### 6.1.2 Optical Storage

Optical storage is an important means of storing individual films or other audiovisual events for distribution as packaged media. Recordable versions of optical discs are also useful for personal archiving. The required capacity corresponds to the typical duration of a film, say 2 to 3 hours (since multiple discs can be used to record the occasional longer film).

The first major commercial exploitation of optical disc technologies was the Compact Disc (CD) launched jointly by Philips and Sony in 1982, which has a net user capacity of about 700MB.

The second generation was the Digital Versatile Disc (DVD), first launched in 1996. The DVD has a large variety of options with different capacities; the typical DVD-9 is a single-sided dual-layer format with a capacity of around 8.5GB.

The third generation of optical storage is represented by the Blu-Ray disc and HD-DVD formats. The capacity of a standard size dual layer Blu-Ray disc is 50GB. Blu-Ray disc players were launched in 2006, but initial sales were slow due to high prices and consumer reluctance to buy whilst the "format-war" with HD-DVD continued. Since February 2008, when Toshiba withdrew its support for the HD-DVD format, sales of Blu-ray players have increased significantly.

Work has now begun on a fourth generation of optical discs, targeted at a capacity of at least 1TB by 2015. The graph of optical disk capacity over time is therefore as illustrated in Figure 15 below, showing an approximately exponential rate of increase in capacity over time.

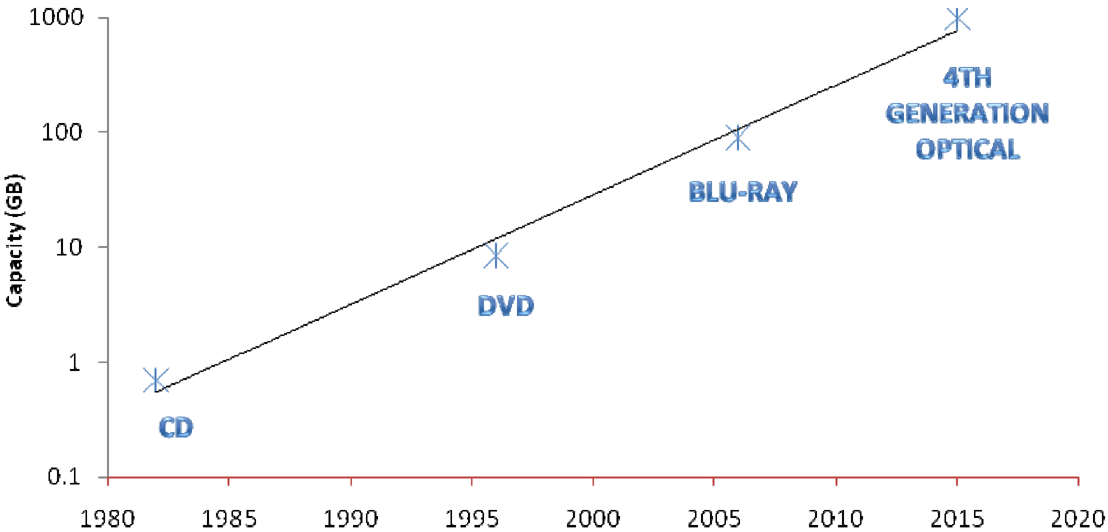



**Figure 15: Optical Disc Storage capacity increase over time**

In April 2009, General Electric (GE) announced that it had achieved a major breakthrough holographic disc technology. Holographic patterns can utilise the third dimension of the disc by encoding information in virtual layers, thus giving a much higher data density. Conventional optical discs store information by using a relatively high power laser to create microscopic pits with reduced reflectivity. GE's holographic technique uses a media which increases its reflectivity when written, yielding up to 50 virtual layers on the disc. GE estimates that 500GB discs based on holographic techniques will be available by the end of 2011.

Holographic recording is just one of the new technologies being examined. The International Symposium on Optical Memory (ISOM) defined the target for Fourth Generation optical discs as a capacity of at least 1TB and recording speed of at least 1Gb/s. ISOM cited four technologies that showed the potential to achieve this goal by 2015: holographic recording, multi-layer recording, near-field recording and Super Resolution Near-field Structure (Super RENS) technology.

Looking even further ahead, other types of optical technology may become practical. For example, NEC have been investigating the possibility of creating a Protein-Coated Disc by coating an optical disc with a special light-sensitive protein made from a genetically altered microbe, which in principle would allow the storage of up to 50 TB on one disc.

### 6.1.3 Flash memory

Flash memory is a specific type of non-volatile memory that can be electrically erased and reprogrammed in large blocks. Flash memory can be used as a hard drive replacement in a PVR, in the form of a solid-state drive. Compared to traditional hard drives, solid-state drives generally have better access times, greater transfer speeds, consume less power and are more reliable. The main drawback is their relatively high cost.

USB memory sticks could also provide a scratch-proof alternative to optical disks for distributing packaged media. The main impediment is again cost, although this is dropping rapidly. At the time of writing, the lowest cost per GB is given by the 16GB memory stick, which retails for about £16. Larger capacities of up to 256GB are also available, although the higher capacity devices currently command a premium price.

The increasing capacity is achieved through a combination of shrinking the geometry of the NAND flash memory and increasing the number of bits that are stored in each cell using a multi-level cell arrangement. This has resulted in a rapid increase in capacity combined with a reduction in cost. If prices continue to fall in the same manner that they have done for the last decade then it can only be a matter of time before such devices could provide a viable alternative to optical discs as means of distributing UHDTV content.

### 6.1.4 Conclusions on Storage

The capacities of hard disks, optical storage and flash memory are all projected to continue to increase, whilst prices are projected to continue to decrease. There are some indications that the most rapid rate pace of improvement will be for solid state memory, followed by optical storage and then hard disks.

Storage media technologies appear to be progressing at a sufficiently rapid rate that they will not impede the launch of UHDTV:

- Current hard disk technologies are already capable of meeting the requirements of UHDTV recording and playback in a PVR.
- An increase in the capacity of optical discs will be required before they are capable of storing a typical film at UHDTV resolution, although this is well within the projected development of the technology by 2012.
- The rapid rate of progress in reducing the cost of solid state memory may result in this technology being used either in place of hard disks in PVRs or in place of optical discs for the distribution of UHDTV packaged media by 2020.

## 6.2 Broadband IP Networks

### 6.2.1 Overview of IP Networks

Broadband IP delivery, via either wired or wireless networks, is becoming an increasingly important alternative to broadcast networks for delivering audiovisual content. Wired IP networks installed so far have predominantly been based on the DSL family of technologies in telecommunications networks and on the DOCSIS family of technologies in cable systems. In the future, these technologies are likely to be replaced by more fibre oriented infrastructures.

More recent technology specifications are tending to become increasingly spectrally efficient and also more flexible in their ability to make variable use of the operating spectrum, depending on availability. With all these technologies, the actual bit-rate that the consumer receives is rather less than the headline "maximum bit-rate" figure quoted by the network operator. The actual bit-rate received depends on a number of factors:

- Distance from the consumer's end device to the network operators termination equipment.
- Number of users sharing the same capacity, sometimes called the contention ratio. This is predominantly determined by the design characteristics of the network, e.g. "cell size" or "homes passed per node".
- Economics of deploying a given technology per cell or node. In general, the cost tends to be higher for smaller cells, so operators frequently deploy cells just ahead of the demand curve.

It can often be difficult to directly compare one technology against another, as operating criteria are rarely identical.

### 6.2.2 Wired Broadband Networks

#### 6.2.2.1 Telecommunications Networks

Telecommunications networks, based on twisted pairs of copper wire, were originally designed and installed to carry voice frequencies over distances of several km from the local telephone exchange to the home. They can be used to provide broadband data services, typically using one of the DSL family of standards, via a modem in the customer premises and a Digital Subscriber Line Access Multiplexer in the exchange. The xDSL technologies use higher frequencies than voice services, so the signals attenuate more rapidly with distance from the exchange.

Most households in the UK can already use ADSL [46] modems to achieve a basic broadband experience, i.e. at least 2Mb/s. However, this is insufficient for broadcast-quality video streaming. ADSL2 [47], ADSL2+ [48] and VDSL [49] have all extended the basic ADSL specification to improve the bit-rate, although invariably this has been associated with even shorter useable distances. BT is in the process of upgrading every telephone exchange in the country to support ADSL2+ by 2011, and it estimates that more than 50% of British households have access to ADSL2+ by the end of March 2009. However, the maximum bit-rate of 24Mb/s would only be achievable for those households that are within about 1km of the exchange.

Providing increased bit-rates for the consumer therefore requires extending the fibre network closer to the home to reduce the length of the twisted pair connection. The "fibre to the kerb" architecture retains the twisted pair only to connect the home to the street cabinet. BT announced in July 2008 that it will begin deploying fibre to the kerb technology, with VDSL from the street cabinet to the home, capable of offering speeds of up to 40Mb/s. It predicts that 40% of UK homes will be able to receive this service by 2012.

Ultimately, a fibre-to-the-home (FTTH) or fibre-to-the-building (FTTB) system would replace the external twisted pair network entirely. This would allow a network operator to offer download speeds in excess of 100Mb/s, but it is very expensive to deploy.

The FTTH Council issues twice-yearly reports on the level of fibre penetration [50]. According to the February 2009 report, the rollout of FTTH and FTTB is remains most advanced in Asia, with

44% of the market in South Korea, 28% in Hong Kong and 27% in Japan. The most developed fibre deployments in Europe are in Sweden, Norway and Slovenia, but all represent less than 10% of their respective national markets. Figure 16 below, extracted from the FTTH Council report, shows the roll-out of FTTH and FTTB in all counties where more than 1% of households are connected directly into high speed fibre networks.

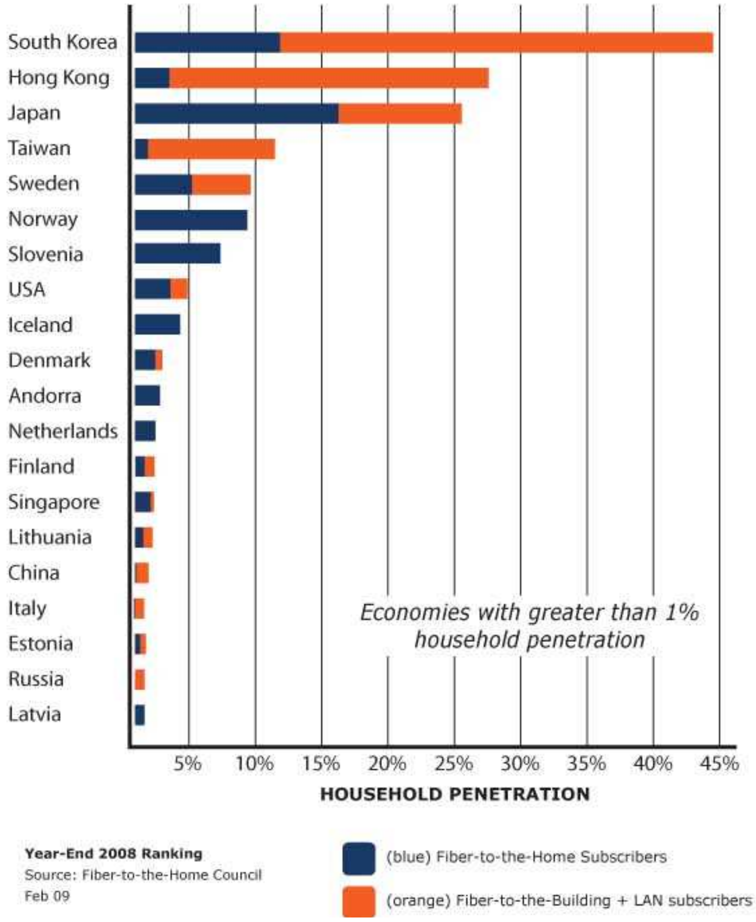



**Figure 16: Rollout of Fibre-to-the-Home and Fibre-to-the-Building**

### 6.2.2.2 Cable Networks

Cable networks, based on coaxial cable, were originally designed and installed to carry analogue TV services. They can be used to provide broadband data services, typically using one of the DOCSIS or EuroDOCSIS standards, via a cable modem in the customer premises and a Cable Modem Termination System at the cable head-end.

Current hybrid fibre-coax (HFC) networks typically deploy fibre to nodes of between 500 and 2000 homes. The connection from the node to the home is the coaxial cable that is shared with the other homes on the node.

EuroDOCSIS 2.0 [51] uses an 8MHz band of spectrum that would originally have been allocated to a single analogue TV channel in order to provide the downstream service. EuroDOCSIS 3.0 [52] increases the downstream broadband capacity by enabling up to four such channels to be bonded together. In the UK, Virgin Media is currently in the process of upgrading its network from EuroDOCSIS 2.0 to EuroDOCSIS 3.0.

Virgin Media already offers bit-rates up to 50Mb/s to customers in the upgraded sections of their network and it has stated that 50Mb/s will be available to all 12.6 million UK homes covered by their network by the summer of 2009. In April 2009 Virgin started a six month pilot trial of a 200Mb/s bit-rate service with 100 customers in Ashford, Kent. The pilot trial will include testing high definition and "3D" television services.

### 6.2.3 Wireless Broadband Networks

#### 6.2.3.1 Mobile Telephony

There are a number of different, and incompatible, families of mobile telephony technologies used worldwide. GSM/UMTS (Global System for Mobile Communications / Universal Mobile Telecommunications System) is the most widely deployed family, originating in Europe and now accounting for over 80% of global mobile users. The CDMA family of standards (Code Division Multiple Access) accounts for about 10% of global users, mostly in the USA. Japan and China have produced their own equivalent technology standards, but these have not been adopted outside of their home territories.

Each of these families is sub-divided into generations (e.g. "3G" for the current state of the art), although these are often not well-defined terms. Rather than significant step changes in capability, the evolution of mobile technologies and standards have been characterised by continual incremental improvements, introduced so that the incremental cost for operators moving up to the next stage can be relatively low, e.g. by adding EDGE (Enhanced Data-rates for GSM Evolution) to a GSM network. Similarly, the current 3G networks continue to evolve incrementally, e.g. by adding capabilities such as HSPA (High-Speed Packet Access).

With the addition of HSPA to a 3G system (upgrading it to "3.5G"), the maximum peak rates for data services is increased to 14 Mb/s in the downlink and 5.8 Mb/s in the uplink. However, the actual data rates that an individual consumer can expect to receive in a practical scenario will be a small fraction of this nominal figure.

Receiving broadcast-quality video streaming via mobile telephony networks is not likely to be possible until "4G" networks roll out. Although there is as yet no universally agreed definition of precisely what "4G" means, one commonly expressed target is a data rate of up to 100 Mb/s between any two points in the world. It remains to be seen if and when this target is achieved.

#### 6.2.3.2 Wi-Fi

The Wi-Fi (IEEE 802.11) family of technologies has experienced rapid growth, especially within the home environment. Network operators, including cable and mobile phone operators, have also offered hotspot services in public areas such as airports and hotels for a number of years. Initially these systems were delivered from a single access point / single backhaul, but as they have grown they are increasingly being deployed using mesh based technologies, where multiple access points transfer data packets to the nodes that have the backhaul connection.

The long-awaited IEEE 802.11n amendment is due to be approved in November 2009 according to the IEEE 802.11 working group project timelines [53]. Work on the 802.11n standard dates back to 2004 and many "Draft N" products are already available. This amendment promises a significant increase in the data rate, increasing the maximum raw data rate from 54Mb/s up to 600 Mb/s.

Many organisations are looking at using Wi-Fi services to complement their 3G mobile telephony data services; Wi-Fi can provide better data rates over limited coverage areas when the end user is temporarily stationary, whereas 3G systems can provide access over much larger coverage areas, especially in rural areas and when the end user is more mobile.

It is also possible to use Wi-Fi alone to provide wireless broadband coverage across a large area through a coordinated deployment of multiple access points in public locations. A good example of this is the "Optimum WiFi" service in New York [54], which provides Wi-Fi access in thousands of public locations throughout the New York metropolitan area, including train platforms, car parks, shopping centres, sports fields and parks. However, as a means of providing wide-area wireless broadband services, the connection-oriented WiMAX (Worldwide Interoperability for Microwave Access) is probably a more direct alternative to mobile telephony networks than the connectionless Wi-Fi technology.

#### 6.2.3.3 WiMAX

The WiMAX [55] Forum is an industry-led organisation that has been formed to certify and promote the interoperability of broadband wireless products based upon IEEE 802.16 [56].

The original IEEE 802.16 specification, published in 2001, was primarily intended for telecom backhaul applications in line-of-sight configurations using spectrum above 10 GHz. Subsequent amendments and revisions have extended the capability of the specification below 10GHz, improving non-line-of-sight capability. A particularly important amendment is IEEE 802.16e-2005, which added support for mobility. The WiMAX Forum expects mobile network deployments to have a typical cell radius of about 3km, whilst network deployments intended purely for fixed reception would have a typical cell radius of about 10km.

Fixed WiMAX subscriber units are available in both indoor and outdoor versions. Indoor units are comparable in size to a cable modem or xDSL modem, whilst outdoor units are roughly the size of a laptop PC; their installation is comparable to the installation of a residential satellite dish. With the potential of mobile WiMAX, there is an increasing focus on portable units. This includes handsets similar to mobile phones, PC peripherals such as USB dongles and embedded devices in laptops. Mobile WiMAX devices typically have omni-directional antennae which are of lower gain than the directional antennas that are typically used for fixed reception.

The 802.16 specifications apply across a wide range of the RF spectrum, and WiMAX could function on any frequency below 66 GHz. There is no uniform global licensed spectrum for WiMAX, and gaining access to sufficient harmonised spectrum across enough territories to enable the roaming that mobile users now expect is a major challenge. In an effort to increase interoperability and decrease cost, the WiMAX Forum has published three licensed spectrum profiles: 2.3 GHz, 2.5 GHz and 3.5 GHz. In the USA, the largest segment of assigned spectrum is around 2.5 GHz.

In 2008 three major U.S. cable operators, Comcast, Time Warner Cable, and Bright House Networks agreed to heavily invest into a new WiMax-powered "mobile broadband company" which also brought together the two largest separate WiMAX companies Sprint Nextel and Clearwire. Google and Intel also invested in the WiMax venture. The company launched in Portland, Oregon on 6 January 2009 under the brand name Clear. Clear's residential modems are being marketed as providing 6 Mb/s download speeds while mobile Internet customers are being promised up to 4 Mb/s download speeds. On 5 March 2009, Clear announced that it would expand its WiMAX network to 9 additional markets in 2009, with additional cities to be added in the future.

Building new networks for broadband wireless requires substantial capacity; prior to the huge investment by Comcast et al, many of the other WiMAX networks had to be subsidised by public funds. Despite the commercial challenges, WIMAX is likely to remain an important technology that will play a part in bringing broadband access to places that other technologies struggle to justify economically, for example the last mile in rural areas.

### 6.2.4 Conclusions on Broadband IP Networks

A wide range of different technologies are available to provide both wired and wireless (fixed or mobile) access to broadband IP networks. Although the details of the technologies continue to evolve over time, wired reception looks likely to continue to retain an order of magnitude advantage over wireless in download bit-rate, with both increasing by about an order of magnitude every 5 to 10 years. This is illustrated in the following diagram (Copyright ©2008 Rysavy Research, from "Mobile Broadband Spectrum Demand" report December 2008 [57]).

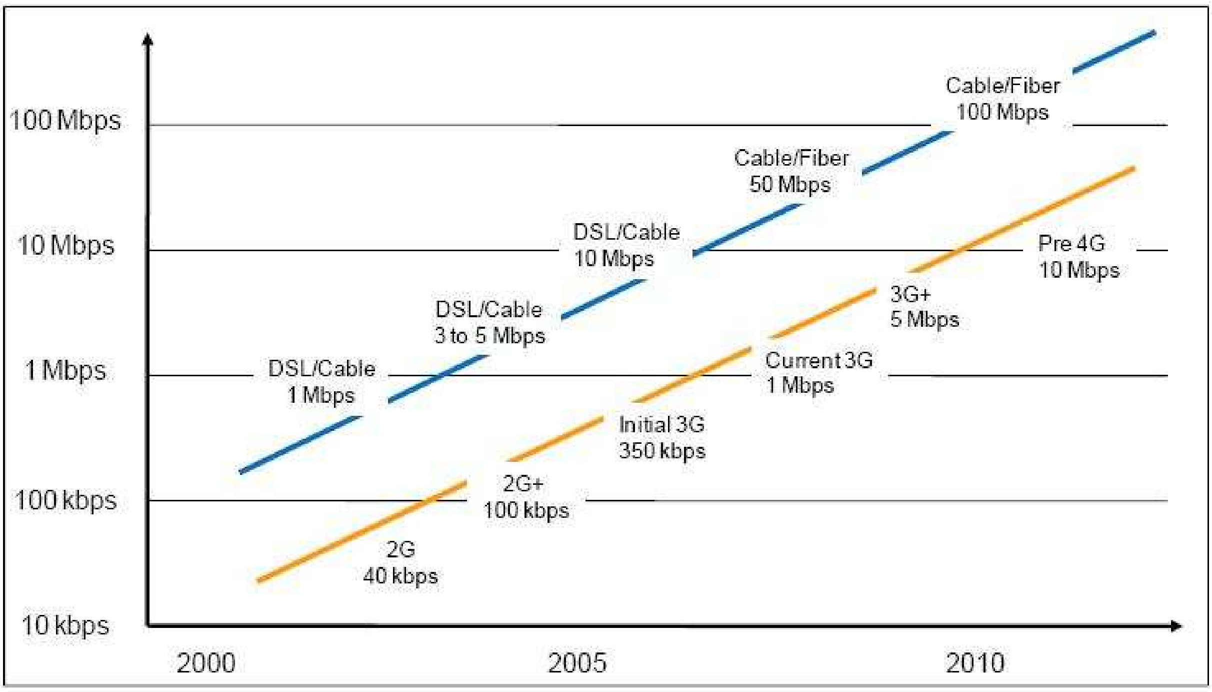



**Figure 17: Broadband Data Rate over Time**

The bit-rates available from the fastest of the currently available wired broadband access technologies are already sufficient for HDTV and even UHDTV. Wired broadband IP networks can be expected to be an increasingly important alternative to broadcast networks for delivering audiovisual content, particularly for personalised or video-on-demand services.

The fastest of the wireless technologies available today is technically capable of delivering HDTV, but only in such constrained circumstances (i.e. the virtual absence of other users in the cell) that it is does make economic sense. Although the technical capabilities will improve with time, it remains doubtful whether providing such HDTV, let alone UHDTV, services to display devices that are small enough to be portable would be sufficiently attractive to persuade users to pay the required premium rates. What probably makes much more sense is using wireless technology for access only when there are no good wired alternatives, which could include rural areas.

## 6.3 Broadcasting

### 6.3.1 Overview of Digital Broadcasting

Digital direct to home broadcasting started over 15 years ago, firstly from satellite, then in the late 1990s from terrestrial transmitters.

The systems used represented a considerable step forward compared to the analogue transmission systems used previously. Specifically, they allowed many more channels to be deployed in the same bandwidth, as well as requiring significantly lower signal strength at the receiver.

However, the performance of the systems was known to be not fully optimal. Their performance was limited by the amount of signal processing power which could be economically implemented in consumer receivers of the time, and also to some extent by the state of knowledge about coding and modulation systems.

More recently, a second generation of systems has begun to be deployed, with significant performance improvements. It is not yet clear whether these systems perform so close to theoretical limits that no further improvement is likely, or whether there is still room for a third generation of systems.

#### 6.3.1.1 Theoretical limits

In a channel of given bandwidth, there is an upper bound on the maximum error free data rate that can be transmitted through the channel. This is a function of both the bandwidth of the channel and the signal-to-noise ratio at the receiver and is known as the Shannon limit, after its discoverer, Claude Shannon. As an example, with a signal-to-noise ratio of 0dB (signal and noise power the same) the maximum data rate that can be transmitted without error is 1 bit per second per Hertz of bandwidth. The limit only applies to an idealised channel of strictly defined bandwidth, and affected by Additive White Gaussian Noise (AWGN). Satellite channels are a reasonable approximation to an AWGN channel, however terrestrial channels are not.

Satellite systems deliver less than the theoretical maximum data rate in a given bandwidth for two main reasons. The first is that, until recently, the best known coding and modulation systems gave a performance some distance from the Shannon limit. The second is that, to allow the implementation of practical demodulators, the symbol rate of a data transmission has to be lower than the bandwidth ideally allows

In the case of terrestrial transmission systems, it is much more difficult to define what the theoretical limits are, since they are very dependent on characteristics of the channel, which is highly variable.

### 6.3.2 Satellite Broadcasting Standards

#### 6.3.2.1 DVB-S

DVB-S [11] is the original satellite broadcasting system. It uses QPSK modulation and a combination of a simple convolutional code and a Reed Solomon block code for error correction. The system allows a trade off between the bit rate in a given channel and the signal strength needed to receive it by changing the ‘rate’ of the convolutional code – i.e. the proportion of the total data capacity used for error correction.

For example, a typical 36 MHz satellite transponder operating at an EIRP of 51dBW may use:

- Symbol rate of 27.5 Mbaud
- QPSK modulation
- 2/3 FEC Rate

This combination gives a useful data rate of 33.8Mb/s.

Soon after the development of DVB-S, the DVB-SNG specification was developed. This was intended for professional applications such as Satellite News Gathering, and allowed higher data rates in a given bandwidth, at the expense of requiring much bigger dishes for reception. This was achieved mainly by the use of higher order modulation (8PSK and 16QAM) and can be regarded as an extension of DVB-S.

At the time DVB-S was in development, similar coding and modulation systems had been already deployed, for example in deep space missions. However, from a practical point of view, the system was very close to the state of the art at the time. Although the error correction coding is quite simple, the decoding in the receiver is actually quite complex. The coding and modulation was not the very best known, but given the amount of processing power achievable in the consumer integrated circuits of the time, was about the best that could reasonably be implemented.

The coding and modulation used by DVB-S performs at least 3dB below the Shannon limit, more at high code rates. There is a further inefficiency caused by the fact that the spectrum of the transmitted signal is not rectangular, but has a root cosine roll off; the bandwidth occupied by the signal is therefore greater than the theoretical minimum. Even at the time of development of DVB-S, it was recognised that these inefficiencies gave scope for performance improvements in future transmission systems.

#### 6.3.2.2 DVB-S2

Soon after the development of DVB-S, there was great interest in a newly invented class of error correcting codes know as Turbo Codes. These codes relied on the concatenation of two relatively simple convolutional codes together with a large interleaver, and claimed performance about 2dB better than the DVB-S scheme, i.e. they could perform at within about 1dB of the Shannon limit. Early implementations had some problems operating at the very low residual bit error rates needed for digital television, although these were subsequently overcome.

Turbo codes sparked a great deal of activity in the development of error codes in general, and it was subsequently found that another class of codes, known as Low Density Parity Check (LDPC) codes also offered some useful potential for improvement. The LDPC codes had been discovered in the early 1960s but then forgotten, perhaps because at the time the processing power and memory needed to implement the very long codes with good performance made them of limited practical use.

In 2003 DVB initiated a project to define a second generation of digital coding and modulation for satellite: DVB-S2 [12]. As well as improved error correction, DVB-S2 changed the square 16QAM modulation used by DVB-DSNG to a circular multilevel constellation, and introduced a similar 32 state constellation. It also reduced the cosine roll off filters from 35% to 20%. All of this resulted in a performance improvement of around 35% greater data capacity or 2.5dB better signal-to-noise performance compared to the earlier systems.

For example, a typical 36 MHz satellite transponder operating at an EIRP of 51dBW may use:

- Symbol rate of 30.9 Mbaud
- QPSK modulation
- 3/4 FEC Rate

This combination gives a useful data rate of 46Mb/s, i.e. about 36% greater capacity than DVB-S for the equivalent C/N requirements.

#### 6.3.2.3 DVB-S3?

The DVB organisation has stated that the performance of DVB-S2 is so good that DVB-S3 will not be developed for a long time. Of course there could be requirements for systems with parameters outside those currently specified by DVB-S2. Thus, it would be possible to deliver higher bit rates in a given channel at the expense of requiring larger receiving dishes or higher power satellites, or conversely reception on very small antennas might be achieved at the expense of bit rate.

However, there probably is still some scope for performance improvements to DVB-S2; depending on operating mode, future coding and modulation schemes may squeeze out an extra dB or so of performance. The current DVB-S2 error correction scheme uses a maximum block size of 64Kbits. In the academic world, codes with block sizes of millions of bits have been investigated, which achieve performances within a fraction of a dB of theoretical limits. Whilst the memory requirements for such a code are not prohibitive nowadays, the processing power needed to decode it is still very large. Furthermore, the time delay inherent in the decoding process may also become an issue with such large codes.

The original DVB-S system used a Nyquist filter with a bandwidth 35% greater than the ideal rectangular filter corresponding to a given symbol rate. Today, typical DVB-S2 transmissions with 8PSK modulation use 25%. If this figure could be reduced to close to zero and combined with marginal improvements in coding and modulation, it is possible to envisage a DVB-S3 with performance better than DVB-S2 by the same amount as DVB-S2 outperforms DVB-S. One way this might be achieved is with multicarrier systems (e.g. COFDM), optimised for bandwidth efficiency rather than operation in multipath channels (i.e. no guard interval). One problem is that such modulation is not compatible with the saturated satellite transponders used for direct-to-home broadcasting at present, but it may be possible to overcome this.

It is also not impossible that fundamentally new techniques may be invented to exploit the remaining inefficiencies in the transmission system. However, it seems probable that the DVB statement is correct, and any improvements to DVB-S2 will be quite a way into the future.

### 6.3.3 Terrestrial Broadcasting

#### 6.3.3.1 DVB-T

DVB-T [13] was developed in the mid to late 1990s, building on work conducted in a number of European research laboratories in the preceding decade. Like the earlier Digital Audio Broadcasting (DAB) system it uses a multicarrier modulation scheme known as Coded Orthogonal Frequency Division Multiplexing (COFDM). This gives excellent immunity to multipath reception, as well as resistance to interference from analogue television transmission systems. Two variants of the system were defined, using about 2000 or about 8000 carriers (2K or 8K). The former system gives better performance for mobile reception; the latter allows rejection of very long echoes which occur in a Single Frequency Network (SFN), i.e. a network of multiple transmitters working on the same frequency.

DVB-T uses the same error correction scheme as DVB-S. This meant that the first generation receivers were able to use the same silicon as the already developed satellite receivers; an important advantage given that DVB-T equipment was required a very short time after the specification was finalised. Fortuitously, these codes give good performance when combined with the multicarrier modulation system.

On each carrier, modulation constellations up to 64QAM are allowed. This means that the system can transmit significantly more data per unit bandwidth than DVB-S, but at the expense of requiring greater signal strength at the receiver. DVB-T has a number of overheads which reduce data capacity, but aid performance and synchronisation in the receiver. These are the guard interval, and assorted 'pilots'. The amount of capacity allocated to pilots is significantly higher than the theoretical minimum, partly because it simplified the design of receivers.

A weakness of DVB-T is poor immunity to impulse interference. This could have been overcome by adding time interleaving, but at the time when the specification was developed it was thought to be impractical to add enough memory in the receiver to give effective time interleaving.

The DVB-T parameter set currently in use in the UK on Multiplex A and 2 is:

- 64QAM modulation
- 1/32 Guard Interval
- 2/3 FEC Rate
- 2K FFT

This combination gives a capacity of 24.1 Mb/s.

#### 6.3.3.2 DVB-T2

DVB-T2 [14] is the second generation terrestrial broadcasting system. Like DVB-T, it uses COFDM, but with up to 32K carriers. Using more carriers permits the same length of echoes to be tolerated as with DVB-T, but with a shorter percentage guard interval, and hence less loss of data capacity. It also has a lower overhead for pilots, closer to the theoretical minimum.

DVB-T2 allows constellations of up to 256QAM per carrier, thus allowing a greater capacity in a given width of channel. DVB-T2 follows DVB-T in inheriting its error correction scheme from the corresponding satellite system, in this case DVB-S2. Although the LDPC codes work very well in an AWGN channel, they are not as good for COFDM working in a channel with strong multipath. To partially overcome this, DVB-T2 defines 'rotated constellations'. Finally DVB-T2 introduces a technique known as Alamouti coding, an example of Multiple Input Multiple Output (MIMO) transmission.

The real-world performance of DVB-T2 is still under investigation in trials. In near line of sight channels, e.g. rooftop antennas, performance improvements similar to those of DVB-S2 over DVB-S can be expected. In channels with severe multipath or subject to interference (in particular mobile channels), performance improvements are much harder to predict and will await the results of the field trials.

In their paper at IBC 2008 [58], Nick Wells and Chris Nokes of the BBC estimated that equivalent Gaussian channel performance to that of DVB-T (with the parameter set used in Multiplex A and 2) would be achieved by DVB-T2 with the following parameter set:

- 256QAM modulation
- 1/128 Guard Interval
- 3/5 LDPC FEC Rate
- 32 FFT

This combination gives a capacity of 35.9Mb/s, i.e. about 50% greater capacity than currently available in the UK Multiplex A and 2 using DVB-T with equivalent Gaussian channel performance.

#### 6.3.3.3 DVB-T3?

DVB-T2 at high bit rates probably achieves such a high level of performance that there is little room for economically viable performance improvement in the short term. However, since the terrestrial channel characteristics are far from Gaussian, it is more difficult to predict precisely how much scope for improvement there may be in the longer term.

Finally, there is one technique which so far has not been exploited very much in the DVB-T family of standards, which would be applicable to both fixed and mobile reception. This is MIMO (multiple input multiple output) which refers to the use of two or more antennas for transmission and reception.

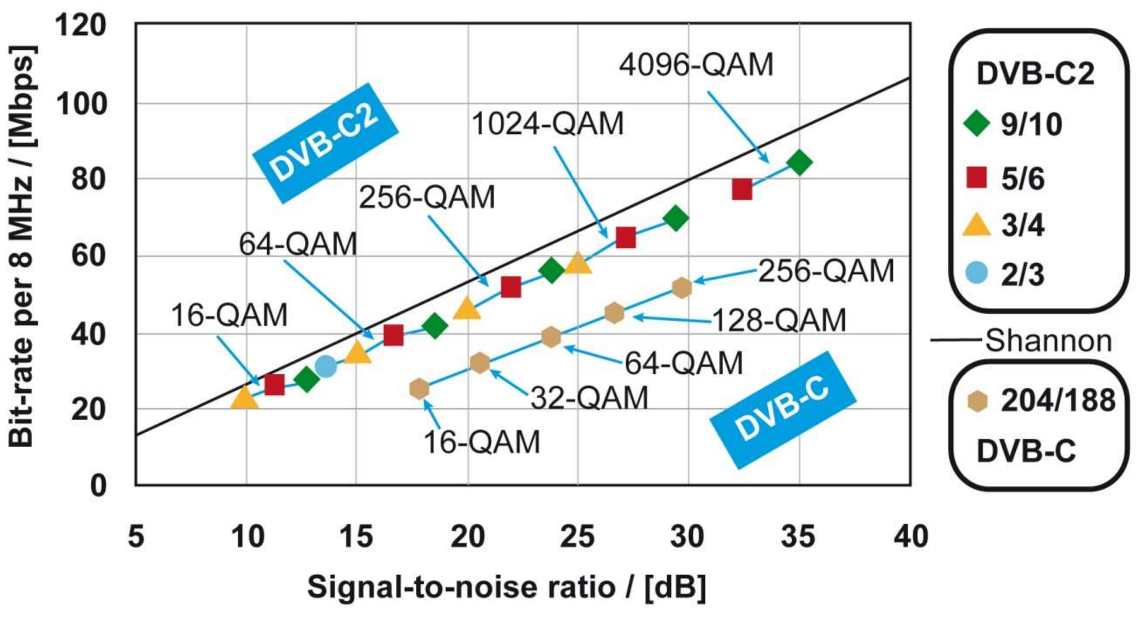
One particularly interesting implementation of a dual antenna MIMO system is where one antenna uses vertical whilst the other uses horizontal polarisation. Both transmitter and receiver would need cross polar antennas, and signal processing would be needed at the receiver to separate the two transmissions, since they inevitably become somewhat scrambled together. However, with current technology the signal processing that is required is relatively straightforward. This technique is very powerful and gives a near doubling of data capacity in a given bandwidth (or conversely a big improvement in signal robustness by allowing more bit rate for error correction). Its main problem is that it requires significant changes to the transmission infrastructure. In particular, making omni-directional antennas which keep a good operation between the two polarisations is both difficult and costly.

A further possible implementation of MIMO is to use several antennas at both receiver and transmitter. This is most practical at higher frequencies (e.g. greater than about 5GHz), where the antenna structures are not too unwieldy. In principle, this technique could result in a several fold increases in data rate in a given channel.

### 6.3.4 Cable Broadcasting

The last of the DVB transmission systems to have its second generation defined was cable, with the DVB-C2 [16] specification being approved at the March 2009 Technical Module meeting. The original DVB-C [15] specification was a single carrier modulation system with modulation constellations up to 256QAM. DVB-C2 uses a COFDM approach with modulation constellations of up to 4096QAM per carrier. The COFDM modulation scheme is insensitive to echoes caused by typical in-house coaxial networks and is not sensitive to impulsive noise interference.

DVB-C2 gives more than a 30% improvement in spectrum efficiency under the same conditions as the current DVB-C deployments, potentially increasing to about 60% improvement for an optimised HFC network after analogue switch-off. The diagram below, taken from the DVB Factsheet on DVB-C2 [17], illustrates the wide range of modulation options available with DVB-C2. These cover scenarios with both lower and higher signal-to-noise ratio than DVB-C was designed to cater for. It can also be seen that the performance of DVB-C2 is close to the Shannon limit.




### 6.3.5 Conclusions on Broadcasting

Significant improvements have been gained in all three of DVB's second generation transmission systems, compared to the first generation solutions. However, the scope for further improvement appears to be more limited, with all three operating close to the limit.

The greatest potential for further improvements appears to be the introduction of MIMO (multiple input multiple output) techniques in terrestrial transmission. With two antennas for both transmission and reception, this could yield as much as a doubling of data capacity. However, it would require changes to both the transmission infrastructure and the home installation, which would be very disruptive and expensive to implement.

In the scenarios explored in Section 7, the assumptions summarised in Table 22 below will be made for the satellite and terrestrial transmission capacities that will be achievable by 2020:

| | Satellite Broadcasting in 2020 | Bit-rate from a 36MHz satellite transponder | Terrestrial Broadcasting in 2020 | Bit-rate from a 8MHz terrestrial channel |
|---|---|---|---|---|
| Pessimistic (lowest decile) | DVB-S2 0% improvement | 46.0Mb/s | DVB-T2 0% improvement | 35.9Mb/s |
| Most Probable | DVB-S3 15% improvement | 52.9Mb/s | DVB-T3 (no MIMO) 20% improvement | 43.1Mb/s |
| Optimistic (highest decile) | DVB-S3 25% improvement | 57.5Mb/s | DVB-T3 inc. MIMO 100% improvement | 71.8Mb/s |

**Table 22: Scenarios for Satellite and Terrestrial Broadcasting in 2020**

# 7 SCENARIOS FOR THE INTRODUCTION "3D" TV AND UHDTV

## 7.1 Background to Scenarios

### 7.1.1 Overview of Scenarios

This chapter explores some possible scenarios for the broadcasting of stereoscopic TV ("3D" TV) and ultra high definition TV (UHDTV). The scenarios focus on the bit-rate requirements that are likely to apply in the year 2020 and consequently forecast the number of services that could be carried in an 8MHz terrestrial channel or a 36MHz satellite transponder. The year 2020 was chosen for the scenarios since by then stereoscopic TV is likely to have either matured to become a mainstream service or else been relegated to a niche market that is of little interest to broadcasters. Similarly, by 2020 UHDTV should have become practical to provide to the consumer at acceptable prices, if it is a service that is of mainstream interest.

Three scenarios for technology development are considered: most probable, pessimistic and optimistic. The pessimistic case is intended to represent a reasonable worst case situation, which there is a 90% probability of exceeding. The optimistic scenario is intended to represent a best case situation, with only a 10% probability of exceeding. In each scenario a number a technology factors are considered: channel coding and modulation, display technology and compression efficiency. It would also be possible to construct various mixed scenarios, e.g. with a pessimistic view of technology developments for compression efficiency but an optimistic view of technology developments for channel coding and modulation.

### 7.1.2 Introduction of "3D" TV

There is clear evidence of consumer demand for stereoscopic content in the cinema at the moment, with premium ticket prices being paid. However, the impressive recent rise in the number of feature films planned to be produced in "3D" in 2010 does not prove that it will necessarily become ubiquitous in the long term. There are three very different future scenarios that are all consistent with the history so far, as illustrated in Figure 18 below:

- "3D" could be a short-term fad, similar to the peak of interest in the 1950s
- "3D" could become a standard effect, but for animated films only
- "3D" could become a standard effect used for all films, akin to the introduction of colour

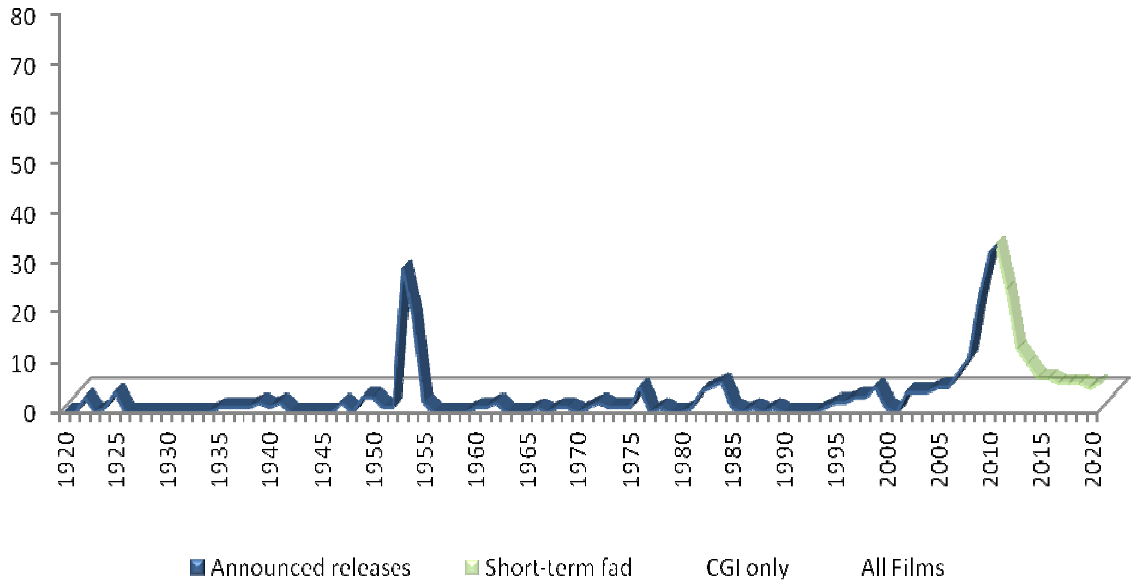



**Figure 18: "3D" feature film releases over time**

There is also current consumer interest in stereoscopic or "3D" TV in the home, but whether this interest would actually translate into real consumer demand is not yet proven. One of the key barriers to delivering "3D" TV services to the home is finding display technology that provides effective stereoscopic rendition in a manner that the consumer would find acceptable for long-term use. In the immediate future, the only viable technologies require the use of some form of glasses, either passive polarised or active shutter glasses. There remains some doubt over how acceptable this will be to the user.

Until this demand is confirmed, broadcasters are unlikely to be willing to invest large sums of money in installing infrastructure or replacing existing set-top boxes. In the short to medium term, there is therefore likely to be range of different interim solutions deployed by different broadcasters around the world to enable them to test the market. For example, a major constraint on BSkyB at the moment is the need for their initial "3D" offering to be supported by currently deployed HDTV set top boxes. The consequence of this is that each eye receives video with half the resolution of 720p/50 or 1080i/25.

The remainder of this chapter will focus on the situation in the year 2020, by which date it is assumed that the transition phase will be past and that the consumer demand will be proved (or disproved). In the presence of confirmed consumer demand, it is assumed that both the broadcaster and the consumer are willing to invest in the infrastructure and equipment necessary to broadcast and display good quality "3D" content. It is therefore assumed that the constraint of being able to use already deployed hardware will cease to be relevant.

In all scenarios it will be assumed that the full 1080p/50 HDTV resolution is required for each eye in order to meet consumer quality expectations in 2020. The subjective impression of resolution of such a system is actually slightly greater than for a 2D 1080p/50 HDTV due to the effect of different information from each eye being processed by the brain.

The displayed "3D" signal would therefore need to have twice the pixel rate of 1080p/50: twice the spatial resolution for a system based on polarised glasses or twice the frame rate for a system based on shutter glasses. It is assumed that one or the other approach will become the clear market leader by the year 2020; if both were to continue to exist side by side then it might be necessary to transmit the content in a more abstract, display-agnostic format to serve both populations.

### 7.1.3 Introduction of UHDTV

The decade from 1995 to 2005 saw digital SDTV launched by terrestrial, cable and satellite and then become commonplace in the majority of households in the UK. We appear to be in the midst of a similarly successful roll-out of HDTV in the decade from 2005 to 2015, as evidenced by the significant current consumer demand for HDTV displays. A logical extrapolation would be to predict that an equivalent roll-out of 4Kx2K UHDTV will occur in the decade from 2015 to 2025. However, this is far from proven; an alternative view would be that consumers are now so satisfied with the picture quality of HDTV that picture quality is no longer a key issue for them in a normal domestic viewing situation, so they would prefer the next stage of TV development to focus on "3D" or personalisation or other issues.

Storage media technologies appear to be progressing at a sufficiently rapid rate that they will not impede the launch of UHDTV. Furthermore, the capacity of packaged media and the delivery bit-rates becoming available through wired and even wireless broadband networks implies that broadcasters will be in danger of being bypassed in picture quality by other delivery media if they do not embrace UHDTV.

For the remainder of this chapter it will be assumed that there is significant consumer demand for UHDTV in the home. In the presence of this confirmed demand, it is assumed that both the broadcaster and the consumer are willing to invest in the infrastructure and equipment necessary to broadcast and display good quality UHDTV content using the "4Kx2K".

It is assumed that in UHDTV broadcasting in 2020:

- The normal frame rate used for broadcasting will remain 50Hz
- The aspect ratio will remain 16:9 and the typical UHDTV video format will be 3840 pixels x 2160 lines
- Increased bit depth will be used, but in an adaptive manner so that there is no resultant increase in bit-rate
- The overall chrominance resolution will continue to be a quarter that of luminance in the transmitted signal, i.e. 4:2:0
- Enhanced colour gamut will be used, but will not require any significant increase in bit-rate.

### 7.1.4 Video Coding and Statistical Multiplexing

The assumed starting point in all scenarios is that 13Mb/s constant bit-rate is required today to give reasonable quality 1080p/50 HDTV video with a state-of-the-art encoder. This is consistent with the result of tests analysed by the DVB [18] and also the 12-14Mb/s range suggested by the EBU presentation at the ABU Digital Broadcasting Symposium in March 2009 [19].

In a constant bit-rate system, each video service in the multiplex has a fixed allocation of data rate regardless of the video 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 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 of the resolution of the video, the details of the compression algorithm and whether the content is 2D or "3D". The graph in Figure 19 below is indicative of the typical benefits that can be expected.

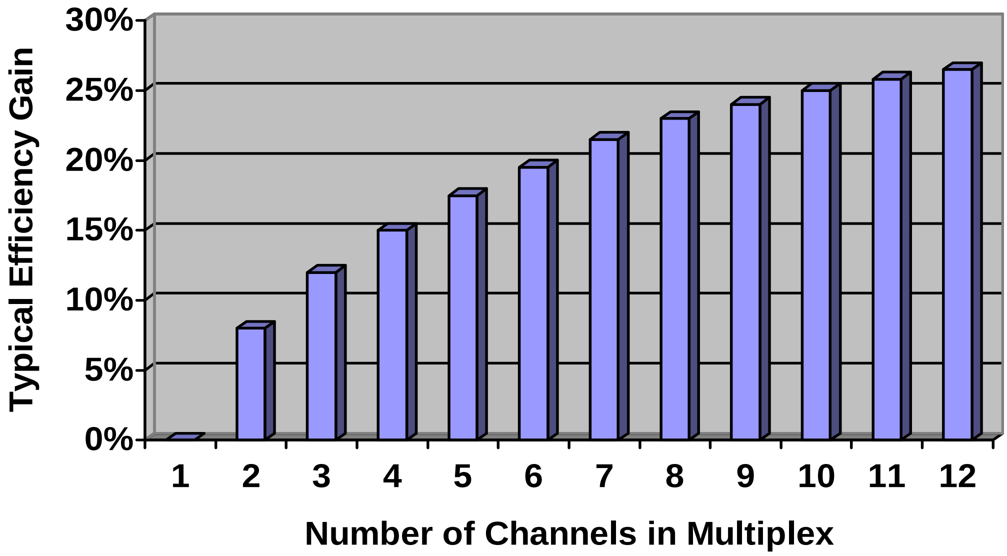



**Figure 19: Typical Coding Efficiency Benefits due to Statistical Multiplexing**

The exact efficiency gain is dependent on both the nature of the video content across all of the channels 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. It will be assumed in all cases that statistical multiplexing is used to the maximum extent practical. It will also be assumed in all cases that no significant improvements in the efficiency of statistical multiplexing will occur by 2020; a slightly pessimistic assumption.

## 7.2 Pessimistic (lowest decile) Scenario for 2020

### 7.2.1 Display Technology

It is assumed that no fundamental breakthroughs in "3D" display technology occur before 2020. The only viable technologies therefore remain the two options that are available today, requiring the use of either polarised or shutter glasses.

### 7.2.2 Compression Efficiency

In this pessimistic scenario, it is assumed that very little improvement in 2D compression efficiency is achieved by 2020; it is assumed that the H.264/AVC compression algorithm will continue to be used and that the encoder implementation improvements are fairly modest. The assumption is that the bit-rate required for 1080p/50 HDTV content is only 30% lower than the bit-rate required by a state-of-the-art encoder today, i.e. 9.1Mb/s.

For "3D", it will be assumed that no form of compression of the information in left and right eye views is found to be practical to use in live events. The stereoscopic representation would therefore require twice the bit-rate of 2D, i.e. 18.2Mb/s.

This scenario is arguably overly-pessimistic, since forms of 2D plus difference coding are already practical today. However, a more extreme version of the pessimistic scenario would be to assume that simulcast of a 2D signal would be the only option that was found to be artistically acceptable to the viewer, i.e. fully independent editorial control of both the 2D and the "3D" versions of the content was essential.

For UHDTV, it is assumed that the compression efficiency measured in terms of bits per pixel is very slightly greater than for HDTV due to the increased correlation between adjacent pixels at higher resolutions. It is therefore assumed that, although UHDTV is 400% of the pixel rate of 1080p/50 HDTV, it will require only 380% of the bit-rate.

### 7.2.3 Channel Coding and Modulation

It is assumed that no significant improvements in channel coding and modulation are made for either satellite or terrestrial transmission; DVB-S2 and DVB-T2 will continue to be used largely as they are today. It is assumed that the bit-rate available when using DVB-T2 in an 8MHz channel will be the 36Mb/s implied by Gaussian channel considerations.

## 7.3 Most Probable Scenario for 2020

### 7.3.1 Display Technology

It is again assumed that no fundamental breakthrough in "3D" display technology will occur before 2020. The only viable technologies will therefore remain the two options that are available today, requiring the use of either polarised or shutter glasses.

### 7.3.2 Compression Efficiency

It is assumed that a significant improvement in compression efficiency is achieved by 2020, through a combination of a new compression algorithm and more sophisticated encoder implementations. It will therefore be assumed that 50% lower bit-rate than today is required for the same picture quality of 1080p/50 content, i.e. 6.5Mb/s.

For "3D", it is assumed that a form of "2D plus Difference", with similar efficiency to that achieved today, is used to broadcast the "3D" signal, requiring 80% more bit-rate than for 2D alone.

For UHDTV, it is assumed that the compression efficiency measured in terms of bits per pixel is slightly greater than for HDTV, due to both an increased correlation between adjacent pixels at higher resolutions and a compression algorithm that is better matched to the statistics of higher resolution video. It is therefore assumed that 400% of the pixel rate requires 360% of the bit-rate.

### 7.3.3 Channel Coding and Modulation

The most probable scenario is that fairly modest improvements in channel coding and modulation are achieved for both satellite and terrestrial transmission by 2020. DVB-S3 is assumed to be used, to give 15% improvement in bit-rate per Hertz of bandwidth compared to DVB-S2. DVB-T3 is assumed to be used, without MIMO, to give 20% improvement in bit-rate per Hertz of bandwidth compared to DVB-T2.

## 7.4 Optimistic (highest decile) Scenario for 2020

### 7.4.1 Display Technology

It is assumed that a major breakthrough in auto-stereoscopic displays occurs so that glasses-free viewing of "3D" content for general entertainment in the home becomes commonplace. However, it would require an extremely optimistic view to expect true 3D representation by 2020, e.g. using holography or laser-created volumetric displays. It is therefore assumed that the new auto-stereoscopic display does not support multi-view representation.

### 7.4.2 Compression Efficiency

It is assumed that a very significant improvement in compression efficiency is achieved by 2020, through a combination of a new compression algorithm and more sophisticated encoder implementations. It will therefore be assumed that 60% lower bit-rate than today is required for the same picture quality, i.e. 5.2Mb/s.

For "3D", it is assumed that only 60% more bit-rate than for 2D to is required to represent stereoscopic video, either by a more efficient form of "2D plus Difference" encoding else by encoding as "2D plus Depth".

For UHDTV, it will be assumed that the compression efficiency measured in terms of bits per pixel is greater than for HDTV due to the increased correlation between adjacent pixels at higher resolutions and the compression algorithm that is better matched to higher resolutions. It will therefore be assumed that 400% of the pixel rate requires 340% of the bit-rate.

### 7.4.3 Channel Coding and Modulation

It is assumed that some improvement in channel coding and modulation is made for satellite transmission; DVB-S3 will be used to give 25% increase in bit-rate per Hertz of bandwidth compared to DVB-S2. For terrestrial transmission, it will be assumed that MIMO techniques will be used with DVB-T3 to give a 100% increase in bit-rate per Hertz of bandwidth compared to DVB-T2.

## 7.5 Delivery of "3D" TV by Terrestrial Broadcasting in 2020

The pessimistic, most probable and optimistic scenarios for the delivery of "3D" TV by terrestrial broadcasting in 2020 are summarised in Table 23 below.

| | Display Technology | 1080p/50 bit-rate | "3D" bit-rate | Terrestrial Transmission |
|---|---|---|---|---|
| Pessimistic (lowest decile) | Requires polarised or shutter glasses | 9.1 Mb/s 70% of today | 18.2 Mb/s 200% of 2D | DVB-T2 0% improvement |
| Most Probable | Requires polarised or shutter glasses | 6.5 Mb/s 50% of today | 11.7 Mb/s 180% of 2D | DVB-T3 (no MIMO) 20% improvement |
| Optimistic (highest decile) | Auto-stereoscopic Display | 5.2 Mb/s 40% of today | 8.3 Mb/s 160% of 2D | DVB-T3 (inc. MIMO) 100% improvement |

**Table 23: Scenarios for Terrestrial Broadcasting of "3D"**

A constant video bit-rate of around 13Mb/s is required today to give reasonable quality 2D 1080p/50 HDTV with a state-of-the-art encoder. The predicted improvements in compression efficiency are applied to this figure in the three scenarios to give the values listed in the second column of Table 23 above. The predicted overheads for "3D" content are then added to these values to give the values listed in the third column.

Table 24 below predicts the number of "3D" services that can be expected to be carried in an 8MHz terrestrial channel, based on the bit-rate available in the channel, the bit-rate required per service and the assumed gain from the use of statistical multiplexing specified in the fifth column. The final column is intended to confirm that there is sufficient residual bit-rate available for audio, SI/PSI, interactive services, etc.

| | "3D" TV Bit-rate (CBR) | No. "3D" services in 8MHz channel | Stat Mux Gain | Total video bit-rate | Bit-rate in a 8MHz terrestrial channel | Residual bit-rate for audio, SI, etc. |
|---|---|---|---|---|---|---|
| Pessimistic | 18.2 Mb/s | **2** | 8% | 33.5 Mb/s | 35.9Mb/s | 2.4 Mb/s |
| Most Probable | 11.7 Mb/s | **4** | 15% | 39.8 Mb/s | 43.1Mb/s | 3.3 Mb/s |
| Optimistic | 8.3 Mb/s | **11** | 26% | 67.7 Mb/s | 71.8Mb/s | 4.1 Mb/s |

**Table 24: Number of "3D" services that can be carried in a Terrestrial Channel**

In the most probable scenario, four "3D" TV services could be expected to be carried in an 8MHz terrestrial channel by 2020. In the pessimistic scenario this decreases to two, whilst in the optimistic scenario it increases to eleven.

The wide range between the scenarios is largely due to the potential doubling of bit-rate that could be provided by a future DVB-T3 channel if MIMO techniques were used, amplified by the "virtuous circle" effect of statistical multiplexing; the larger the number of channels, the less bit-rate is required per channel.

## 7.6 Delivery of "3D" TV by Satellite Broadcasting in 2020

The pessimistic, most probable and optimistic scenarios for the delivery of "3D" TV by satellite broadcasting in 2020 are summarised in Table 25 below.

| | Display Technology | 1080p/50 bit-rate | "3D" bit-rate | Satellite Transmission |
|---|---|---|---|---|
| Pessimistic (lowest decile) | Requires polarised or shutter glasses | 9.1 Mb/s 70% of today | 18.2 Mb/s 200% of 2D | DVB-S2 0% improvement |
| Most Probable | Requires polarised or shutter glasses | 6.5 Mb/s 50% of today | 11.7 Mb/s 180% of 2D | DVB-S3 15% improvement |
| Optimistic (highest decile) | Auto-stereoscopic Display | 5.2 Mb/s 40% of today | 8.3 Mb/s 160% of 2D | DVB-S3 25% improvement |

**Table 25: Scenarios for Satellite Broadcasting of "3D"**

The second column of Table 26 below predicts the number of "3D" services that can be expected to be carried in a 36MHz satellite transponder, based on the bit-rate available in the channel, the bit-rate required per service and the assumed gain from the use of statistical multiplexing. The sixth column is to confirm that there is sufficient residual bit-rate available for audio, SI/PSI, interactive services, etc.

| | "3D" TV Bit-rate (CBR) | No. "3D" services in 36MHz transponder | Stat Mux Gain | Total video bit-rate | Bit-rate in a 36MHz satellite transponder | Residual bit-rate for audio, SI, etc. |
|---|---|---|---|---|---|---|
| Pessimistic | 18.2 Mb/s | **2** | 8% | 33.5 Mb/s | 46.0 Mb/s | 12.5 Mb/s |
| Most Probable | 11.7 Mb/s | **5** | 17.5% | 48.3 Mb/s | 52.9 Mb/s | 4.6 Mb/s |
| Optimistic | 8.3 Mb/s | **8** | 23% | 51.3 Mb/s | 57.5 Mb/s | 6.2 Mb/s |

**Table 26: Satellite Broadcasting of "3D"**

In the most probable scenario, five "3D" TV services could be expected to be able to be carried in a 36MHz satellite transponder by 2020. In the pessimistic scenario this decreases to two, whilst in the optimistic scenario it increases to eight.

The differences between the scenarios are much less pronounced than in the terrestrial case, because even in the most optimistic scenario, the capacity achievable by DVB-S3 channel coding and modulation cannot exceed the Shannon limit.

## 7.7 Delivery of UHDTV by Terrestrial Broadcasting in 2020

The pessimistic, most probable and optimistic scenarios for the delivery of UHDTV by terrestrial broadcasting in 2020 are summarised in Table 27 below.

| | 1080p/50 bit-rate | UHDTV bit-rate | Terrestrial Transmission |
|---|---|---|---|
| Pessimistic (lowest decile) | 9.1 Mb/s<br>70% of today | 34.6 Mb/s<br>380% of 1080p/50 | DVB-T2<br>0% improvement |
| Most Probable | 6.5 Mb/s<br>50% of today | 23.4 Mb/s<br>360% of 1080p/50 | DVB-T3 (no MIMO)<br>20% improvement |
| Optimistic (highest decile) | 5.2 Mb/s<br>40% of today | 17.7 Mb/s<br>340% of 1080p/50 | DVB-T3 (inc. MIMO)<br>100% improvement |

**Table 27: Scenarios for Terrestrial Broadcasting of UHDTV**

The second column of Table 28 below predicts the number of UHDTV services that can be expected to be carried in an 8MHz terrestrial channel, based on the bit-rate available in the channel, the bit-rate required per service and the assumed gain from the use of statistical multiplexing. The sixth column gives the residual bit-rate available for audio, SI/PSI, interactive services, etc.

| | UHDTV Bit-rate (CBR) | No. UHDTV services in 8MHz channel | Stat Mux Gain | Total video bit-rate | Bit-rate in a 8MHz terrestrial channel | Residual bit-rate for audio, SI, etc. |
|---|---|---|---|---|---|---|
| Pessimistic | 34.6 Mb/s | **1** | 0% | 34.6 Mb/s | 35.9Mb/s | 1.3 Mb/s |
| Most Probable | 23.4 Mb/s | **2** | 8% | 43.1 Mb/s | 43.1Mb/s | 0.04 Mb/s |
| Optimistic | 17.7 Mb/s | **4** | 15% | 60.1 Mb/s | 71.8Mb/s | 11.7 Mb/s |

**Table 28: Number of UHDTV services that can be carried in a Terrestrial Channel**

In the most probable scenario, two UHDTV video services would just fit in an 8MHz terrestrial channel, but with insufficient residual capacity for audio or SI/PSI. In the pessimistic scenario there is capacity for only one UHDTV services, whilst in the optimistic scenario four could be provided. The wide range between the scenarios is largely due to the potential doubling of bit-rate that could be carried by a future DVB-T3 channel coding and modulation scheme if MIMO was used, amplified by the effect of statistical multiplexing.

## 7.8 Delivery of UHDTV by Satellite Broadcasting in 2020

The pessimistic, most probable and optimistic scenarios for the delivery of UHDTV by satellite broadcasting in 2020 are summarised in Table 29 below.

| | 1080p/50 bit-rate | UHDTV bit-rate | Satellite Transmission |
|---|---|---|---|
| Pessimistic (lowest decile) | 9.1 Mb/s<br>70% of today | 34.6 Mb/s<br>380% of 1080p/50 | DVB-S2<br>0% improvement |
| Most Probable | 6.5 Mb/s<br>50% of today | 23.4 Mb/s<br>360% of 1080p/50 | DVB-S3<br>15% improvement |
| Optimistic (highest decile) | 5.2 Mb/s<br>40% of today | 17.7 Mb/s<br>340% of 1080p/50 | DVB-S3<br>25% improvement |

**Table 29: Scenarios for Satellite Broadcasting of UHDTV**

The second column of Table 30 below predicts the number of UHDTV services that can be expected to be carried in a 36MHz satellite transponder, based on the bit-rate available in the channel, the bit-rate required per service and the assumed gain from the use of statistical multiplexing. The sixth column shows the residual bit-rate available for audio, SI/PSI, interactive services, etc.

| | UHDTV Bit-rate (CBR) | No. UHDTV services in 36MHz transponder | Stat Mux Gain | Total video bit-rate | Bit-rate in a 36MHz satellite transponder | Residual bit-rate for audio, SI, etc. |
|---|---|---|---|---|---|---|
| Pessimistic | 34.6 Mb/s | **1** | 0% | 34.6 Mb/s | 46.0 Mb/s | 11.4 Mb/s |
| Most Probable | 23.4 Mb/s | **2** | 8% | 43.1 Mb/s | 52.9 Mb/s | 9.8 Mb/s |
| Optimistic | 17.7 Mb/s | **3** | 12% | 46.7 Mb/s | 57.5 Mb/s | 10.8 Mb/s |

**Table 30: Satellite Broadcasting of UHDTV**

In the most probable scenario, two UHDTV services could be expected to be carried in a 36MHz satellite transponder by 2020. In the pessimistic scenario this decreases to only one, whilst in the optimistic scenario it increases to three. The differences between the scenarios are much less than in the terrestrial case, because even in the most optimistic scenario, the capacity achieved by DVB-S3 channel coding and modulation cannot exceed the Shannon limit.

# 8 VIEWS OF KEY INDUSTRY PLAYERS

## 8.1 Organisations Consulted

The consultation process involved carrying out structured interviews with five of the leading players working on new broadcasting services, both in the UK and internationally. However, it should not be assumed that the organisations interviewed endorse the conclusions of this report, since the conclusions were not discussed with them.

A simplified overview of the spread of the main activities of the five organisations is given in Table 31 below. Primary activities are denoted as ☑, secondary activities as ✓. Many of the organisations also have tertiary activities (e.g. BSkyB's involvement in the terrestrial Freeview service) but these are omitted to avoid excessive clutter.

| | Terrestrial | Satellite | Manufacturer | Broadband | Content |
|---|---|---|---|---|---|
| Arqiva | ☑ | ✓ | | | |
| BBC | ✓ | ✓ | | | ☑ |
| BSkyB | | ☑ | ✓ | ☑ | ✓ |
| ITV | ✓ | | | | ☑ |
| Samsung | | | ☑ | | |

**Table 31: Summary of Activities of Organisations Interviewed**

### 8.1.1 Arqiva

Crawley Court
Winchester
Hampshire
SO21 2QA

Participant in discussions:
Mike Brooks – Head of Technical Development of DVB-T2

### 8.1.2 BBC Research

British Broadcasting Corporation
Kingswood Warren
Tadworth
Surrey
KT20 6NP

Participant in discussions:
Dr John Zubrzycki - Portfolio Manager

### 8.1.3 BSkyB

British Sky Broadcasting Ltd.
New Horizons Court
Shield Drive
Isleworth
Middlesex
TW8 9EX

Participant in discussions:
Brian Lenz – Director of Product Design, Strategic Product Development, Customer Group

### 8.1.4 ITV

Future Technologies and Interactive
ITV plc
222 Grays Inn Road
London
WC1X 8HF

Participants in discussions:
Simon Fell – Director of Future Technologies
Colin Smith – Technical Analyst, Interactive

### 8.1.5 Samsung

Samsung Electronics Co.
416 Maetan-3Dong Yeongtong-Gu
Suwon-City
Gyeonggi-Do
Korea 443-742

Responses coordinated by Kyong-Sok Seo – Digital Media Research & Development Centre

## 8.2 Opinions expressed by Organisations

### 8.2.1 Consultation Process

Each prospective interviewee was told that ZetaCast had been asked by Ofcom to talk to a number of the key players in the broadcasting industry to determine their views on the possible future delivery of new types of services beyond HDTV, such as "3D" TV and Ultra High Definition TV.

The chosen interviewees were generally individuals closely involved in the development of content delivery. In most cases they agreed to take part in the interview themselves, but in some cases they nominated other individuals within the organisation who they felt would be more appropriate.

The format for the structured conversation was explained at the start of the interview. A set of 34 standard questions were asked, to make it easier to pick out common trends and highlight differences. The set questions were interspersed with periods of free format discussion to allow other relevant points to be raised.

Each interviewee was sent the notes from their own interview to allow them to make corrections or add further comments. They did not see any the responses of any other organisation or the any of the main report.

The results of the interviews are summarised in the following sections. Table 32 below gives the symbols used to identify the individual company responses to the 34 standard questions.

| | Symbol |
|---|---|
| Arqiva | ❶ |
| BBC | ❷ |
| BSkyB | ❸ |
| ITV | ❹ |
| Samsung | ❺ |

**Table 32: Organisations interviewed – tagging**

### 8.2.2 "3D" TV Display Technology

One of the key barriers to delivering "3D" TV services to the home is finding display technology that provides effective stereoscopic rendition in a manner that the consumer would find acceptable for long-term use. Which of the following display technologies would you regard as the most promising for introducing stereoscopic general entertainment services (sports, movies, etc.) in the home prior to 2020?

1. Stereoscopic display technologies using coloured glasses?

| 5 Extremely promising | 4 Very promising | 3 Fairly promising | 2 Slightly promising | 1 Not promising |
|---|---|---|---|---|
| | | | ↑ ❸ | ↑↑↑↑ ❶❷❹❺ |

2. Stereoscopic displays using polarised glasses?

| 5 Extremely promising | 4 Very promising | 3 Fairly promising | 2 Slightly promising | 1 Not promising |
|---|---|---|---|---|
| ↑ ❸ | ↑↑↑ ❷❹❺ | | ↑ ❶ | |

3. Stereoscopic displays using shuttered glasses?

| 5 Extremely promising | 4 Very promising | 3 Fairly promising | 2 Slightly promising | 1 Not promising |
|---|---|---|---|---|
| | ↑↑ ❹❺ | ↑ ❸ | ↑↑ ❶❷ | |

4. Auto-stereoscopic displays that don't require glasses?

| 5<br>Extremely promising | 4<br>Very promising | 3<br>Fairly promising | 2<br>Slightly promising | 1<br>Not promising |
|---|---|---|---|---|
| | ↑ ❹ | ↑↑ ❶❸ ↑ ❷ | ↑ ❺ | |

5. Some form of personal display system (e.g. head-mounted display)?

| 5<br>Extremely promising | 4<br>Very promising | 3<br>Fairly promising | 2<br>Slightly promising | 1<br>Not promising |
|---|---|---|---|---|
| | | | ↑↑↑ ❶❷❸ | ↑↑ ❹❺ |

Though all organisations agreed that the use of glasses to watch TV in the home may not be ideal, most believed that familiarity and acceptance with glasses will increase over time because the viewing experience is compelling enough to overcome this barrier.

From all the types of "3D" TV display technologies, system based on both polarised and shutter galsses were deemed to have the best chance of success in the shorter term. There was a slight leaning towards polarised, because these glasses are lighter and cost less and, in one company's opinion, "*quality is higher, there is less judder than shuttered glasses".* This same company believes that stereoscopic TV is cost effective and the increased cost on the monitor is manageable for the manufacturer to recover; it therefore makes it a viable solution for the viewer.

Most companies were of the opinion that auto-stereoscopic displays do not yet provide a good enough user experience, however this may improve over time and therefore they are still considered to be a promising technology for the longer term. Auto-stereoscopic techniques that enable compatibility with 2D viewing were preferred, such as parallax barrier and 2D/"3D" switchable lenticular lens.

Head-mounted displays were deemed not appropriate for home TV viewing; however they may be suitable for applications such as gaming.

### 8.2.3 2D Backwards Compatibility of "3D" Broadcasts

To provide backwards compatibility for viewers with 2D displays, a 2D programme could be simulcast alongside its "3D" equivalent. Alternatively, the "3D" signal could be encoded in a manner that allows a 2D version to be extracted from the "3D" broadcast.

The simulcast approach is technically straightforward and also provides full artistic freedom to optimise the content for viewing in each mode, e.g. by having more frequent scene cuts in the 2D version. However, a coding method which allows a 2D version to be extracted from the "3D" broadcast minimises the bit-rate overhead to deliver both 2D and "3D" versions. A particularly interesting compatible coding method is "2D plus depth", since this approach also allows the "3D" viewer to optimise the perception of depth to match their viewing conditions.

How critical is providing 2D backwards compatibility in a bit-rate efficient manner when considering delivering "3D" services delivered via:

6. Satellite?

| 5 | 4 | 3 | 2 | 1 |
|---|---|---|---|---|
| Critical Issue | Very Important | Fairly Important | Slightly Important | Not an issue |
| ↑↑ ❹❺ | | ↑ ❶ | ↑ ❷ | ↑ ❸ |

7. Cable?

| 5 | 4 | 3 | 2 | 1 |
|---|---|---|---|---|
| Critical Issue | Very Important | Fairly Important | Slightly Important | Not an issue |
| ↑ ❹ | ↑ ❺ | ↑ ❶ | ↑ ❸ ↑ ❷ | |

8. Terrestrial?

| 5 | 4 | 3 | 2 | 1 |
|---|---|---|---|---|
| Critical Issue | Very Important | Fairly Important | Slightly Important | Not an issue |
| ↑↑ ❹❺ ↑↑ ❶❸ | ↑ ❷ | | | |

9. IPTV?

| 5 | 4 | 3 | 2 | 1 |
|---|---|---|---|---|
| Critical Issue | Very Important | Fairly Important | Slightly Important | Not an issue |
| | ↑ ❺ | ↑ ❹ | ↑↑ ❶❸ | ↑ ❷ |

It was unanimously accepted that 2D and "3D" content should ideally be shot differently. Some companies highlighted that post-production handling was also different, with one concerned that the lack of skill set in these areas is currently an issue for the UK industry.

For some organisations, "3D" backwards compatibility with the 2D infra-structure is of very high importance or even essential in the short- to mid-term, and the current infra-structure used for high definition television should be re-used in its entirety if faster take up is to be achieved.

There was unanimous agreement that providing 2D backwards compatibility in a bit-rate efficient manner when delivering "3D" content over a terrestrial platform was very important if not critical.

### 8.2.4 Increasing Spatial resolution

The current HDTV transmissions in Europe are based on either the 720p/50Hz or 1080i/25Hz video formats. Recent top-of-the-range displays will also display the 1080p/50Hz format, although there is currently no broadcast material in this format.

By 2020, do you expect any of the following video formats to be used for broadcast television via **satellite**?

10. 1080p/50Hz (1080 lines x 1920 pixels at 50 frames/s)?

| 5 | 4 | 3 | 2 | 1 |
|---|---|---|---|---|
| Virtually Certain | Very Likely | Fairly Likely | Unlikely | Very unlikely |
| ↑↑ ❶❺ | ↑↑ ❷❹ ↑ ❸ | | | |

11. 4Kx2K (e.g. 2160 lines x 3840 pixels at 50 frames/s)?

| 5 | 4 | 3 | 2 | 1 |
|---|---|---|---|---|
| Virtually Certain | Very Likely | Fairly Likely | Unlikely | Very unlikely |
| | ↑ ❸ | ↑↑↑↑ ❶❷❹❺ | | |

12. 8Kx4K (e.g. 4320 lines x 7680 pixels at 50 frames/s)?

| 5 | 4 | 3 | 2 | 1 |
|---|---|---|---|---|
| Virtually Certain | Very Likely | Fairly Likely | Unlikely | Very unlikely |
| | | | ↑↑↑↑↑ ❶❷❸❹❺ | |

By 2020, do you expect any of the following video formats to be used for broadcast television via **cable**?

13. 1080p/50Hz (1080 lines x 1920 pixels at 50 frames/s)?

| 5 | 4 | 3 | 2 | 1 |
|---|---|---|---|---|
| Virtually Certain | Very Likely | Fairly Likely | Unlikely | Very unlikely |
| ↑↑ ❶❺ | ↑↑ ❷❹ | ↑ ❸ | | |

14. 4Kx2K (e.g. 2160 lines x 3840 pixels at 50 frames/s)?

| 5 | 4 | 3 | 2 | 1 |
|---|---|---|---|---|
| Virtually Certain | Very Likely | Fairly Likely | Unlikely | Very unlikely |
| | ↑ ❹ | ↑↑↑ ❶❷❺ | ↑ ❸ | |

15. 8Kx4K (e.g. 4320 lines x 7680 pixels at 50 frames/s)?

| 5 | 4 | 3 | 2 | 1 |
|---|---|---|---|---|
| Virtually Certain | Very Likely | Fairly Likely | Unlikely | Very unlikely |
| | | | ↑↑↑↑ ❶❷❹❺ | ↑ ❸ |

By 2020, do you expect any of the following video formats to be used for broadcast television via **terrestrial**?

16. 1080p/50Hz (1080 lines x 1920 pixels at 50 frames/s)?

| 5 | 4 | 3 | 2 | 1 |
|---|---|---|---|---|
| Virtually Certain | Very Likely | Fairly Likely | Unlikely | Very unlikely |
| | ↑ ❶ ↑ ❺ | ↑↑ ❷❹ | ↑ ❸ | |

17. 4Kx2K (e.g. 2160 lines x 3840 pixels at 50 frames/s)?

| 5 | 4 | 3 | 2 | 1 |
|---|---|---|---|---|
| Virtually Certain | Very Likely | Fairly Likely | Unlikely | Very unlikely |
| | | | ↑↑↑ ❶❷❺ | ↑↑ ❸❹ |

18. 8Kx4K (e.g. 4320 lines x 7680 pixels at 50 frames/s)?

| 5 | 4 | 3 | 2 | 1 |
|---|---|---|---|---|
| Virtually Certain | Very Likely | Fairly Likely | Unlikely | Very unlikely |
| | | | ↑↑ ❷❺ | ↑↑↑ ❶❸❹ |

By 2020, do you expect any of the following video formats to be used for **IPTV**?

19. 1080p/50Hz (1080 lines x 1920 pixels at 50 frames/s)?

| 5 | 4 | 3 | 2 | 1 |
|---|---|---|---|---|
| Virtually Certain | Very Likely | Fairly Likely | Unlikely | Very unlikely |
| ↑ ❺ | ↑↑ ❷❹ | ↑↑ ❶❸ | | |

20. 4Kx2K (e.g. 2160 lines x 3840 pixels at 50 frames/s)?

| 5 | 4 | 3 | 2 | 1 |
|---|---|---|---|---|
| Virtually Certain | Very Likely | Fairly Likely | Unlikely | Very unlikely |
| | ↑↑ ❷❹ | ↑ ❺ | ↑ ❸ | ↑ ❶ |

21. 8Kx4K (e.g. 4320 lines x 7680 pixels at 50 frames/s)?

| 5 | 4 | 3 | 2 | 1 |
|---|---|---|---|---|
| Virtually Certain | Very Likely | Fairly Likely | Unlikely | Very unlikely |
| | | ↑ ❺ | ↑↑ ❷❸ | ↑↑ ❶❹ |

Coding efficiency was expected to improve over time, with Scalable Video Coding playing an important role in some application areas. On the other hand, significant improvements in channel coding and modulation were not expected. For terrestrial, MIMO techniques would provide further and significant improvement, but they were considered to be unlikely to be implemented in the UK.

Most companies also agreed that there will not be any significant difference of video formats between the different delivery mechanisms. Some companies believed that the difference in quality from 720p and 1080i to 1080p/50Hz does not bring enough benefit to justify the large investment required in transmission infrastructure and the impact on legacy receivers which will not be able to support it. For terrestrial delivery, spatial resolutions greater than 1080p were deemed unlikely to be implemented. For satellite delivery, 4Kx2K was expected to bring more noticeable benefits and was therefore more likely to be implemented by 2020.

It was generally agreed that 8Kx4K resolution is not likely to be used for any transmission platforms in the UK in the 2020 timescale.

### 8.2.5 Other Display Enhancements

What other display enhancements do you expect to be provided in the broadcast TV signal by 2020?

22. Increased frame rate (i.e. more than 50 frames/s)?

| 5 | 4 | 3 | 2 | 1 |
|---|---|---|---|---|
| Virtually Certain | Very Likely | Fairly Likely | Unlikely | Very unlikely |
| | ↑ ❹    ↑ ❸ | ↑↑ ❷❺    ↑ ❶ | | |

23. Increased aspect ratio (i.e. wider than 16:9)?

| 5 | 4 | 3 | 2 | 1 |
|---|---|---|---|---|
| Virtually Certain | Very Likely | Fairly Likely | Unlikely | Very unlikely |

↑↑↑ ↑ ↑
❷❹❺ ❸ ❶

24. Increased bit depth (i.e. greater than 8 bit representation)?

| 5 | 4 | 3 | 2 | 1 |
|---|---|---|---|---|
| Virtually Certain | Very Likely | Fairly Likely | Unlikely | Very unlikely |

↑ ↑ ↑↑ ↑
❸ ❹ ❷❺ ❶

25. Improved colour gamut (i.e. better than Rec. 709)?

| 5 | 4 | 3 | 2 | 1 |
|---|---|---|---|---|
| Virtually Certain | Very Likely | Fairly Likely | Unlikely | Very unlikely |

↑ ↑ ↑ ↑ ↑
❹ ❸ ❺ ❷ ❶

### 8.2.6 Timescales

When do you expect the following service enhancements to be provided in broadcast TV services delivered by satellite, cable, terrestrial or IPTV:

26. Some form of stereoscopic TV which requires the use of glasses?

| 5 | 4 | 3 | 2 | 1 |
|---|---|---|---|---|
| By 2012 | By 2015 | By 2020 | By 2030 | Not by 2030 |

↑↑↑↑↑
❶❷❸❹❺

27. Some form of auto-stereoscopic TV which does not require the use of glasses?

| 5 | 4 | 3 | 2 | 1 |
|---|---|---|---|---|
| By 2012 | By 2015 | By 2020 | By 2030 | Not by 2030 |

↑ ↑ ↑↑↑
❹ ❶ ❷❸❺

28. 1080p/50Hz (1080 lines x 1920 pixels at 50 frames/s)?

| 5 | 4 | 3 | 2 | 1 |
|---|---|---|---|---|
| By 2012 | By 2015 | By 2020 | By 2030 | Not by 2030 |
| ↑ ❺ | ↑↑↑↑ ❶❷❸❹ | | | |

29. 4Kx2K (e.g. 2160 lines x 3840 pixels at 50 frames/s)?

| 5 | 4 | 3 | 2 | 1 |
|---|---|---|---|---|
| By 2012 | By 2015 | By 2020 | By 2030 | Not by 2030 |
| | | ↑↑↑↑ ❷❸❹❺ | ↑ ❶ | |

30. 8Kx4K (e.g. 4320 lines x 7680 pixels at 50 frames/s)?

| 5 | 4 | 3 | 2 | 1 |
|---|---|---|---|---|
| By 2012 | By 2015 | By 2020 | By 2030 | Not by 2030 |
| | | | ↑↑↑ ❸❹❺ | ↑↑ ❶❷ |

It was expected that by 2012 some form of stereoscopic TV requiring glasses was likely to be provided and that by 2020 some form of auto-stereoscopic TV would be delivered in broadcast TV services by satellite, cable, terrestrial or IPTV.

One of the companies interviewed claimed it was reasonable to assume that TV sets would be replaced every 5 years, on average. Therefore the market could be ready for "3D" screens within 5 years, when people would naturally replace their monitors, as long as these also provided backwards compatibility with HDTV viewing. The expectation was that a "3D" TV monitor would become mass market when the premium paid for these screens was in the order of £100.

Most companies expected that resolutions higher than 720p/1080i, such as 1080p/50, would happen by 2015 and ultra high resolution 4Kx2K by 2020, but significant market demand for the latter was regarded to be probably about 15 years away.

The general view was that the introduction on UHDTV and stereoscopic TV could happen independently, with stereoscopic TV happening before UHDTV. However, as the visual impact of "3D" is greater, demand for it may be greater.

### 8.2.7 Other issues

How important will non-broadcast content be in driving the up-take of new display technology by the consumer:

31. Games on computer or video console?

| 5 Critical | | 4 Very Important | | 3 Fairly Important | | 2 Slightly Important | | 1 Not important |
|---|---|---|---|---|---|---|---|---|
| ↑↑↑ ❶❸❹ | | ↑↑ ❷❺ | | | | | | |

32. Films viewed from packaged media (e.g. optical disc)?

| 5 Critical | | 4 Very Important | | 3 Fairly Important | | 2 Slightly Important | | 1 Not important |
|---|---|---|---|---|---|---|---|---|
| ↑↑ ❶❹ | | ↑↑ ❷❺ | ↑ ❸ | | | | | |

33. Downloaded content?

| 5 Critical | | 4 Very Important | | 3 Fairly Important | | 2 Slightly Important | | 1 Not important |
|---|---|---|---|---|---|---|---|---|
| ↑ ❺ | | | ↑ ❶ | ↑ ❹ | ↑ ❸ | | | ↑ ❷ |

34. User generated content?

| 5 Critical | | 4 Very Important | | 3 Fairly Important | | 2 Slightly Important | | 1 Not important |
|---|---|---|---|---|---|---|---|---|
| | | ↑ ❺ | | | ↑ ❶ | ↑↑ ❸❹ | | ↑↑ ❷❸ |

Non-broadcast content such as games and viewing packaged media in a home cinema were considered to be very important in driving the up-take of new display technology by the consumer. Gaming was considered likely to play a particularly key part in speeding up the demand for new stereoscopic display purchase; it may also be a driver for ultra high definition.

User generated content such as photography used in digital photo frames was considered by some to be a possible driver for the "3D" market.

As for consumer demand, the jury was still out on whether consumers would attach more value to channel variety, increased resolutions of existing programming or new types of services such as increased interactivity. There is particular uncertainty on how demand for "3D" content in the home will develop, but early indications from cinema and research indicate that there is a potential market if the quality can be delivered and the costs can be minimised throughout the value chain.

# 9 ABBREVIATIONS

| | |
|---|---|
| 2D | Two Dimensional |
| 3D | Three Dimensional |
| 3GPP | 3rd Generation Partnership Project |
| ADSL | Asymmetric Digital Subscriber Line |
| AWGN | Additive White Gaussian Noise |
| b | bit |
| B | Byte (8 bits) |
| BD-ROM | Blu Ray Disc - Read Only Memory |
| BPON | Broadband Passive Optical Network |
| CBR | Constant Bit-rate |
| CD | Compact Disc |
| CDMA | Code Division Multiple Access |
| CGI | Computer Generated Imagery |
| COFDM | Coded Orthogonal Frequency Division Multiplexing |
| CRT | Cathode Ray Tube |
| DCI | Digital Cinema Initiative |
| DLP | Digital Light Processing |
| DOCSIS | Data-Over-Cable Service Interface Specification |
| DSL | Digital Subscriber Line (as in xDSL) |
| DTT | Digital Terrestrial Television |
| DVB | Digital Video Broadcasting |
| DVB-AVC | DVB Audio-Visual Coding |
| DVB-C | DVB specification for Channel Coding and Modulation on Cable |
| DVB-C2 | DVB Cable, Second Generation |
| DVB-H | DVB Handheld (terrestrial) |
| DVB-S | DVB Satellite |
| DVB-S2 | DVB Satellite, Second Generation |
| DVB-SH | DVB Satellite Handheld (hybrid satellite/terrestrial) |
| DVB-T | DVB Terrestrial |
| DVB-T2 | DVB Terrestrial, Second Generation |
| DVD | Digital Versatile Disc (or Digital Video Disc) |
| EDGE | Enhanced Data-rates for GSM Evolution |
| EGPRS | Enhanced General Packet Radio Service |

| | |
|---|---|
| FTTB | fibre-to-the-building |
| FTTH | fibre-to-the-home |
| GB | GigaByte ($2^{30}$ = 1,073,741,824 Bytes) |
| Gb | Gigabit |
| GSM | Global System for Mobile Communications |
| H.264/AVC | ITU-T H.264 / MPEG-4 Advanced Video Coding (ISO/IEC 14496-10:2005) |
| HDMI | High-Definition Multimedia Interface |
| HDTV | High Definition Television |
| HSPA | High Speed Packet Access |
| HVC | High-Performance Video Coding |
| IMAX | Image MAXimum |
| IPTV | Internet Protocol Television |
| ISO | International Standardisation Organisation |
| ISOM | International Symposium on Optical Memory |
| KB | KiloByte ($2^{10}$ = 1,024 Bytes) |
| LCD | Liquid Crystal Display |
| LTE | Long Term Evolution |
| MB | MegaByte ($2^{20}$ = 1,048,576 Bytes) |
| MIMO | Multiple Input, Multiple Output |
| MPEG | Moving Pictures Experts Group (ISO/IEC JTC1/SC29/WG11) |
| OFDM | Orthogonal Frequency Division Multiplexing |
| OLT | Optical Line Terminal |
| ONT | Optical Network Terminal |
| P2P | Point to Point |
| PCM | Phase Change Memory |
| PDP | Plasma Display Panel |
| PON | Passive Optical Network |
| PSNR | Picture Signal-to-Noise Ratio |
| PVR | Personal Video Recorder |
| QAM | Quadrature Amplitude Modulation |
| SVC | Scalable Video Coding (of H.264/AVC) |
| SDTV | Standard Definition Television |
| SFN | Single Frequency Network |
| SI | Service Information (defined by DVB) |
| SSD | Solid State Drive (e.g. Flash Drive) |

| | |
|---|---|
| STB | Set-top-box |
| TB | TeraByte ($2^{40}$ = 1,099,511,627,776 Bytes) |
| TDMA | Time Division Multiple Access |
| UHD | Ultra High Definition |
| UHDTV | Ultra High Definition Television |
| UMTS | Universal Mobile Telecommunications System |
| USB | Universal Serial Bus |
| VBR | Variable bit-rate |
| VDSL | Very high bitrate DSL |
| VOD | Video on Demand |
| W-CDMA | Wideband-CDMA |
| WDM | Wavelength-Division Multiplexer |
| Wi-Fi | Wireless Fidelity (IEEE 802.11) |
| WiMAX | Worldwide Interoperability for Microwave Access (IEEE 802.16) |
| WLAN | Wireless Local Area Network |
| xDSL | Generic term for the DSL family of standards |

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